UNIVERSITY OF CAPE COAST

ASSESSMENT OF THE ECOLOGICAL, GROWTH AND MORTALITY PARAMETERS OF *Crassostrea tulipa* IN SELECTED WATER BODIES IN GHANA AND THE GAMBIA

BY

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Thesis submitted to the Department of Fisheries and Aquatic Sciences of the College of Agriculture and Natural Sciences, University of Cape Coast, in partial fulfillment of the requirements for the award of Master of Philosophy Degree in Fisheries Science

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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……………………...

Name……………………………………………………………………………

Supervisors' 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.

Principal Supervisor's Signature…………………………. Date……………..

Name…………………………………………………………………………

Co-Supervisor's Signature……………………………… Date……………..

Name……………………………………………………………………

ABSTRACT

This study carried out a comparative assessment of the shellfish fishery in six water bodies; three in Ghana (Densu, Narkwa and Whin) and three in The Gambia (Allahein, Bullock and Tanbi). It assessed the ecological, growth and mortality parameters of *Crassostrea tulipa* in these waterbodies for 12 months from March 2021 to March 2022. Findings revealed that, the water bodies in The Gambia were generally deeper, less turbid and with better salinity ranges that enhanced the survival of the oysters than the Ghanaian waterbodies. This contributed to better condition indices and bigger sized oysters at the sites in The Gambia. *Crassostrea tulipa* at all the six sites significantly deviated from isometric growth. They were short-lived species with higher growth rate (K/yr) values and higher natural mortality (M/yr) values. Z/K ratios showed that the populations were mortality induced (natural mortality) although Bullock and Narkwa showed fishing induced mortality. The $E_{current}$ at these two sites also showed an overfished population. $Lc_{50}/L\infty$ ratio suggested growth overfishing in Ghana while those in The Gambia were of appropriate sizes. All the populations significantly deviated from a 1:1 sex ratio except Allahein in The Gambia and Densu in Ghana. The estimated maturity size indicated that the species in both countries all attained maturity before they were harvested except Densu in Ghana. All the harvesting sites in The Gambia were running some form of co-management structure in conjunction with the Gambian government where restrictions such as seasonal closures, size restrictions, were in place. In Ghana, Densu also has co-management modalities led mainly by the women shellfishers and supported by the Government, Densu and Tanbi have co-management plans and have been granted exclusive use rights. The fishers in these jurisdictions were better off in income than oyster fishers in Ghana.

KEY WORDS

Catch per Unit Effort

Growth

Hydrographic factors

Mortality

Reproductive capacity

The West African Mangrove Oyster, *Crassostrea tulipa*

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DEDICATION

To my sister, Halima Abdallah, and my family.

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CHAPTER ONE

INTRODUCTION

Ghana's economy relies heavily on its fishery resources, which have also made substantial contributions to Ghana's socioeconomic growth. This is evidenced by the fact that fisheries alone support about 3 million Ghanaians both directly and indirectly and contribute about 1.5% to the nation's GDP (FAO, 2016). Ghanaians have a very vibrant fish-eating culture as reports have shown that fish is projected to provide 60% of the animal protein needs for both the poor and the affluent (Dovlo *et al.*, 2016*;* Mohanty *et al.*, 2019); while finfish is generally complemented by shellfish.

The West African Mangrove Oyster *Crassostrea tulipa* (Lamarck, 1819) is found along the coast of West Africa from Senegal to Angola (Yankson *et al.*, 1994; Sutton *et al*., 2012). It has significant economic potential and is now the focus of study in the sub-region. *Crassostrea tulipa* is a bivalve and comprise the phylum of Molluscans. They are highly suited to harsh environmental conditions and are known to reside in estuarine systems. They may also be found on the bottom soil or stuck to hard things like rocks or mangrove roots (Obodai *et al.,* 1991; Yankson, 2004). In West African coastal towns, oyster meat serves as an economical form of dietary protein for local residents, and the shell can be utilized further for building materials, poultry feed ingredients, and traditional medicines (Asare *et al.,* 2019). Additionally, oyster harvesting provides some form of employment and alternative livelihood to those exploiting it (Osei *et al*., 2020a).

Currently, oyster production is purely capture-based and there is not much available regional data (Chuku *et al.*, 2020a) detailing the characteristics of aspects of their biology, level of exploitation, or environmental impacts on their survival. Predominantly, the means of income of the oyster harvesters are fishery-based, engendering high level of dependency. With the oyster fishery being an unrestricted and open-access resource (Osei *et al*., 2020a), this has led to unreserved utilization causing a decline in the oyster population and loss of habitats (Osei *et al*., 2020a).

It is described as an 'invisible fishery' (Chuku *et al*., 2021), due to the sparse literature on biological and ecological data such as stock sizes, the impact of environmental conditions on growth and reproduction; and as a result, informed management decisions cannot be put in place to sustain the fishery.

The objective of this research was to describe the state of the shellfish fishery through stock assessments, where aspects of their growth, reproduction, ecological effects on their survival, and level of exploitation in their natural habitat will be assessed.

Background to the Study

70% of the planet world's earth surface is covered by coastal ecosystems and provide a thriving livelihood for coastal dwellers. Fisheries play critical roles in food security, livelihoods and economic development globally (Amadu *et al*., 2021). Shellfish fisheries are an important aspect of small-scale fisheries in most undeveloped nations. It has been estimated that shellfishery in the Densu estuary alone contributes an annual catch of 238 to 352T appraised at a value of $ 56,193-$74,902 (Osei *et al*., 2020a). The United Nations (UN) Sustainable

Development Goals (SDG) 14: life below water pays critical attention to the management and sustainable utilization of our aquatic resources and is a major priority for the Agenda 2030. SDG 14, aside from conservation; puts emphasis on the people and coastal societies that are dependent on these resources, especially those in developing countries (FAO, 2016). However, declining global fisheries production in the face of increasing world population, climate change effects, and environmental degradation is a source of threat to global food security and social welfare (Amadu *et al.*, 2021).

The species had previously been exploited in Ghana, but sparingly and mainly in three coastal communities: Ekumfi Narkwa in the Central Region, Tsokomey in the Greater-Accra Region, and the Whin Estuary in the Western Region, where there is concurrently a substantial oyster harvesting activity. Women and children, especially during low tides, are typically involved in the collection of oysters from shallow near shore intertidal regions, either from oyster beds or mangrove roots. through handpicking. Besides, an investigation by Asare *et al*. (2019), and Atindana *et al*. (2020), show that, although women form the majority of oyster harvesters in Ghana; in the Whin estuary (80 women in number) and Narkwa lagoon (89% of the oyster harvesters) respectively, a smaller number of men are also involved in the venture, especially with cockle harvesting. In The Gambia, the same can be observed. In the Tanbi wetland system alone, they are about 500 women exploiting the water body (Chuku *et al*., 2020). These women have been given exclusive rights by the government to exploit the resources and ensure their management and sustainability.

Bivalves are a large class of molluscs, also known as Pelecypods. They have an invertebrate with a soft body that is housed inside a two-part, hinged shell that serves as their exterior covering. The majority of bivalves lack the radula and the odontophore, two typical molluscan organs, as well as the head. There are over 9,200 living species of bivalves inhabiting the sea or brackish waters and the best known examples are clams, mussels, scallops and oysters. Oysters belong to the family Ostreacea in the bivalve class of the phylum Mollusca. Most of the commercially significant species are grouped under the three major genera; Ostrea, Crassostrea and Saccostrea, using the current systematic structure and a number of other minor genera (Carriker and Gaffney, 1996). The adults of this species live on the bottoms of the intertidal and subtidal zones all around the planet. The shell morphology of the oysters is erratic and that sets them apart from other bivalves. Environmental factors primarily determine the form of the shell, and they can develop over or around nearby objects, including other oysters. Oysters are plankton feeders, and they filter microalgae and maybe bacteria using their gills.

Adult oysters globally, inhabit intertidal zones or are bottom dwellers. They differentiate from the rest of the bivalves with their irregular shell morphology; and that is characteristically dependent on their environmental constraints. They have the ability to grow on or around nearby hard surfaces; even on other oysters. They feed on plankton by filtering bacteria and micro-algae with their gills.

For Ghanaians, the West African mangrove oyster (*Crassostrea tulipa*) is a significant bivalve seafood source (Obodai *et al.*, 2010). Their meat, has a high nutritional value just as it is for other bivalves due to its protein richness (Salaskar and Nayak, 2011) as well as other food nutrients like minerals, vitamins and fatty acids (especially omega-3 fatty acids), which has been commended for intake amongst women who are expecting or nursing (Reames, 2012). Additionally, oyster shells are extremely valuable commercially due to their numerous applications in the fields of construction, agriculture and medicine (Yankson, 2004).

One of the key components of fisheries management is a stock assessment, which is done to determine the extent of stock exploitation, define their present stock size and to estimate future yields (King, 2007). Management measures that emanate from this focus on ensuring optimum yield whiles promising biological and economic sustainability. In the tropics and ultimately, the West African sub-region, stock assessment is dependent on length-based data (Ofori-Danson and Kwarfo-Apegyah, 2008). Understanding the different population dynamics and exploitation levels is essential in managing molluscan resources. (Al-Barwani *et al*., 2007; Adjei-Boateng and Wilson, 2012) and this requires length/weight data of the organisms. Reproductive capacities of the organisms are also an aspect that should be understood to be able to predict the best/suitable period and condition for harvesting the species. It is also important to understand how the population responds to varying environmental conditions.

Statement of the Problem

Oysters, although are abundant, ecologically significant and economically important, little is known about their diversity, biology and ecology as well as their evolutionary history. The fishery for the West African mangrove oyster (*Crassostrea tulipa*) has been described as a complex socio-ecological system that is characterized by a 3-dimensional strong dependence of resource users (primarily women) on the biodiversity and stocks of oysters, which in turn are heavily reliant on the bio-physical environment with its intrinsic, chemical, and ecological characteristics. Oyster fisheries contribute immensely to the livelihoods of women engaged in the fishery, and to a variety of social and economic services in their households and in society at large (Gopal *et al*., 2012).

Along with the high level of dependency on this resource, is an escalated level of an unregulated fishery and this has led to an unreserved exploitation (Osei *et al*., 2020a). Again, Chuku *et al.* (2020) described the fishery as an invisible one due to insufficient literature on the biology and ecology of these species. With the increasing decline of fish production globally, which FAO (2020) reported a 1.65% fluctuation in fish production in 2018 from 2016, shellfish production is being increased to complement finfish production in order to ensure access to cheap protein and eradicate hunger (UN-SDG 2; Zero Hunger). This means there is a need for a comprehensive study of the biological and ecological data such as stock sizes, and the impact of environmental and climate conditions on their growth and reproduction, extend the regional scope of the study to The Gambia and beyond to help fisheries stakeholders make informed management decisions for sustainable exploitation of the fishery. In sum, there is intense pressure on the West African stocks of *Crassostrea tulipa,* yet no existing data is available to guide management.

Purpose of the Study

This study dwells on the fact that the species under consideration give coastal residents who engage in its commerce a solid and reliable source of income (women and children). Hence, the study seeks to compare and document data on *Crassostrea tulipa;* with a focus on their morphology, well-being, reproduction, stock size, impacts of environmental and climatic changes on the stock and exploitation levels of these species, from two different countries (Ghana and The Gambia) and six waterbodies in focus with the hopes that findings from this study will help promote sustainable exploitation of this resource for present generation and generations to come. In addition, it is anticipated that the outcome of the study will be beneficial to current and prospective oyster farmers.

Research Objectives

The primary objective of this research was to assess the ecological, growth and mortality parameters of *Crassostrea tulipa* in selected water bodies in Ghana (Densu Estuary, Narkwa Lagoon and Whin Estuary) and The Gambia (Allahein Estuary, Bullock Mangrove Area and Tanbi Wetland Area). These sites have an existing oyster shellfishery.

The specific objectives were to:

1. Examine the likely impacts of hydrographical and nutrient changes on the growth and reproduction of *Crassostrea tulipa* in each of the water bodies.
2. Evaluate the growth parameters, condition index, mortality rates and extent of exploitation of the oyster populations in the selected water bodies.
3. Determine the reproductive capacity of the species by estimating the sex ratio, maturity size, and breeding pattern.
4. Assessing the scale of shellfisheries in both countries and the management modalities in place for each of the sampling locations.

Significance of the Study

Crassostrea tulipa trade is a significant source of income for women, who typically work the trade in coastal areas alongside their children. in Ghana. It has the potential to enhance the production of shellfish for global consumption and it is being explored for commercial cultivation in many West African nations (Chuku *et al*., 2020a) in accordance with The United Nations (UN) Sustainable Development Goal (SDG) 2; to help eradicate hunger and ultimately, poverty. This study is of significance because it encapsulates the principles of socioeconomic independence, particularly for women and children and sustainability. The African Union (AU) and Economic Community of West African States (ECOWAS) have put in place policies for addressing food security challenges. This work contributes to the AU Agenda 2063 by ensuring healthy and well-nourished citizens, eradicating poverty, inequality and hunger. Although numerous investigations have been conducted to comprehend the biology of the species, not much scientific information is available to describe the dynamics of the stock population for better management and sustainable utilization.

This study attempts to examine how well the oyster fishery is doing in Ghana and The Gambia, by describing the growth, reproduction, the relationship between the stock and ecological factors affecting them as well as the level of exploitation of the populations in the water bodies selected. A preliminary 11-country assessment was carried out by USAID-URI with a detailed further study conducted in the Densu estuary by Osei *et al.* (2020). This work seeks to expand its scope beyond Densu to include Whin and Narkwa, in Ghana and The Gambia to improve data availability on oyster stocks in the West

African sub-region and provide a comparative assessment of the fisheries in both countries and if possible, replicate 'working' management regulations to strengthen the fishery.

Delimitations of the Study

Oyster species are found in most lagoons and estuaries but the aquatic systems considered for this study from both Ghana and The Gambia were chosen based on a number of factors. First, the sites selected are from a preliminary study carried out by USAID-URI, which noted that the fact that there was evidence of a robust oyster fishery in these communities, and that mostly women were involved made these locations considerably more significant. Additionally, the research fits the areas of interest of the funds allocated for the study. The selected ecosystems are generally shallow, therefore vertical stratification was not taken into consideration while sampling the physicochemical characteristics of the water in three replications within the water column at the individual stations. It was anticipated that there would not be much of a variation in the hydrographic parameters from top to bottom, as some stations sometimes are entirely exposed at low tide.

Limitations of the Study

Daily catch-effort data which are a crucial part of the study were being employed at the communities surrounding and exploiting the waterbodies under study. However, some communities had closed their season for harvesting at the time of the data collection both in Ghana and The Gambia.Tsokomey community in the Greater Accra Region, whose harvesters exploit the Densu estuary had closed the oyster harvesting activities until 30th April 2022 when the season opened and harvesting continued. The same also happened in Kartong-Allaheine. Although it can be noted as an uncontrollable limiting factor to the study, it affected the research in terms of collection of continuous catch and effort data.

Definition of terms

Aquaculture - It is the breeding/rearing of aquatic animals (finfish and shellfish) for food and income.

Bivalves – They are a large class of molluscs, also known as Pelecypods/ Lamellibranchiata. They have an outer layering in the form of a shell with two hinged parts and encloses a soft-bodied invertebrate that can be found in various aquatic habitats from freshwater to marine waters.

Stock – A group of individual species, of similar morphology, population parameters and habitat use, that occurs in a certain locality at one time**.**

Organisation of the study

Six chapters constitute this thesis. The topic, goal, objectives, and importance of the study are all stated in Chapter 1 which is the introduction, along with background information and other key concepts. A overview of the literature that is relevant to the research and its methods is presented in Chapter 2. The study's methodology and design are outlined in Chapter 3. Where applicable, diagrams are utilized. Statistical tools and techniques for data collection and analysis are presented, and the study locations are clearly drawn out. The study's findings are given in tables and figures with concise summaries in Chapter 4, and analysis and conclusions are formed in a discussion in Chapter

5. In Chapter 6, conclusions and recommendations are provided. The list of references and the appendices are additional sections included in this thesis.

CHAPTER TWO

LITERATURE REVIEW

This chapter analyses the literature relevant to the study that pertain to the biology and ecology of the West African mangrove oyster to establish the theoretical framework of the study. It focuses on the morphology of the species, their ecological importance, the physicochemical conditions that enhance their survival and reproduction, their growth, condition, exploitation and management of the fishery.

Bivalve molluscs

One of the most prominent, diverse, and vast categories of animals in the animal kingdom is the phylum Mollusca, which has at least 50,000 species documented and around 200,000 existing species. (Gosling, 2015). It inhabits nearly the entire world's oceans, from the warm tropics to the cold Arctic, and from the deep ocean to sandy and rocky shorelines. A few of them have even settled down near hydrothermal vents that are found beneath 13,000 feet in the Pacific Ocean. Bivalve molluscs, or simply bivalves, are species of the phylum Mollusca and the class Bivalvia. Within the Mollusca, bivalves are the second-largest class (Appukuttan, 1996). Typically seen as soft-bodied invertebrates, these creatures contain two distinct valves secreted by two mantle lobes that are joined at the dorsal end by a hinge (Gosling, 2015). The left and right valves of a bivalve's shell is produced mainly by the mantle edge's outer fold and kept together by an adductor muscle. Additionally, the mantle has an inner muscular fold that significantly regulates the flow of water into and out of the mantle cavity, which is caused by the cilia on the gills (Spencer, 2002). The material from the mantle's edge is added to the shell to increase circumference, while material from the general mantle surface is deposited to increase the thickness of the shell. The diet or seawater are the two sources of calcium for shell formation (Gosling, 2015). Although it is widely believed that oyster age may be estimated by their concentric marks, this approach might not be reliable. In order to get an accurate approximation, Kraeuter, Ford, and Cummings (2007) advocated sectioning the hinge plate in place of the technique. Bivalves breathe and eat by syphoning vast amounts of saltwater that is filtered via their gills (Leavitt, 2010).

In order to pull water into the mantle cavity, transmit it via the ostia, up to the exhalant chamber, and finally out the exhalant hole, lateral cilia are placed along the sides of the gill filaments (Gosling, 2015). The sexes are distinct in the genus Crassostrea (Quayle and Newkirk, 1989). Eggs are produced by the female gonad or ovary (ova). Spermatozoa are produced by the male gonad or testis. Gametes, or spermatozoa and eggs, are released externally into the open ocean in both situations, where fertilization occurs. The gametes are released from the genital pores, which exit into the exhalant chamber above the gills (Spencer, 2002).

Bivalves have a significant economic impact on many nations across the world, whether it is via the development of a successful industry or the provision of affordable protein to those in need. Although most tropical and subtropical nations utilize shellfish for sustenance, particularly bivalves and crustaceans, they still provide as a significant source of essential protein for many rural people, as stated by Quayle (1980). The calcium carbonate oyster shells are under risk due to the ocean waters' declining pH values. Lower pH levels may make saltwater more corrosive, which might make it more difficult for adult and young oysters to form and maintain their shells (La Peyre *et al.*, 2009; Barton *et al.*, 2012). It will be more difficult for oysters to obtain food from calcifying plankton species that need certain water chemistry to maintain their exterior calcium carbonate skeletons. Oysters are likely to be affected by rising ocean temperatures because they accelerate the melting of glaciers and polar ice caps and duration and frequency of toxic algal blooms, which raise the sea level.

According to reports by Osei *et al.* (2020b), biofouling has little effect on the development and survival of both wild and farmed oysters. Oysters function as a refuge and home for a variety of estuarine species, filter and purify the water, reduce coastal erosion, and are vital to preserving the quality of the coastal and marine environment in addition to supporting food security and enhancing incomes, providing protection from severe weather events like hurricanes (Ahn and Ronan, 2020).

West African Mangrove Oysters, *Crassostrea tulipa* (Lamarck, 1819)– biology and ecology

Along the Atlantic coastlines of Africa and South America, three species of mangrove oysters—*Crassostrea rhizophorae*, *Crassosterea rasiliana*, and *Crassostrea gasar (tulipa)*—have been discovered (Ajana, 1980; Lapegue *et al.*, 2002). Because *Crassostrea tulipa* (Lamarck, 1819) is a filter feeder like the other oyster species, it depends on the habitat's natural primary production of phytoplankton for nutrition (Adite *et al.*, 2013). They obtain nourishment by filtering a lot of brackish water and storing food particles (Efiuvwevwere and Amadi, 2015). The species can survive a wide range of temperature and salinity conditions since it has a built-in resistance to the harsh, adverse environments of marine intertidal areas.. (Ajana, 1980; Obodai *et al.*, 1991). Oysters from estuaries and lagoons both remain in good to excellent condition for the most of the year (Yankson *et al.*, 1994). Mature oysters are stimulated to reproduce by healthy nutrition and favorable environmental factors. Both sexes' gametes are discharged into the open water column, where chance encounters between male and female gametes result in fertilization.

Physico-chemical parameters of coastal systems

The West African coastline is defined by the existence of marginal estuaries with a variety of morphologies and origins that are encircled by significant densities of population (Amadi, 1990). Because they are interconnected with mangrove swamps, salt marshes and tidal flats, estuaries are among Ghana's most valued ecosystems. These wetlands are important coastal features in Ghana and serve as vital habitats for a variety of fish and animal species that are vital to the nation's economy. They are an essential resource for recreation, conservation, breeding places for commercially significant marine birds, and significant fisheries, including oysters (Dahanayayaka and Aratne, 2006; Blaber, 2008; Plavan *et al.*, 2011). Oysters most commonly cling to the roots of mangrove trees in these brackish environments, or, in the lack of such roots, to the stony substrate of the marsh bottom. In Ghana, not less than 90% of the southern coastal estuaries and lagoons have *C. tulipa* (Sultan *et al.*, 2012).

The environment has an impact on bivalves' ability to survive in the wild (Villarroel *et al.*, 2004). In general, the oysters of the genus Crassostrea are thought to be euryhaline creatures that can withstand the diversity of environmental variables (Quayle, 1989). Studies have revealed that *Crassostrea* *tulipa* and other bivalves' development and reproduction are significantly impacted by the hydrographic conditions present (Angell, 1986; Quayle and Newkirk, 1989; Obodai, 1997; Yankson, 2004; Buitrago *et al.*, 2009; Efiuvwevwere and Amadi, 2015; Asare *et al.*, 2019; Chuku *et al.*, 2020; Osei *et al.*, 2020b). These hydrologic factors include but not limited to temperature (18 - 33°C), dissolved oxygen (>1 mg/L), salinity (4 – 50 ppt), pH (6 – 8.5), depth (2 – 5m), and turbidity (5 – 25 NTU) (Obodai, 1997; Mahu *et al.*, 2022). The underlying premise is that when the oysters are not subjected to prolonged dramatic changes in the variables, or when the parameters are within their tolerance ranges, growth and reproduction of oysters are stimulated. Sedentary bivalve molluscs can survive a broad range of water conditions that are often present in their native estuarine or coastal environments; nonetheless, these variations in environmental variables have a significant impact on their growth rates and flesh condition.

Natural processes such as the weathering of nutrient-rich rocks, river input and regeneration result in the addition of nutrients to estuarine systems and other coastal water bodies (Nie *et al.*, 2018). However, nutrient concentrations in coastal ecosystems have grown due to population development in recent decades and other nutrient-sources, such as mining, agriculture, use of fossil fuels (atmospheric deposition), wastewater treatment facilities and other activities (Horta *et al.*, 2021). Because of this, eutrophication, which is regarded as one of the biggest dangers to the ecological health of coastal ecosystems, is directly linked to these increasing nutrient inputs, especially nitrate and phosphate (Malone and Newton, 2020). However, nutrients are considered to be one of the primary factors that influence phytoplankton production (Human *et al.*, 2018). Yet, a number of interrelated hydro-geomorphological processes as well as other physicochemical elements are involved in the intake and cycling of macronutrients that phytoplankton introduce into estuarine environments (Kuuppo *et al.*, 2006). Oysters, which depend on algae for their nutritional needs, and other estuary creatures, may suffer direct effects from low or high nutrient availability for algal formation.

Oyster physiological condition and growth

The amount of meat that fills the shell or its degree of body mass is described by the condition index of bivalves, which is significant in the fisheries (Quayle, 1980). It provides information on the species' commercial viability (Davenport and Chen, 1987), and it is prudent to keep record of the oyster condition index since it aids harvesters in selecting the best times of year to harvest (Davenport and Chen, 1987; Yankson, 2004). It is also a measure of how biotic and abiotic variables interact with the physiological state of bivalves. It is a crucial idea in fisheries management and may be applied to evaluate the condition and ability of any fishery to withstand fishing pressure. The development of intervention measures that fisheries managers can easily implement, particularly with regard to maintaining a healthy fish population through control of the fishing effort, can thus be facilitated by this simple approach and interpretation.

Seasonal variations in Condition Index are the result of intricate interactions between several variables. These include, but not limited to metabolic activities such as growth and reproduction; salinity, food and temperature (Hickman and Illingworth, 1980; Thippeswamy and Joseph, 1988). Hemachandra and Thippeswamy (2008) discovered that gonadal development prior to spawning causes an increase in overall size in most bivalves, since the gonad makes up the majority of the visceral mass (Krampah *et al.*, 2016).

According to Kamara (1982), oysters tend to be significantly smaller in size due to overpopulation among mangrove oysters growing in the wild, stress brought on by high ambient temperatures alongside unavailability of food at reduced water levels when the oysters are exposed. In both multi- and single-locality studies, the effects of food availability, current speed and water depth on oyster growth and condition have been investigated (Hicks and Tunnel, 1995) to give perspective to different growth processes in the bivalves.

According to Vakily (1989), the combined effects of a variety of environmental conditions, including food supply, water temperature, settling density, currents, exposure and pollution, may cause disparities in metabolic growth rates. Due to the complexity of the influences of the many factors, it is challenging to quantify these existing correlations between growth and environmental factors (Vakily, 1992). The constant b, sometimes referred to as the coefficient of allometry, is used in length-weight growth studies to indicate the degree at which the respective animal body is changing form throughout growth (Thejasvi *et al.*, 2013). Most bivalves have a growth coefficient (b) that ranges from 2.4 to 4.5 (Wilbur and Owen, 1964); when b = 3, the relationship is considered to be isometric (Carlender, 1977).

Oyster reproduction

Studies have been conducted to comprehend the reproductive biology of *Crassostrea tulipa*, one of the shellfish resources that has been frequently considered for cultivation (Kamara, 1982; Yankson, 1996). In open lagoons, oyster breeding is continuous, but seasonal in estuaries and closed lagoons, according to preliminary studies on oyster numbers by Obodai *et al.*(1991). This sexually is identified as protrandric hermaphrodites, initially differentiating as males and then, in some cases, as females to achieve a 1:1 sex ratio (Yankson, 1996). The ability to describe a species' reproductive capabilities necessitates understanding the sex ratios. Studying a species' reproductive cycle is crucial for managing its fisheries (da Costa *et al.*, 2012).

The process of sexual identification involves histologically preparing the gonads or visually examining wet gonad smears under a microscope. However, the most accurate techniques for examining the bivalve reproductive cycle are those based on the gonads' histology or squash preparations (Gosling, 2003), in which evaluations are done periodically throughout the year to spot changes in the morphology of the gonad tissue over time (Seed, 1976; Seed and Suchanek, 1992). Due to several biotic and abiotic variables, marine bivalves have been observed to have yearly, semi-annual, or continuous reproduction cycles (Newell *et al.*, 1982). Food (phytoplankton) for oyster development is often easily available in tropical seas (Quayle and Newkirk, 1989). As a result, the animals may breed all year round (Angell, 1986). Yankson (1996) reported that changes in the environment might be responsible for the observed sexual distinction as a reproductive strategy. The oysters guarantee breeding success and larval survival even in unfavourable circumstances by ensuring higher proportion of differentiated females in the population to the males because, a few males are able to generate enough sperms to successfully fertilize eggs from a higher number of females. Therefore, the rapid increase in the proportion of females in the young estuarine oysters may constitute an adaptive trait against impending environmental mortality and this may cause a shift in the sex ratio of the population.

Estimation of growth parameters

Improving stock assessment and fisheries management requires an understanding of bivalve population dynamics, including recruitment, growth, and mortality (Sparre and Venema, 1992; Cadima, 2003). Millions of people who largely rely on these resources for their livelihoods and socioeconomic well-being may suffer tremendous damage if the populations are not managed effectively. A thorough understanding of population dynamics and the ability to establish causal relationships between management actions (such as harvest control rules) and a population are prerequisites for developing management methods that successfully conserve stocks and optimize sustainable yields (Cochrane, 2002). Bivalve growth indices and death rates are therefore essential inputs for stock evaluations. This is owing to the fact that they provide valuable insights on the variation of bivalve size and the loss in population biomass brought on by fishing and/or other natural factors (Pauly, 1984; Santos *et al.*, 2022).

In comparison to age data, length-based approaches have been employed extensively in the tropics to estimate aquatic fish species. Due to the stated difficulties in aging tropical fish and shellfish and the simplicity with which length-based data may be gathered, length data are preferred Pauly, 1984; Ofori-Danson and Kwarfo-Apegyah, 2008). Numerous mathematical models have been developed as a result of this circumstance, using length-related data to estimate growth and mortality factors (Pauly and David, 1981; Gayanilo *et al.*, 2005).

In order to determine the population characteristics of bivalves (oysters), multiple size and growth relationships are established using shell morphometrics. Bivalves' growth performance may be affected by environmental variables, and as a result, bivalves from various geographical regions may have varying growth performance indices that may be due to the local environment. According to Henderson (2006) and Garca-Berthou *et al.* (2012), fluctuations in temperature, light, and food availability are responsible for the seasonal growth in bivalves. In fact, the parameters influencing their growth vary from species to species as well as from stock to stock within a single species. There is some biological interpretation of the parameters. $L\infty$ is also known as the "asymptotic length" and is defined as "the mean length of very old (strictly: infinitely old) fish". The "curvature parameter", K controls the fish's rate of approach to its $L\infty$. Some species, the majority of which are short-lived, nearly reach their $L\infty$ in a year or two while also having a high K value. Other species take several years to attain anything close to their $L\infty$, and their development curves are flat with low K values. The fish's initial length is determined by the third parameter, t_0, sometimes known as "the initial condition parameter." (Pauly and David, 1981).

Estimation of mortality rates

Bivalve mortality is an indicator of the loss of bivalves due to death. Either natural or fishing mortality occurs in fisheries that are overfished. Natural mortality is used to describe all causes of death that are not related to anthropogenic harvest. These include diseases, predators, unfavorable environmental circumstances (such as pollution), competition, cannibalism, or any other factor(s) that might result in fish mortalities (Ahmad *et al.*, 2018). On the other hand the removal of bivalve stock by any fishing method is termed fishing (harvest) mortality (Enin, 1995). The decline in oyster populations over time may be caused by mortality. Natural mortality, (M) and fishing mortality (F) are instantaneous rates that are added together to estimate the instantaneous total mortality coefficient (Z), where Z=M+F. (Gulland,1969). These rates are typically computed annually. To predict the yield levels that would be attained under different exploitation scenarios, mathematical yield models often include estimates of fish mortality rates. These are employed in bioeconomic studies of fisheries or as resource management metrics. The main-stream commercially exploited fish and shellfish populations globally lack an accurate stock assessment due sparse data for evaluating biodiversity and stock mortality due to fishing (Sultana *et al.*, 2022).

Oyster exploitation and economic importance

Due to their widespread distribution, increased ecological and economic interest, and high visibility, mangrove oysters have received a lot of media attention. Men and women work together in the fishing business in Africa with distinct roles, despite cultural variations between the different nations. In the majority of West African nations, the women process and market the fish while the males actively participate in fishing (especially in marine fisheries) (Du Preez, 2018; USAID FtF and Biodiversity COMFISH Plus Project, 2018). Traditional beliefs and socially created conventions prevent women from participating in fishing, but some communities allow women to finance fishing expeditions or buy boats and related fishing equipment (Torell, *et al.*, 2015; Du Preez, 2018; Owusu, 2020). Therefore, in Africa's fisheries, women are extremely important. Women who live near inland and small coastal waterbodies, such estuaries and lagoons, harvest fish like oysters and crabs, among other species. In the sub-region, the majority of the responsibilities executed by womenfolk in the fishing industry are occasionally considered an extension of their domestic responsibilities and are not knowledged in policy and management planning. Women who work in the fishing industry are significant to the survival of their families. They also provide a considerable contribution to the majority of fisheries and aquaculture activities in addition to their domestic interests. A myriad of social and economic services are offered by women in fishing communities both in their homes and in society at large (Gopal *et al.*, 2012).

Only 5% of oyster populations worldwide are considered to be "wild," according to Jeremy Jackson's landmark 2008 article on the ecological collapse of the world's fisheries. Today, reef beds around coastal estuaries are where the majority of oysters consumed worldwide are formally cultivated (Crow and Carney, 2012). The West African mangrove oyster, *Crassostrea tulipa* (Lamarck, 1819), offers an economical source of protein, vitamins, minerals, and fatty acids (which pose no risk to human cholesterol levels, Agbekpornu *et al.*, 2022), employment opportunities and alternative livelihoods (Ajana, 1980; Ansa and Bashir, 2007) for a large number of coastal communities in Ghana (Yankson, 1990; Asare *et al.*, 2019; Osei *et al.*, 2020a, 2021). Currently, they are commonly accessible and cheap. The sale of oysters supports the diversification of livelihoods, which potentially reduces poverty. Oyster shells are utilized in the building industry as a foundation filler and as a component of paint. Shells are also used to fill flooded areas and to fill mud homes to stop erosion after heavy rains. In the cosmetics industry, shells are used as a component of face powder. They are also utilized in animal husbandry as component of animal feed and a treatment for livestock and poultry. After the meat is removed, the liquid remaining in the shell is used to stop bleeding, and the shells themselves are used to cure wounds (Janha *et al.,* 2017; Osei *et al.,* 2020a). In addition, oysters are essential for maintaining the health of the oceans because they shelter countless estuarine species, clean and filter the water, minimize bank erosion, and function as a barrier against hurricanes and other severe weather (Mahu *et al.,* 2022). Improved environment for many biodiversity-enhancing plant and animal species would result from more sustainable oyster management techniques, which would also enhance mangrove conservation, regeneration, and re-establishment. Fish spawn among mangroves, and birds and insects live there as well. When the shells are not properly disposed off, their abrasive quality hurts kids (Janha *et al.,* 2017).

According to Botta *et al.* (2020) although being globally promising, oyster production is inhibited by regulatory problems among other things. Therefore, the fisheries needs to be managed through sound analytical techniques for a sustainable exploitation. Oysters are a strong candidate for the assessment of seasonality in tropical fish populations due to their sessile character, which means they are still susceptible to the effects of changing environmental conditions. In the foreseeable future, the world's oyster fishery might severely diminish as a result of the aggregated effects of climate change, environmental degradation such as overharvesting of mangroves and other forms of pollution and ocean acidification. It has been estimated that, more than 85 percent of total of coral reefs are being destroyed worldwide (Mahu *et al.,* 2022). Acquiring nutrition, principally protein, is a key universal worry for the mounting human populace since many wild fish species are overexploited and there is a limited amount of livestock and agricultural production. The artisanal fishing sector within the gulf includes an important and unique subsector called oyster fisheries, which has a substantial economic impact in Ghana, Benin, Sierra Leone, The Gambia, Senegal, and Nigeria. The oyster fishery in West Africa is dominated by women, and thus aiding in addressing the accessibility to, including the utilization of marine biodiversity, as well as the gender imbalance that occurs in the wider fishing business. In addition to significantly assisting vulnerable populations' nutritional and financial needs, oyster fishing also contributes significantly to the region's economy. In underserved communities across the region, the involvement of women in the oyster industry has made a substantial contribution to reducing poverty and improving food security. (Jimoh, 2010; Carney 2017; Atindana *et al.*, 2020).

However, the industry confronts enormous uncertainties due to the effects of climate change, environmental degradation, and rising fishing pressure (Mahu *et al.*, 2022). Climate change has a variety of impacts on oyster ecosystems and their reefs. Due to the acidity of the ocean due to rising CO_2 emissions, existing reefs are being destroyed and their shell strength is at risk (Atindana *et al.*, 2020). The ideal ranges for their development and survival may be exceeded by rising temperatures brought on by global warming. Oysters and their predators will interact differently because of the changing environment brought on by climate change.

Their numbers have reportedly declined dramatically over the past few decades despite their significance. Over 85% of oyster reefs have reportedly already been destroyed globally, according to Beck and Brumbaugh, and the health of the remaining 15% is reportedly deteriorating. In order to increase output and support livelihoods, recent research have centred on prospects for culture, sustainable agricultural production, and enhancement of native populations of the mangrove oyster. The main causes of declining oyster populations include both climatic (such as temperature, precipitation, and their fluctuation) and non-climatic (such as overharvesting, pollution, mangrove degradation, and disease outbreaks) variables (Atindana *et al.*, 2020). Oysters are disadvantaged compared to other fish species because, as adults, they remain sessile, which hinders them from migrating and evaluating shifting water conditions.

Oyster fishery in Ghana

Fishing has been the primary source of food for people who exploit fish. Some of the many benefits of fishing are the security of food supply, the creation of jobs, and rewarding commercial enterprise (Globefish, 2014; Yankson, 2004). According to statistics, oysters accounted for 54% of the world's production of both cultivated and wild bivalves, while scallops provided 24%, 18% came from mussels, and clams contributed 4%. (FAO, 2018). In Ghana, these shellfish are exploited wild stock (Osei *et al.*, 2020a). Ghana has the latent to expand its local shellfish industry given the state of the fisheries sector presently. By addressing the protein demands of the folks in coastal areas and preventing catastrophes related to food insecurity that are projected to occur in a decade, the expansion of the shellfish trade will increase offshore artisanal industry landings, especially the small pelagics, which are currently in decline and crisis. In a few isolated coastal settlements in Ghana, oyster harvesting has been going on both actively and passively, and it is typically considered as an open access fishery (Chuku *et al.*, 2020a; Osei *et al.*, 2020a). However, it was observed that certain communities were engaging in an active type of fishing with some management strategies in place; three of these communities were chosen for this study (Densu, Narkwa and Whin). Oysters were not sold in Ghana until ten years ago (Janha *et al.*, 2017). However, in recent years, the market value of oyster products has been increased by processing the meat by seasoning, frying, smoking, and packaging it for sale. The livelihoods of small-scale coastal fishing communities are severely impacted by the depleting marine fish stocks, which are likely caused by climate change and other environmental pressures. The provision of alternative sources of income has therefore become important in recent years as a means of alleviating food shortage and generating occupation. Small-scale, subsistence fishing communities are considerably more at risk. Traditional food fisheries in these communities are rapidly declining and that has been attributed to overfishing and habitat degradation, according to Aheto *et al.* (2011). Consequently, there is a high rate of poverty and hunger, especially in societies with unrestricted access to fisheries and narrow options for generating income (Béné and Friend, 2011; Baker-French, 2015). According to the FAO (2006), Ghana's small-scale fishing communities have a poverty and malnutrition rate of over 46.3% of their population.

Strong management systems must be put in place to protect the oyster resources because the fishery's open access nature results in unreserved exploitation. A co-management strategy for the Densu Delta oyster fishery was created in Ghana (Chuku *et al.*, 2022). The Densu Oyster Pickers Association and Development Action Association, a non-governmental organization, worked together locally to implement the project. They used a model in which their actions were programmed. For instance, shellfish harvesting was prohibited during the customary rituals that typically precede traditional festivities such as Homowo for Gas. At other Ghanaian oyster harvesting locations, same practice is also carried out. There were fishing holidays at numerous coastal shellfish harvesting spots around the region, which are believed to historically been sacred days for the gods. Oyster gathering in the Densu estuary is traditionally a female-dominated occupation, like many artisanal shellfish fisheries in the global south, while some men also participate in this industry. Women's work as oyster pickers in this area has either gone unnoticed, been grossly undervalued, or not been documented at all. Members of the Densu Oyster Pickers Association (DOPA) were assisted by the USAID/SFMP initiative in gaining knowledge, self-assurance, leadership, and advocacy skills (Osei *et al.*, 2020a, Chuku *et al.*, 2021; Chuku *et al.*, 2022).

Oyster fishery in the Gambia

Female user groups in Senegambia have harvested and processed mangrove oysters without significant harm to the mangrove ecosystem going back to the earliest records of their activities (Crow and Carney, 2012). those who eat and earn their living off TWNP oysters. A huge percentage of the oyster collectors were economically disadvantaged women who were either widows or divorcees with dependent children. Consequently, the ability of wild populations to restock was negatively impacted by the increased commercialization of immature oysters (Ngaido, 1990). When oysters became scarce close to Banjul, the capital, female collectors used boats to travel further into the Tanbi wetlands. In large measure, it was discovered that the mangrove and estuarine ecosystems of West Africa were accessible to all. The majority of the locations where shellfish were harvested either lacked formal regulations or legislation to regulate the shellfisheries and mangrove systems, or the resource users were unaware of them (Chuku *et al.*, 2022). Nearly all the sites selected for this study have been designated as Ramsar sites (Allahein estuary, Bullock mangrove area and Tanbi wetland systems). Potential shellfisheries can be found on more than 495,000 hectares of coastal Ramsar areas throughout the region. Explicit and formally recognized community-based regulatory frameworks are present in The Gambia. Among them are regulations for the Tanbi Wetlands National Park in The Gambia's cockle and oyster harvest (The Gambia Ministry of Fisheries Water Resources and National Assembly Matters, 2012).

The Gambia had the most formally recognized community-based women's groups in the West African subcontinent (Chuku *et al.*, 2022). The TRY Oyster Women's Association in The Gambia is the only national organization for women who work in the shellfish industry that has membership from official satellite groups in various local communities. They are an independent parent organization that serves as an umbrella for a number of officially recognized satellite community-level oyster women groups. They are resource-user-led. Chuku *et al.* (2022) noted that the association has made sure that female shellfishers are represented at the decision-making table and that management plans that conserve the resource and benefit resource users are carried out.

CHAPTER THREE

MATERIALS AND METHODS

The materials and methods used to carry out this research are comprehensively outlined in this Chapter. The study sites are included, along with any illustrations that are required to clarify the methodology used for the study. Inferential software and statistical analysis tools are also factored in.

Study sites

The study was conducted in six water bodies from six different coastal communities in Ghana and The Gambia to comparatively assess the ecology and stock of the West African mangrove oyster species and its fishery in both countries. These water bodies constituted four estuaries, a lagoon, and a wetland area (Table 1). The selection of the sites was based on several metrics but prominent amongst them is the presence of thriving populations of *Crassostrea tulipa* and the presence of an oyster fishery/shellfishing livelihood (Asare, 2019; Janha *et al.*, 2017; Chuku *et al.*, 2020a; Chuku *et al.*, 2022). The site maps in Figure 1 and Figure 2 depict geographical aerial views of the study sites captured with an Unmanned Aerial Vehicle (UAV).

Table 1*: Summary of study areas selected from each country*

COUNTRY	STUDY LOCATION		
Ghana	Densu estuary	Narkwa lagoon	Whin estuary
The Gambia	Allahein estuary	Tanbi wetland	Bullock mangrove area

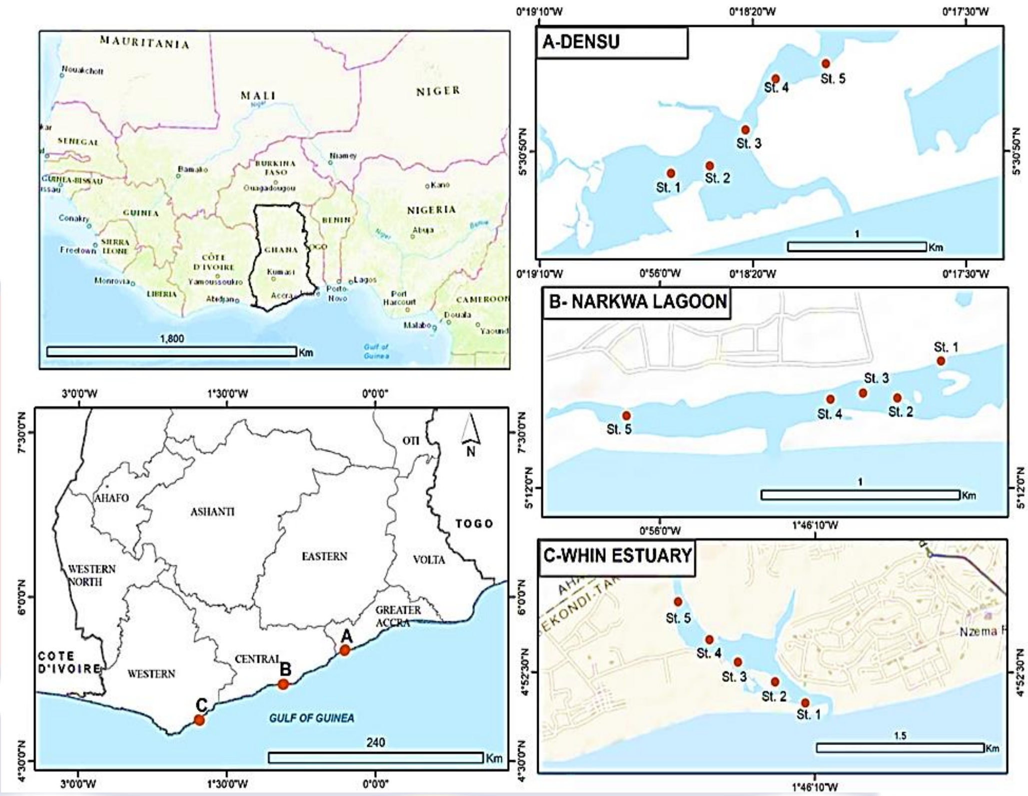

Figure 1: Map of Ghana showing the selected sites and sampling locations at each site.

Densu estuary

The Densu estuary (Figure 1A), located in the Greater-Accra Region, takes its source from the Densu River which begins in the East Akim Abuakwa District of Ghana's Eastern Region, in the Atewa Mountains (Oteng-Yeboah, 1996). The river is dammed upstream; known now as the Weija Dam, and splits into smaller rivers that empty into the sea downstream. The spilling/overflowing of the dam and its subsequent shutting during and following the wet season, respectively, control how much freshwater enters the system (Chuku *et al.*, 2020a). The estuary also serves as a feeding and breeding site for migrating birds, crabs, and fish. Its sandy bottom offers a good substrate for an enormous of the West African mangrove oyster. The oyster bed sometimes gets exposed at low tides. The study focused on the southern part of the river where the estuary is located (Figure 1A) with a thriving oyster population. The communities, which surround the Densu Estuary namely, Bortianor, Tsokomey, Tetegu and Faana, comprise about 54.8 % Gas, 32.7 % Ewes, and 8 % other tribes, as reported by Dadson (1995). The Tsokomey community served as the study's entry point. The people in this community mainly engaged in fishery-related activities (Figure 2). Additionally, the fishing gears and techniques employed by these fishers include oyster handpicking, ‘acadja’ (brush parks), castnet, drag-net (seine), and traps (Osei *et al*., 2020a).

The majority of the women who engage in oyster fishing actually rely on their children for support (Janha *et al.*, 2017; Chuku *et al.*, 2020; Osei *et al.*, 2020a). They were drawn to the industry because it requires little capital and the oysters can be easily harvested by handpicking in shallow waters without the need for swimming expertise. According to Chuku *et al.* (2022), there are 150 women and 10 men who work as oyster divers. The Fisheries Commission of Ghana’s Ministry of Fisheries and Aquaculture Development created a community-based management plan for the oyster fishery with help from the local NGO, Development Action Association (DAA).

Figure 2: Summary of fishing and fishery-related activities ongoing in the Densu estuary.

Narkwa lagoon

The Narkwa lagoon system (Figure 1B) is located in the Ekumfi District in the Central Region of Ghana and orients itself parallel to the Gulf of Guinea with a somewhat centrally placed mouth, which is usually open to the sea (Chuku *et al.*, 2020a). The lagoon is fed by one of the tributaries of the Okye River which discharges itself into the sea through the lagoon. Although Asare *et al.* (2019) described the lagoon as largely open; Chuku *et al.* (2020a) observed that the mouth of the lagoon occasionally closes by a sand bar, and that this occurs once in few years, creating floods within the low-lying settlement. After a few months, the riverine source's water force breaks the sand bar, or it is mechanically opened by a bulldozer to prevent floods. The main livelihoods of the residents of the hamlet are farming, oyster and cockle harvesting, and fishing. The oyster species are found on the sandy/muddy bottom areas of the lagoon. Men are mostly responsible for landing finfish, whereas women are in charge of shellfish. In a 2016 study, women made up roughly 89% of the shellfishers (Asare *et al.*, 2019), but males play a participatory role in cockle harvesting.

Whin estuary

The Whin estuary (Figure 1C) is located on the eastern fringes of New Amanful, a suburb of the Takoradi Township in the Western Region. The estuary positions itself oblique to the sea and it is generally a shallow system with some deeper portions. The communities, which exploit the Whin estuary with female and male oyster collectors, are New Amanful, Adakope, and Apremdo (Atindana *et al.*, 2020). The Whin River continuously supplies freshwater to the estuary. The estuary is a major source of income for the residents of New Amanful, who primarily rely on fishing and shellfish harvesting (Figure 3). Women primarily harvest oysters, but the males fish for shrimp among other species in the estuary. There are about 80 women oyster harvesters in the surrounding communities (Atindana *et al.*, 2020). When compared to other sites in Ghana, the estuary supports significantly denser mangrove vegetation and a fish community that is highly diversified (Chuku *et al.*, 2020a). Unfortunately, there is evidence of community members actively cutting down mangroves for various purposes.

Figure *3:* Summary of fishing and fishery-related activities ongoing in the Whin estuary.

Allahein estuary

The Allahein River estuary (Figure 4A) is located at the border between Southern Senegal and The Gambia. Communities in The Gambia that utilize the Allahein estuary are Kartong and Berending and usually, their target resources are oysters and cockles to support their livelihoods. This body of water, aside from being of high ecological importance, also serves as a crossing point for community members between The Gambia and south Senegal. The crossing is done either with a boat or on foot at low tides. Mangrove vegetation is very abundant in this estuary and is guarded against indiscriminate cutting by management officials in the surrounding villages. The overexploitation of the shellfish resource, however, has proven to be a significant challenge because of the increase in the number of people harvesting from the Allahein estuary.

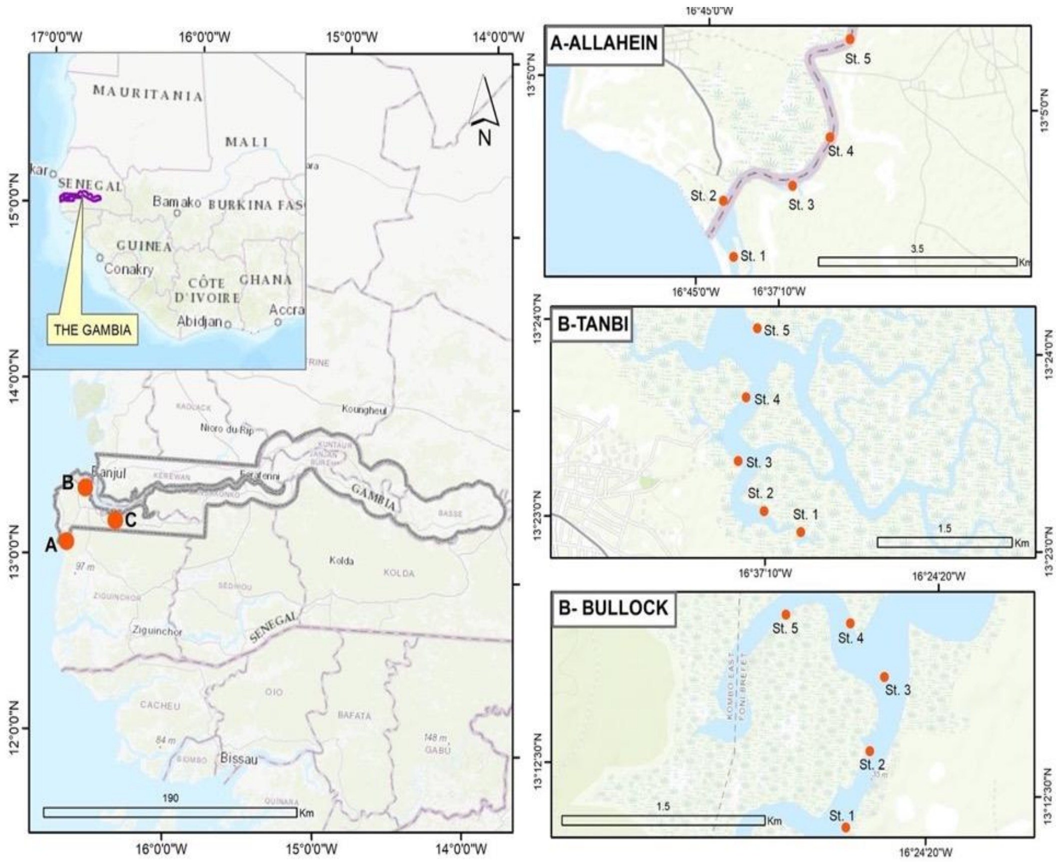

Figure 4: Map of The Gambia showing the selected sites and sampling locations at each site.

Tanbi Wetland Area (National Park)

The Tanbi Wetland National Park of The Gambia (Figure 4B) lies adjacent to the capital of Banjul located on the south bank of the Gambia River estuary in The Gambia. It covers the mangrove and oyster resources that are important for people's livelihoods (Figure 5). Its size is about 6300 ha (Crow and Carney, 2013) and supplies Banjul's large peri-urban population with fuelwood and construction materials, and supports the artisanal fishery industry (Satyanarayana et al., 2012). Tanbi was designated a RAMSAR site (No. 1657) in February 2007 and then gazetted as a national park in 2008 as a result of being prioritized by the worldwide conservation community as a "wetland of international importance" (RAMSAR 2011). (DPWM 2008). The key human activities in and around the park are rice farming, vegetable gardening, and shellfishing.

But notwithstanding the long track record of oyster harvesting in the area, which dates back at least as far as the 19th century and maybe even older, current modifications in oyster harvesting methods have started to harm the mangroves in Tanbi (Crow and Carney, 2012). According to Lau and Scales (2016), oyster harvesting is one of the main sources of income in the Tanbi, particularly for women. It is estimated that 507 harvesters, mostly women from the Jola ethnic group, work in this challenging but lucrative occupation for a living and that hundreds more could be engaged in related tasks like making white lime from oyster shells (Njie and Drammeh, 2011). The Gambia government has granted women shellfishers in this region exclusive usage rights to the oyster and cockle fisheries, as well as management power over the shellfishery (Dia, 2012.) This is the first time a national government has granted these rights to female shellfishers in sub-Saharan Africa

Figure 5: Densely populated mangrove roots exposed at low tide.

Bullock Mangrove Area

The Bullock mangrove area (Figure 4C) is located in the West Coast Region of The Gambia, approximately 50 – 70 km from Banjul (Chuku *et al.*, 2022). Along the Bullock-Berefet stretch, there are significant expanses of mangroves and several creeks, commonly referred to as "bolongs." Bullock, Sutu-Sinjang, Ndemban Chapechum, Besse, and Berefet are among the nearby communities that utilize the mangrove area's resources. Fishing, rice cultivation, and vegetable farming all benefit from the shallow water. Firewood collection from the mangroves proves a key livelihood for the folks. However, the coastal zone is under threat as a result of harmful anthropogenic activities mainly from the mangrove cutting, thus, local efforts by the community members are by replanting mangrove saplings to restore the lost ones. The women and their children are mostly seen harvesting the oysters, occasionally supported by their husbands for marketing (Figure 6). The women oyster harvesters in The Gambia mostly belong to the Try Oyster Women's Association.

Figure 6: Summary of oyster harvesting activities ongoing in the Bullock Mangrove area.

Study Design

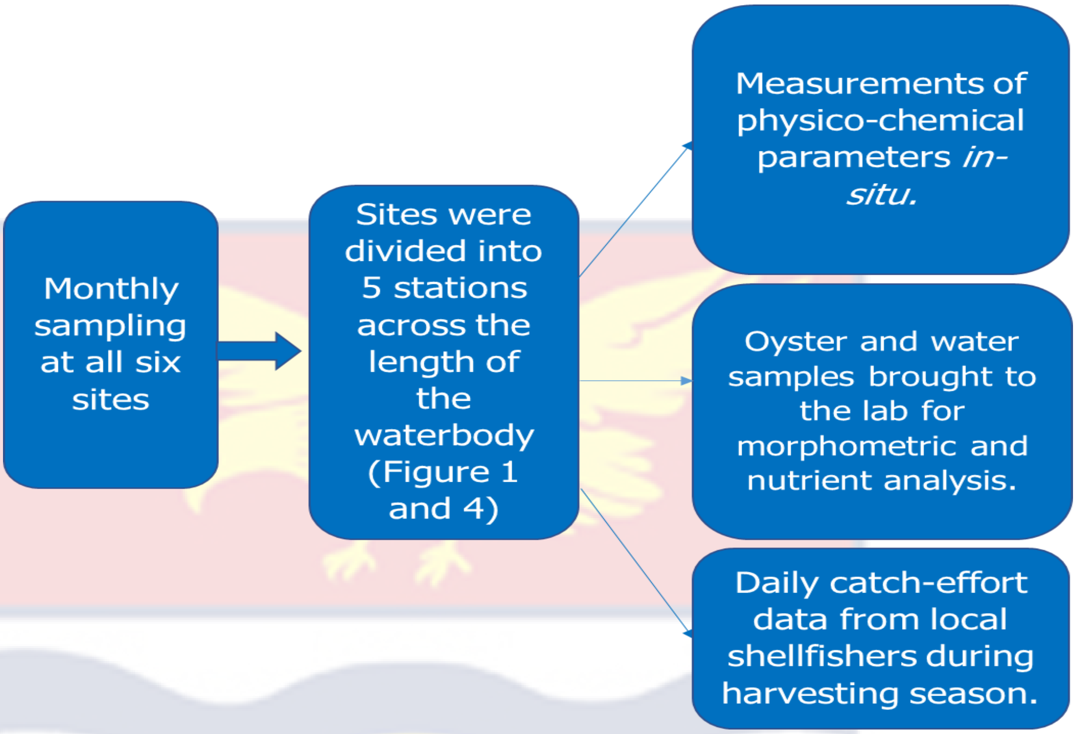

Figure 7: An illustration of the study design for the research.

Field Sampling and Data Collection

This study was part of the USAID-Women Shellfishers and Food Security Project; as such monthly sampling at low tides; with support from TRY Oyster Women's Association in The Gambia, was conducted for a period of 12 months, which spanned the wet and dry seasons from March 2021 to February 2022 in all the six water bodies. Water samples were collected, station-marked, stored on ice, and transported to the Fisheries and Coastal Research Laboratory at UCC for water quality analysis. At each sampling station, physicochemical parameters of the water bodies were determined in-situ using a multi-parameter water quality instrument and a refractometer with an in-built salinity scale. This was done in triplicates. Water depth was measured directly with the multi-parameter probe at each station. Oyster samples were collected from mangrove roots or handpicked from the waterbed and transported in a bag to the laboratory and scrubbed clean for further analysis. A minimum of 60 oyster samples were collected for each month of data collection. Samples were picked at random from each sampling station along the waterbody.

Measurement of physicochemical parameters and nutrient concentrations.

Physicochemical parameters measured *in-situ* were water temperature (T/°C), dissolved oxygen (DO/mg L^{-1}), salinity (ppt), and pH, with a multi-parametric water quality instruments checker (Horiba U-52 series) in triplicates at each of the five stations for each site. Turbidity (NTU), Nitrate (mg/L NO_3^-.) and Phosphate (mg/L PO_4^{-3}) concentrations were determined with the Hach DR 900 Colorimeter which uses the principle of absorbance spectrophotometry to operate.

For turbidity analysis, programme 745 was selected on the Hach DR 900 instrument. A sample cell was filled with 10 ml of distilled water to serve as a blank. The collected sample from the field was shaken vigorously and poured into a second sample cell up to the 10 ml mark. After zeroing the instrument with the blank, the prepared sample was wiped and inserted into the cell holder, covered and allowed to read. Results were recorded in NTU.

For nitrate and phosphate concentration analysis, the USEPA Powder Pillow procedure protocol was followed using the powder pillow reagents; NitraVer®5 and PhosVer®3 respectively. This analysis was carried out quarterly on the water samples collected in the months of June 2021, September 2021, December 2021 and March 2022. To analyze nitrate, the selected programme on the instrument was 355 N, Nitrate HR PP. A sample cell was filled up to the 10 ml mark with the sample collected from the field. Contents of one reagent powder pillow (NitraVer®5) were emptied into it and shaken vigorously for 1 minute and then placed down for a 5-minute reaction time. An amber colour formed immediately after the presence of nitrate was found in the sample. After blanking the instrument, the ready sample was cleaned and placed into the cell holder for reading. The results were recorded in mg/L NO_3^-. A similar procedure was used for the determination of phosphates using the PhosVer®3 reagent powder. The selected programme wavelength on the instrument was 490 P React. PP. After emptying the powder pillow reagent contents into the sample cell with water sample from the field, it was shaken vigorously for 30 seconds and then placed down for a 2-minute reaction time. A blue colour formed, indicating the presence of phosphate in the sample. The sample was then cleaned and placed into the cell holder for reading after the instrument has been blanked and the results were recorded in mg/L PO_4^{-3}.

Measurement of morphometric parameters of the oyster populations.

Oyster samples collected from the field were detached from their respective substrates with a knife and cleaned with a brush to get rid of biofoulers and dirt. Samples were arranged on absorbent paper in a laboratory tray before measurements were taken. The dimensions of the oyster included; the shell height (SH) which measured the maximum distance from the hinge/umbo to the ventral shell margin, the shell length (SL) which measured the widest distance perpendicular to the shell height, and the shell width (SW) which measured the thickest part of the two shell valves. Measurements were taken using a pair of dividers and a ruler with a precision of 0.1cm. The whole shell weight (WW) of the oyster was recorded and shucked open with a knife to remove the visceral content. The wet meat weight (WMW) was taken after the moisture has been dabbed off. The weight of the empty shells (SWgt) was recorded too. The measurement of weights done using a portable electronic weighing balance, to the nearest 0.01g.

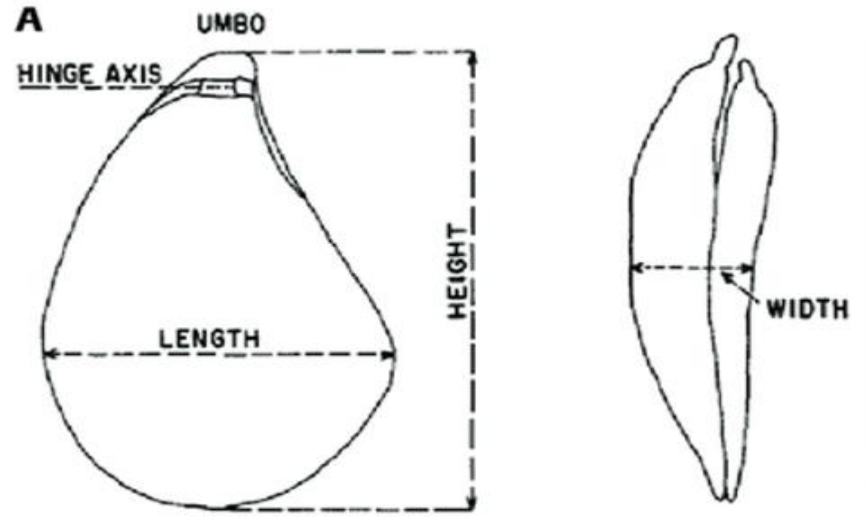

Figure 8: An illustration of the dimensions of an oyster shell that are measured adapted from Galtsoff 1964. (Source: Retrieved from google photos, May 2022).

Sex identification and maturity size.

Smears of oyster gonads were placed on a slide, mounted under an electronic microscope (Motic BA310) at a magnification of x10, and observed to identify the sex and gonadal development of the oysters. While the male gonads exhibit heavily condensed dot formations, the female gonads appear to be oval or pear-shaped, equally or occasionally sparsely scattered as explained in the literature. To estimate the sex ratios, specimens were sorted into mature (male or female) and immature groups. The maturity size (Lm_{50}) was calculated by fitting a sigmoid curve to the cumulative frequency of the different shell height/length classes in the sample, tracing a line from the 50% point on the frequency (Y) axis to the curve, and measuring the length at which 50% of the population matures on the shell height (X) axis.

Determining the condition index.

Sexed individual specimens were wrapped in an aluminium foil with their respective numberings and put in the oven to dry for 36 hours at 105 degrees Celsius to ensure all moisture has been dried off and had reached a constant weight. Then the dried weights (DW) were taken with the same electronic weighing balance to the nearest 0.01g. The condition index depends on the dried weight (g) of the specimen and the volume (cm^3) of the shell cavity. The inner shell volume is taken as the numerical difference between the whole weight of the specimen and the shell weight of the specimen (Lawrence and Scott, 1982). The condition index was then calculated using the formula;

$$\text{Condition Index} = \frac{\text{Weight of dry meat(g)}}{\text{Inner shell volume }(\text{cm}^3)} \times 100$$

Data Analysis

Assessment of the effect of physico-chemical parameters in the waterbodies

To determine the combined effect of the hydrographic parameters assessed in the waterbodies, the Principal Component Analysis statistical association was computed using the Minitab 18 Statistical Software.

Size assessment of the oyster population

Shell morphometric data were used to construct a size-frequency distribution and shell height variation using Minitab 18 Statistical Software and the modal/mean size from each site and country was statistically compared. The whole weight–meat weight relationship was also estimated with regression analysis using MS Excel 2016.

Isometric or allometric growth in populations was ascertained using the length-weight relationship regression analysis;

$$W = aL^b \text{ (Ricker, 1975),}$$

W is the weight (g), L is the shell height (cm) and a and b are constants. Isometry or allometry of the population was determined by testing the deviation or otherwise of the slope of the relationship "b" from the isometric value of 3.0 using the student t-test.

Estimation of growth parameters, mortality rates and exploitation levels

The data were pooled month-wise to fit the Von Bertalanffy growth model using the TrophFishR package in the R software. Asymptotic length ($SH\infty$) growth coefficient (K) and t_0/t_anchor (i.e. the portion of the year where annually repeating growth curves cross length equal to zero) of the von Bertalanffy equation for growth in length was estimated. This was done by employing a bootstrapped approach and the genetic algorithm ELEFAN_GA_boot within the TropFishR and fishboot packages (Taylor and Mildenberger, 2017; Mildenberger, 2019; Schwamborn *et al.*, 2019; Scrucca, 2013). Bootstrap experiments were based on 1000 resamples. The VBGF equation was given by:

$$SH_t = SH\infty \text{ (1 - e-k(t- } t_0\text{))}$$

(Pauly and David, 1981; Saeger and Gayanilo, 1986)

Based on the linearized length-converted catch curve generated by the TropFishR R package, the total mortality rate (Z) of the population was estimated (Mildenberger, 2019; Schwamborn *et al.*, 2019). For this, it was assumed that during the selected time period, the fisheries dynamics linked to each of the investigated stocks remained substantially stable. The instantaneous natural mortality (M) was estimated from Pauly's (1980) empirical equation:

$$\mathbf{Log_{10}M = -0.0066 - 0.279\ log_{10}\ SH\infty + 0.6543\ log_{10}\ K + 0.4634\ log_{10}\ T}$$

(With inputs from the growth parameters), where T is the mean annual water temperature (in degrees Celsius, °C) determined for each of the six sites in Ghana and The Gambia.

Fishing mortality (F) was obtained from the relationship;

F = Z – M (Gulland, 1977).

All estimates were computed using the R programme. The reliability of these growth parameters was evaluated by applying growth performance using the index of Pauly and Munro (1984). i.e,

$$\mathbf{\varphi' = Log_{10}K + 2\ Log_{10}L_\infty}$$

The current exploitation ratio ($E_{current}$), which measured the level of exploitation of the oyster fishery was estimated using the formula;

E = F/Z (Gulland, 1969).

A combination of the growth and mortality indices were used to describe and compare the fishing pressure among sites.

Assessing Catch per Unit Effort (CPUE) and existing status of the oyster fisheries.

The daily catch-effort data were collected from each of the sites through participatory data collection with the local oyster harvesters during the harvesting season. However, two of the sites; Densu and Allahein had closed their fishery in the period data was collected although Densu had reopened theirs before data collection had ended. The data was used to estimate and compare the daily catch per unit effort/fishing pressure (kg/person/hour) for all the sites. The daily harvest and income value at some of the locations were determined by computing the prices of 1 kg of oyster meat to their daily total harvest in order to make an assessment of the income status of the fishers. A comparative assessment of management practices in each of the countries was done to identify which can best be replicated and implemented for each country through Focus Group Discussions (FDGs) with the fishers at each site. The FDGs were conducted with key informants (KIs) at all the six sites in Ghana and The Gambia to solicit site-specific information on the shellfishery, governance regimes and management structures, with issues discussed broadly covering the scope and state of the shellfishery, harvests, access, condition of mangroves, governance, and management regimes, among others. The inclusion criteria for participants of the FGD were that the participant should be part of the leadership (or elderly person) of shellfishers association or group in the community, and they should be engaged in the fishery for not less than fifteen years. Government officials at the sites (mainly fisheries officers) were also included in the discussions. The discussions were guided by the inductive content analysis approach (Lincoln & Denzin, 2003).

Chapter Summary

The materials and methods used to execute the research, as well as the study locations have been described in detail in this Chapter. Statistical analytical tools and software employed to make inferences have also been indicated.

CHAPTER FOUR

RESULTS

Findings made from the data studied from literature on oyster biology and environmental conditions in addition to data collected from different field investigations and observations have been organized and submitted in the chapter. The outputs from the different data analysis and statistical inferences (at 95% confidence interval) were described. The observations have been organized into coherent graphs, tables, diagrams and pictures and presented where applicable. Standard error bars and corresponding values were indicated for the means presented in the tables and graphs.

Assessment of hydrographic parameters

This reports the general trends observed for the various hydrographic parameters assessed in the data collection period. The grey lines represent the Gambian water and the black lines, for easy comparison represent the Ghanaian waterbodies.

Physico-chemical parameters

Dissolved Oxygen (mg/L)

Figure 9 presents the monthly mean dissolved oxygen variations in the six water bodies in Ghana and The Gambia. Concentrations of dissolved oxygen in the waterbodies studied ranged from an average of about (2.3 ± 0.12) mg/L to (10.34 ± 0.55) mg/L. As seen in Figure 9, the variations were distinct. Ghana recorded observable D.O variation peaks in November 2021 (7 - 10 mg/l), while the Gambia ecosystems recorded their highest peaks in December 2021 (4 - 6 mg/l). A one-way ANOVA test carried out showed the statistical difference in

D.O readings between the sampled water bodies is significant (df = 5, $p < 0.05$). To identify how significantly different the parameters were in each water body, a Tukey test was conducted (Appendix B.1). It showed there was no statistical difference between the sampling stations.

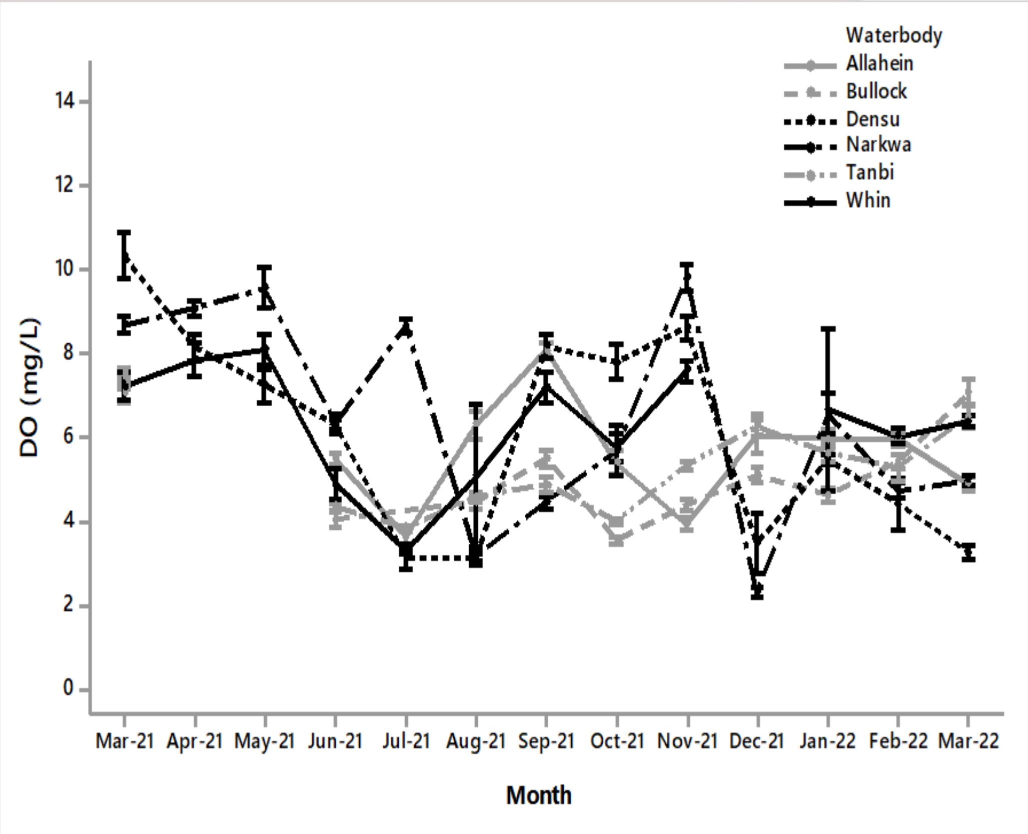

Figure 9: Monthly mean ± S.E *(vertical bars)* dissolved oxygen variations in the six water bodies in Ghana and The Gambia.

Temperature (°C)

Figure 10 presents the monthly mean temperature variations in the six water bodies in Ghana and The Gambia. Water temperature varied from (24.0 ± 0.07) °C to (34.0 ± 0.37) °C in the six waterbodies studied. Temperature changes for water bodies in each country followed the same trends but were appearing to be opposites between the two countries. That is, where there was a peak in Gambian waters, the Ghanaian systems declined in that progressive order. The Gambian ecosystems recorded their highest temperature reading in October 2021 (32.4 ± 0.14) ºC at Allahein and (32.2 ± 0.12) ºC at Bullock, while Ghana recorded their highest temperature reading (34 ± 0.37) ºC in March 2021 at Narkwa Lagoon. A one-way ANOVA test carried out showed the statistical difference in temperature readings between the sampled water bodies is significant (df = 5, $p < 0.05$). To identify how significantly different the parameters were in each water body, a Tukey test was conducted (Appendix B.2). It showed there was no statistical difference between the sampling stations.

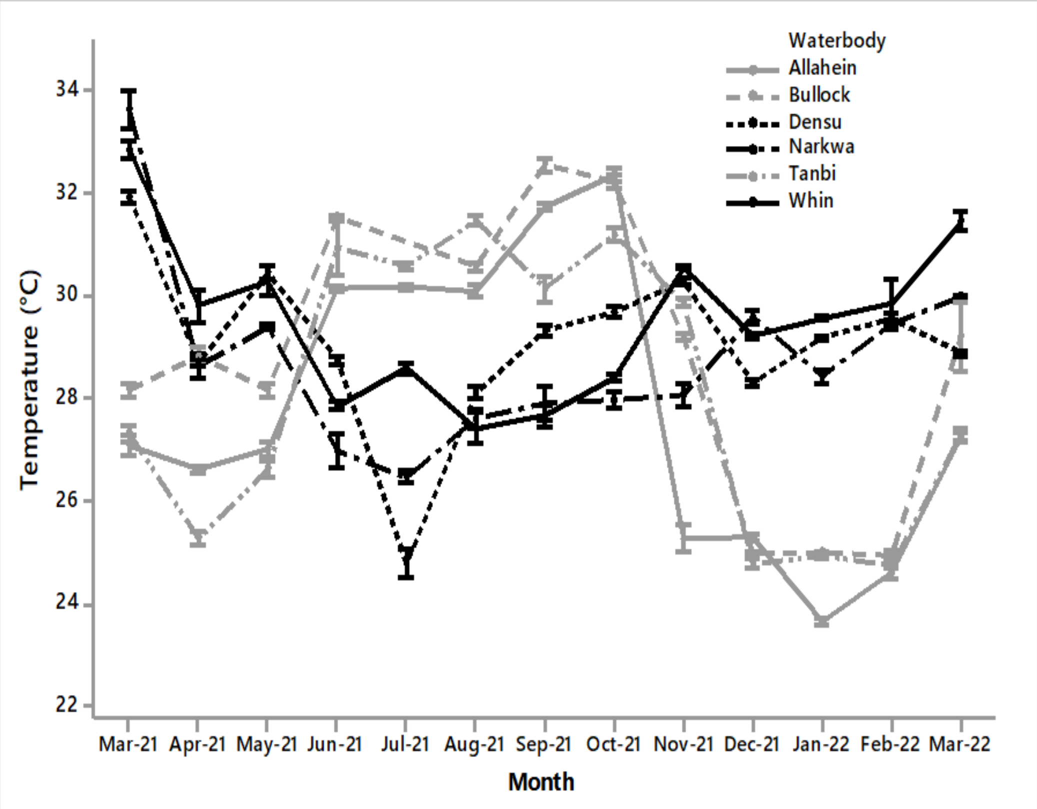

Figure 10 : Monthly mean ± S.E (vertical bars) temperature variations in the six water bodies in Ghana and The Gambia.

Salinity (ppt)

Figure 11 shows the monthly mean salinity variations in the six water bodies in Ghana and The Gambia. Salinity readings in The Gambia were generally higher and with steady trends (20-42 ppt) than Ghana's readings (0-30 ppt), nearing freshwater conditions and fluctuating greatly. The Gambian systems displayed similar trends among the water bodies with the peak salinity recorded at 40 ppt in December at the Allahein estuary. Ghana however recorded very dissimilar salinity recordings and trends for its sites through the months of July to November, but a unanimous increase from November to December 2021. A one-way ANOVA test carried out showed the statistical difference in salinity readings between the sampled water bodies is significant (df = 5, $p < 0.05$). To identify how significantly different the parameters were in each water body, a Tukey test was conducted (Appendix B.3). It showed there was no statistical difference between the sampling stations.

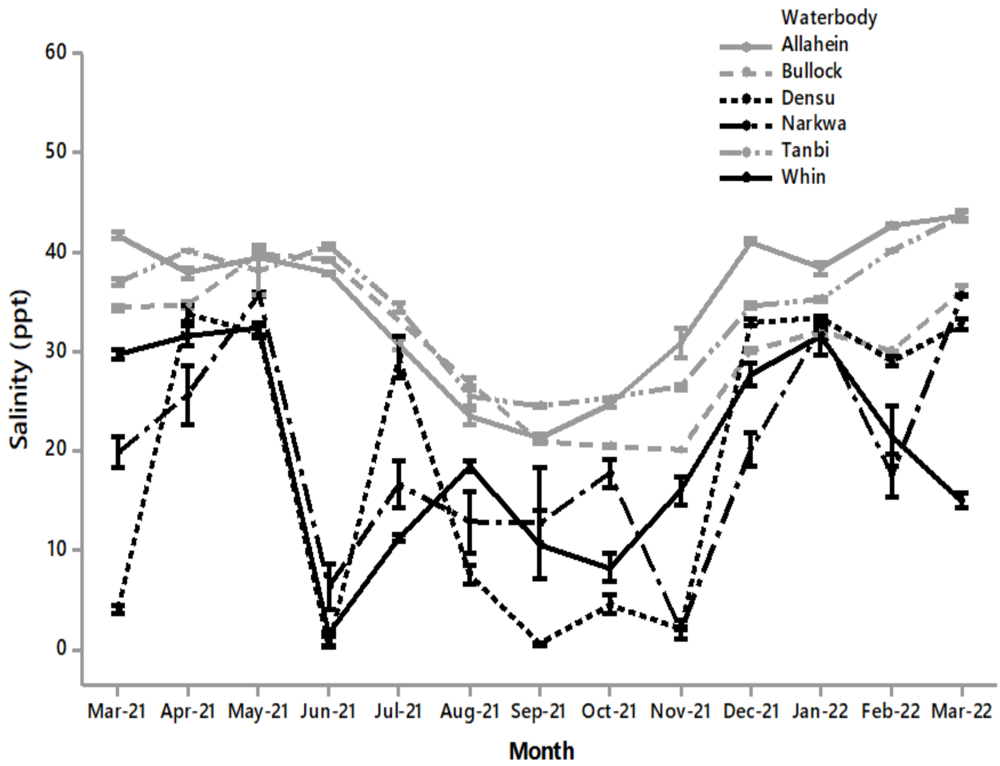

Figure 11: Monthly mean ± S.E (vertical bars) salinity variations in the six water bodies in Ghana and The Gambia.

pH

Figure 12 shows how pH values were fluctuating among the different systems. The average range of values was from 6.7 ± 0.12 to 10.02 ± 0.06 for all the systems. In general, the Ghanaian systems recorded higher pH values than the Gambian waters even though it was in an oscillatory manner. Ghanaian pH readings started with a steady increase from March 2021 until they peaked in July 2021 at the Whin estuary with a value of about 10.0 and then depreciated from August to October 2021 before rising steadily again. However, in The Gambia, were quite steady and stable in general. It started with a steady decrease from March 2021 (7.5 – 8.5) to May 2021 (6.7 - 7.0), until it started to increase again in June/July 2021. There was a sharp increase in Allahein pH readings in June 2021 and then leveled from July 2021 to March 2022. A one-way ANOVA test carried out showed the statistical difference in pH readings between the sampled water bodies is significant ($df = 5$, $p < 0.05$). To identify how significantly different the parameters were in each water body, a Tukey test was conducted (Appendix B.4). It showed there was no statistical difference between the sampling stations.

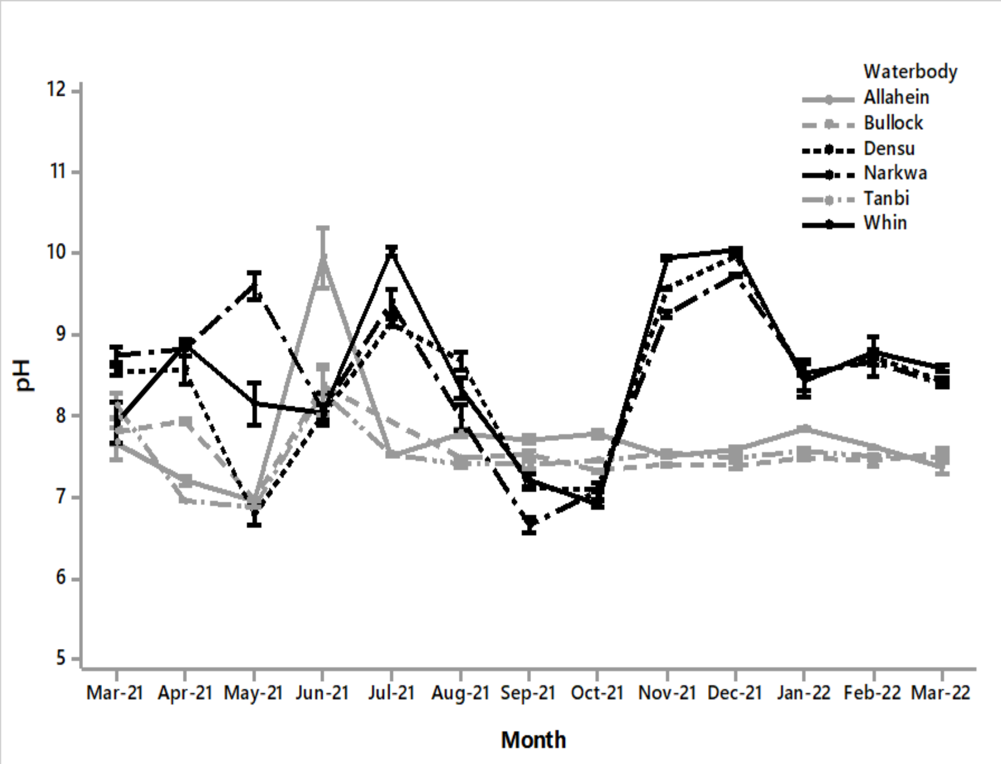

Figure 12: Monthly mean ± S.E (vertical bars) pH variations in the six water bodies in Ghana and The Gambia.

Depth (m)

Figure 13 shows the depth ranges for the six waterbodies that were sampled. The Gambian systems were generally deeper than the Ghanaian systems. The depth values alternated from 1.5 m to 4.0 m with Allahein being the shallowest among the three. The Ghanaian systems had an average depth range of 0.5-1 m. However, in August 2021, Narkwa Lagoon recorded higher depth readings averaging 2.22 m although Whin estuary recorded the lowest depths throughout here. A one-way ANOVA test carried out showed the statistical difference in depth readings between the sampled water bodies is significant (df = 5, $p < 0.05$). To identify how significantly different the parameters were in each water body, a Tukey test was conducted (Appendix B.5). It showed there was no statistical difference between the sampling stations.

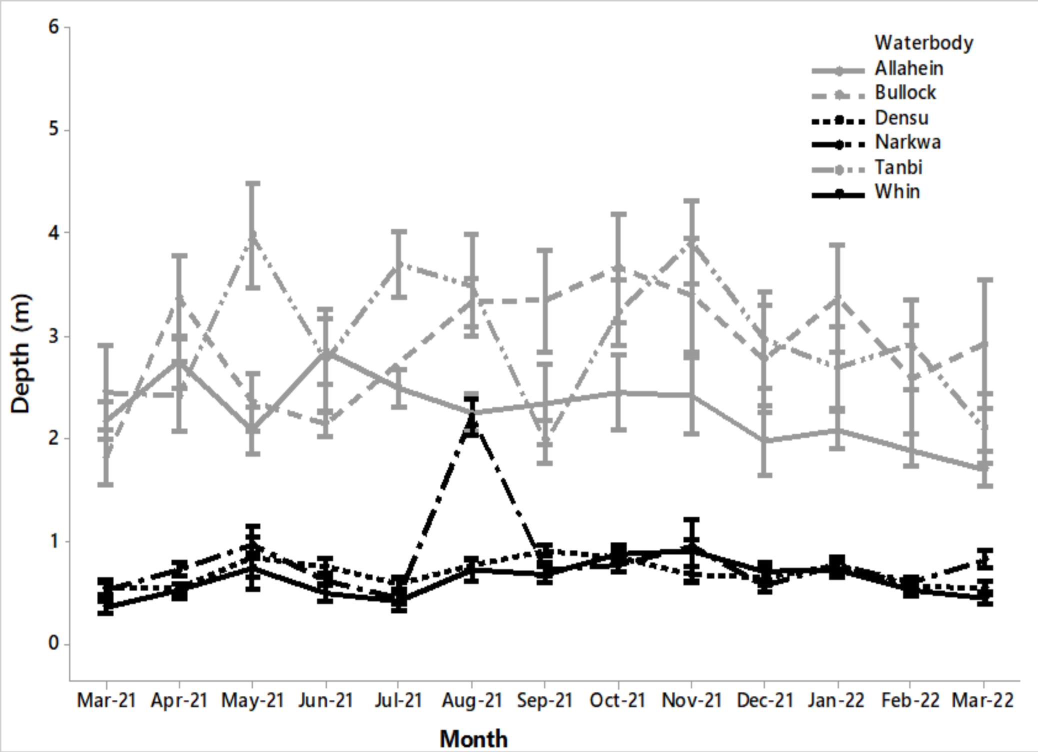

Figure 13: Monthly mean ± S.E *(vertical bars)* depth variations in the six water bodies in Ghana and The Gambia.

Turbidity (NTU)

Again, Figure 14 presents another distinctive difference in turbidity readings between the two countries. Ghana's readings (20-150 NTU) were higher than The Gambia's readings (0-15 NTU). While the systems in Ghana had dissimilar readings fluctuating widely among them, The Gambia's readings were closely similar and steady across the months. Whin estuary in Ghana recorded the highest turbidity reading in June 2021 at about 150 NTU. A one-way ANOVA test carried out showed the statistical difference in turbidity readings between the sampled water bodies is significant (df = 5, $p < 0.05$). To identify how significantly different the parameters were in each water body, a Tukey test was conducted (Appendix B.6). It showed there was no statistical difference between the sampling stations.

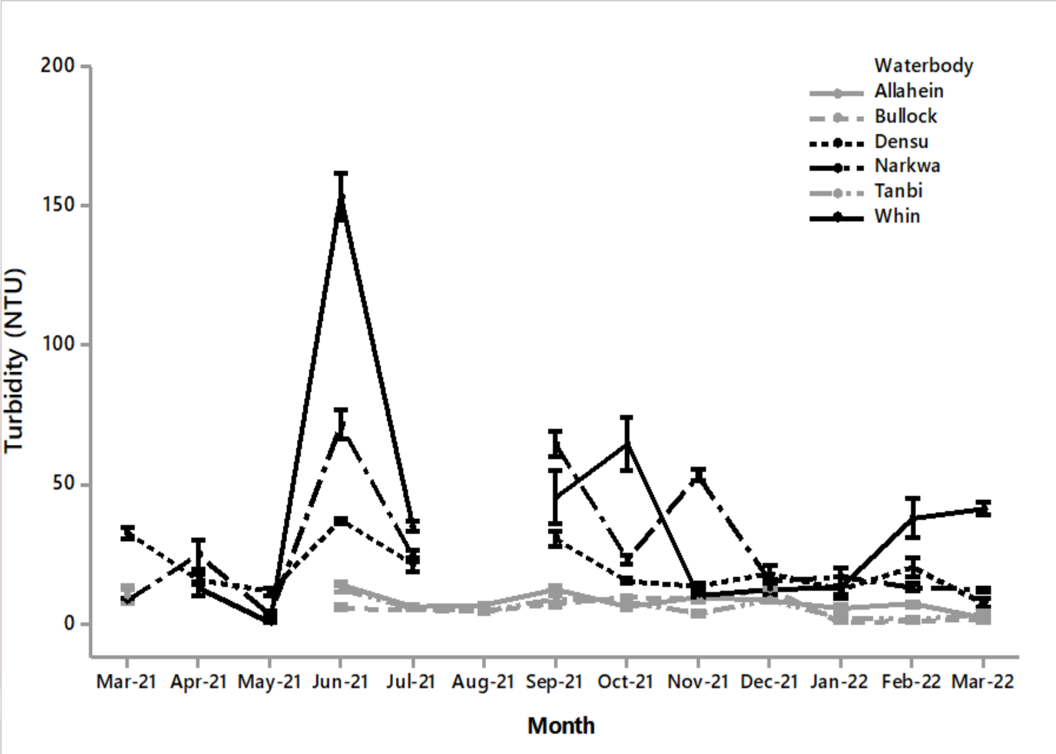

Figure 14: Monthly mean ± S.E (vertical bars) turbidity variations in the six water bodies in Ghana and The Gambia.

Principal Component Analysis

Principal Component Analysis for waterbodies in Ghana

The Principal component analysis tests carried out on the waterbodies in Ghana showed that the first three components, according to the Kaiser criterion, had eigenvalues that were greater than 1. These components made a cumulative contribution of about 70% in the Ghanaian systems, presented in Table 2. Salinity and pH have large positive loadings on component 1 while Turbidity had large negative loadings on component 2, also presented in Figure 15.

Table 2*: Eigenanalysis of the Correlation Matrix for waterbodies in Ghana*

Eigenvalue	1.7604	1.3260	1.0647	0.8187	0.6331	0.3971
Proportion	0.293	0.221	0.177	0.136	0.106	0.066
Cumulative	0.293	0.514	0.692	0.828	0.934	1.000

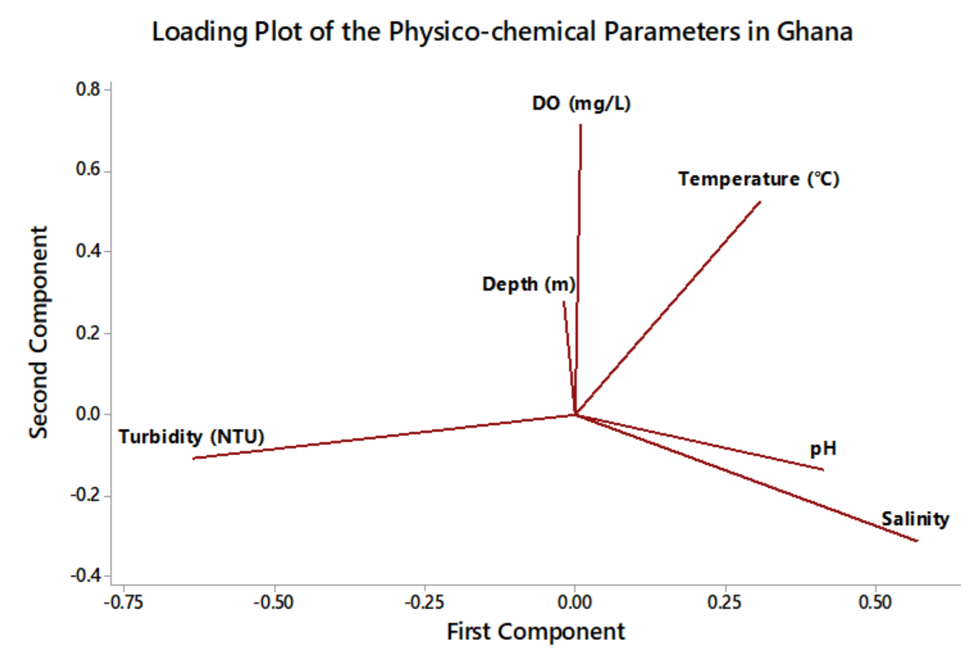

Figure 15: A loading plot showing the combined effects of the physico-chemical parameters in Ghanaian waterbodies.

Principal Component Analysis for waterbodies in The Gambia

In The Gambia, the waterbodies after conducting a PCA on them also showed that the first three components also made a cumulative contribution of about 68% using the Kaiser criterion (Table 3). In the loading plot of the physico-chemical parameters, Salinity and temperature were showing higher positive loadings on the first component and second components respectively (Figure 16).

Table 3: *Eigenanalysis of the Correlation Matrix for waterbodies in The Gambia*

Eigenvalue	1.7414	1.3607	0.9784	0.8701	0.6626	0.3867
Proportion	0.290	0.227	0.163	0.145	0.110	0.064
Cumulative	0.290	0.517	0.680	0.825	0.936	1.000

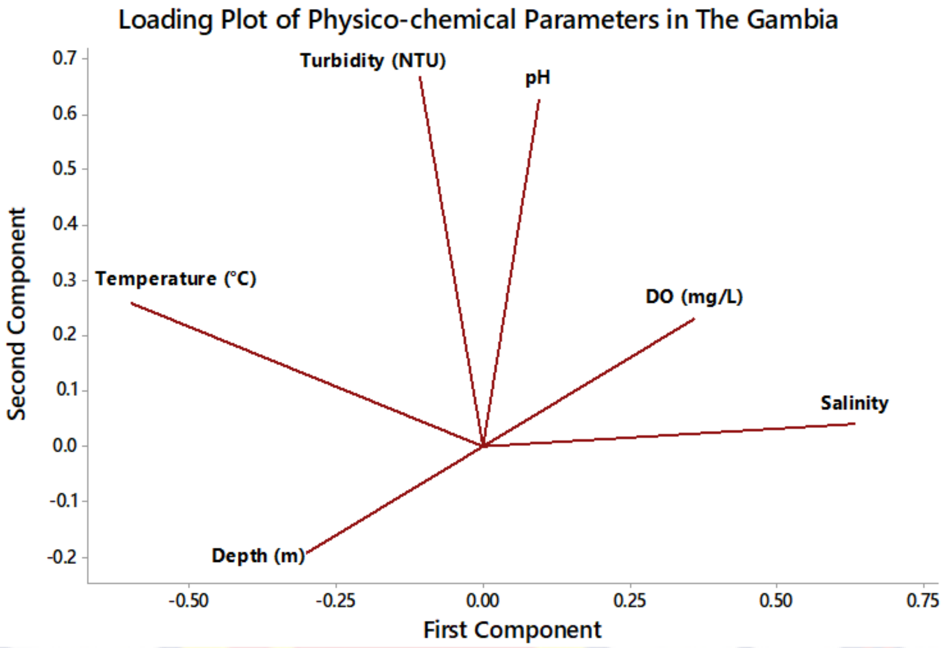

Figure 16: A loading plot showing the combined effects of the physico-chemical parameters in The Gambia waterbodies.

Nutrients Concentration

Nitrates (NO_3)/ mg/L

Nitrates concentration as recorded in Figure 17 shows varying concentrations of nitrates among the six systems. The concentrations were high in all the systems, in all the months sampled except December 2021, which recorded very low values (<5mg/L). However, in September 2021, the highest nitrate concentration was recorded in Allahein (22.64 ± 3.26) mg/L.

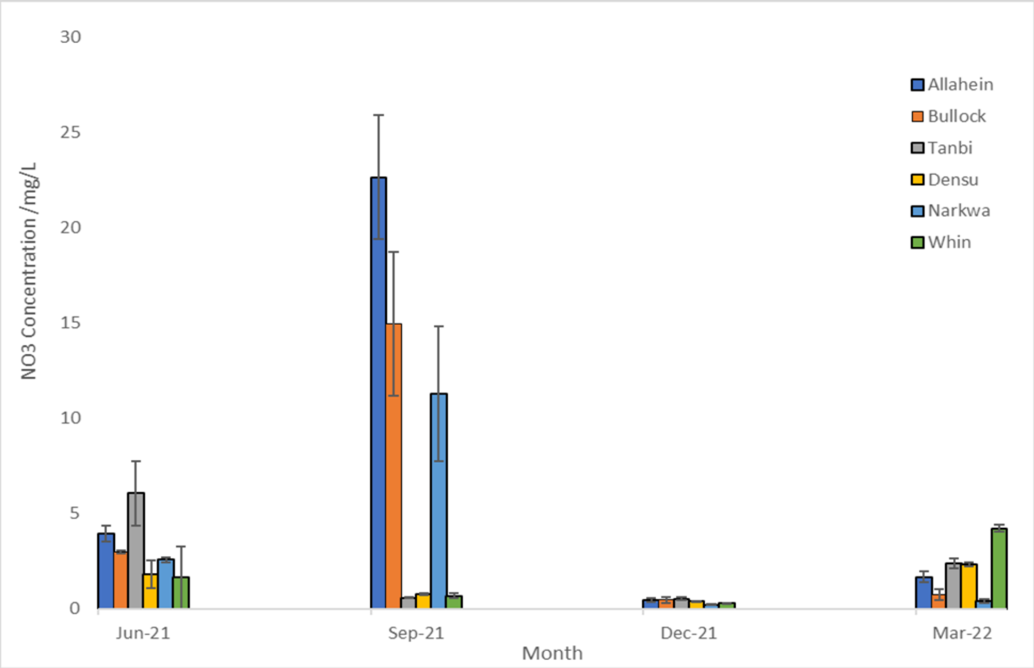

Figure 17: Mean nitrate concentrations ± S.E (vertical bars) in the six water bodies in Ghana and The Gambia.

Phosphates (PO_4)/mg/L

Again, varying concentrations of Phosphate can be observed in Figure 18 from the six systems. Just like for nitrates, the highest phosphate readings were recorded in September 2021 with Bullock having the highest reading of (10.97 ± 0.80) mg/L. The concentrations were averagely high in all the system, however, the lowest phosphate concentrations were recorded in March 2022 for all the systems recording as low as <2mg/L.

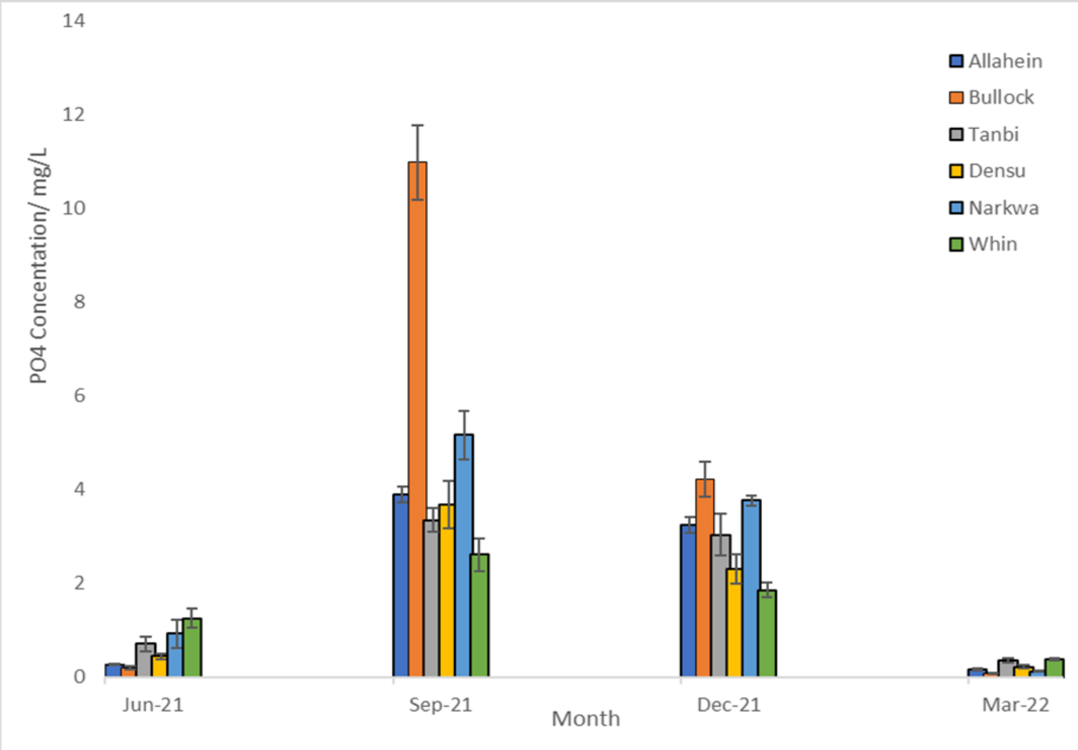

Figure 18: Mean phosphate concentrations ± S.E (vertical bars) in the six water bodies in Ghana and The Gambia.

Assessment of sizes and growth of the shellfish stocks

Monthly size variations of *Crassostrea tulipa*

Figure 19 presents the monthly mean variation in the shell heights of the mangrove oysters that were encountered throughout the study period. The grey lines represent the Gambian systems and the black lines, for easy comparison represent the Ghanaian systems. The species from Narkwa lagoon were distinctively smaller than the rest of the species encountered at the other systems. Species from The Gambian systems were generally similar in size whereas the Ghanaian systems had species with varying sizes. It can also be observed that in May 2021 and October 2021, almost all six systems recorded larger sizes before declining to smaller sizes across the remaining months. In

The Gambia, Bullock had comparatively larger species than the other two systems. In Ghana also, Densu recorded on average, larger-sized oysters.

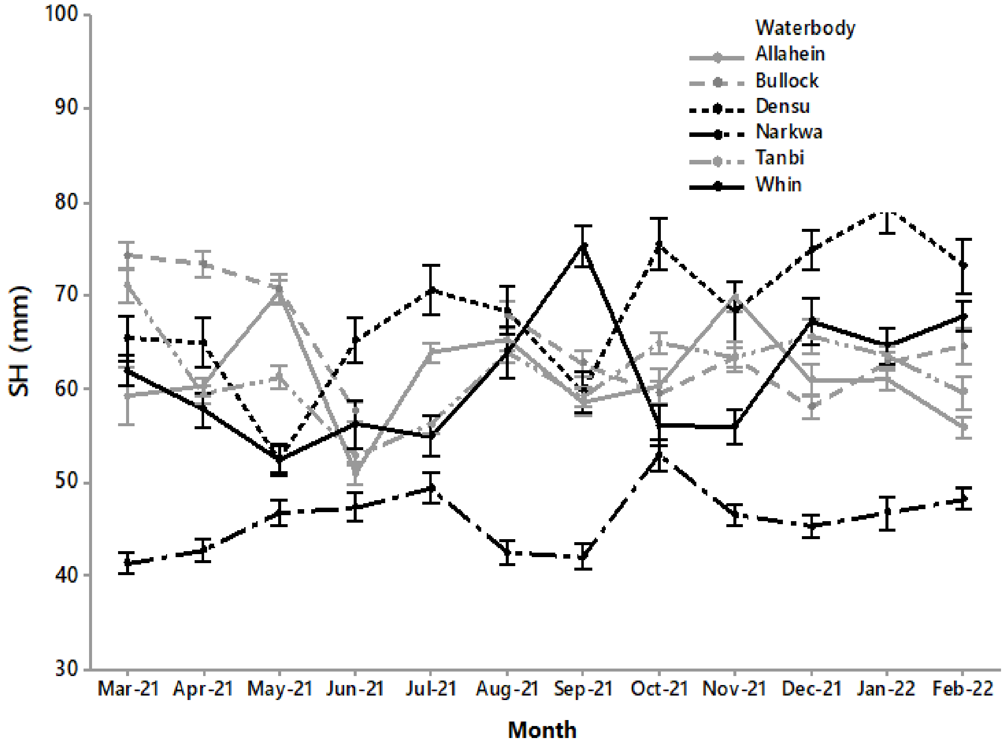

Figure 19: Monthly mean ± S.E (vertical bars) variations in shell height of oysters sampled from the six water bodies in Ghana and The Gambia.

Length-Frequency distribution of *Crassostrea tulipa.*

In Figure 20, the Length-Frequency distribution of the oyster populations at all six systems in Ghana and The Gambia. All the sites showed a unimodal distributions except Allahein and Narkwa shown in Table 4. The Gambian population, however, showed distributions skewed more towards larger sizes of 60mm and more, including Densu in Ghana. The remaining sites showed smaller-sized distributions around 40-60 mm with Narkwa recording the smallest-sized individuals.

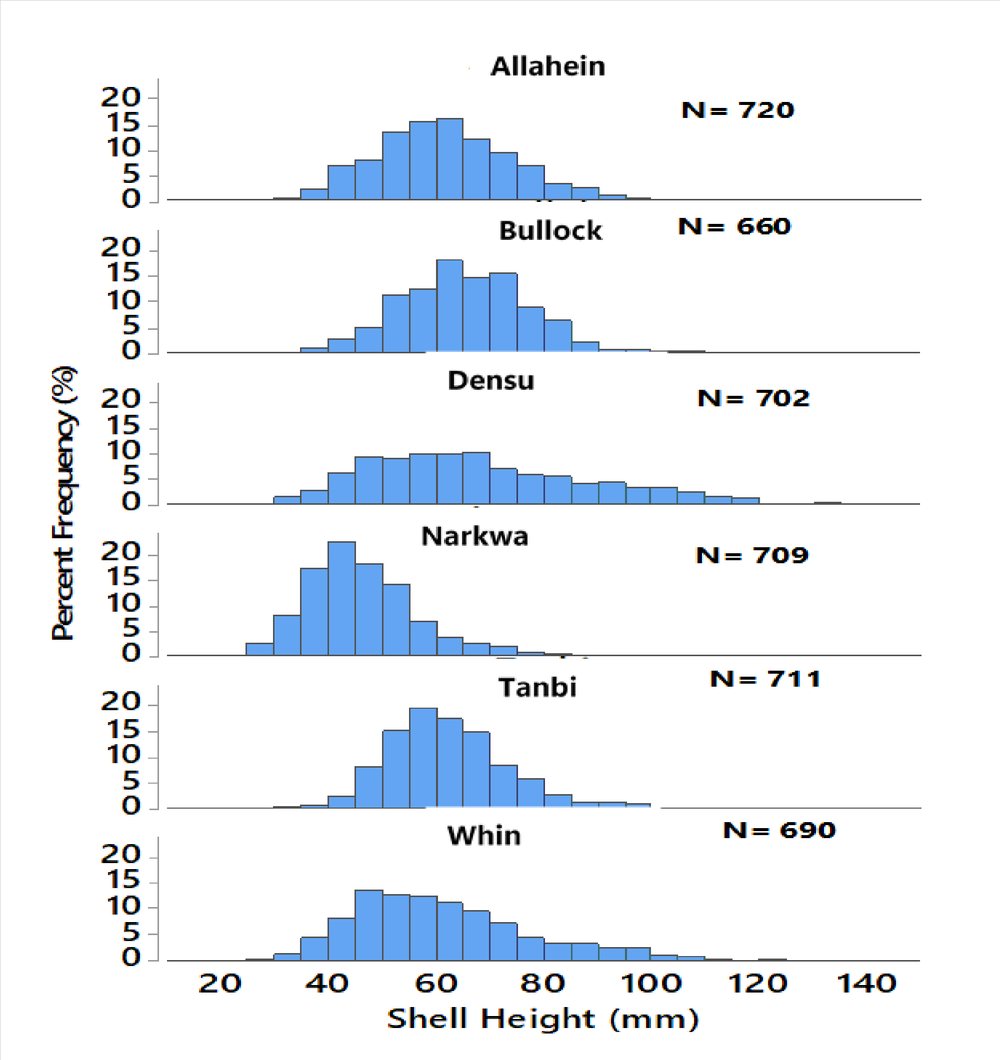

Figure 20: Length-frequency distribution of mangrove oysters (*Crassostrea tulipa*) sampled from the six water bodies in Ghana and The Gambia.

Table 4: *Some descriptive statistics of the shell height of oysters in Ghana and The Gambia*

Country	Site	Mean size/mm	Modal size/mm	Range/mm
The Gambia	**Allahein**	61.3 ± 0.5	58, 62	93
	Bullock	64.9 ± 0.5	61	80
	Tanbi	61.7 ± 0.4	57	74
Ghana	**Densu**	68.2 ± 0.8	68	105
	Narkwa	46.0 ± 0.4	40, 42, 45	111
	Whin	61.0 ± 0.6	48	106

Length-Weight relationship of *Crassostrea tulipa.*

Allahein Estuary

Figure 21 shows the regression analysis between shell height (mm) and the corresponding total weight (g) of the mangrove oysters in Allahein. The shell height-total weight relationship was defined by the equation: TW = $0.0011SH^{2.3883}$, where Tw= total/whole weight in grams and L = shell height in millimetres. The coefficient of determination (R^2) of the regression analysis suggested a significant positive relationship (R^2 =0.723) between the shell height and total weight of the oysters. The slope value (b=2.39), significantly deviated from 3.0 ($p < 0.05$), which indicated that total weight increased relatively less compared with shell height, showing negative allometry among the population at Allahein.

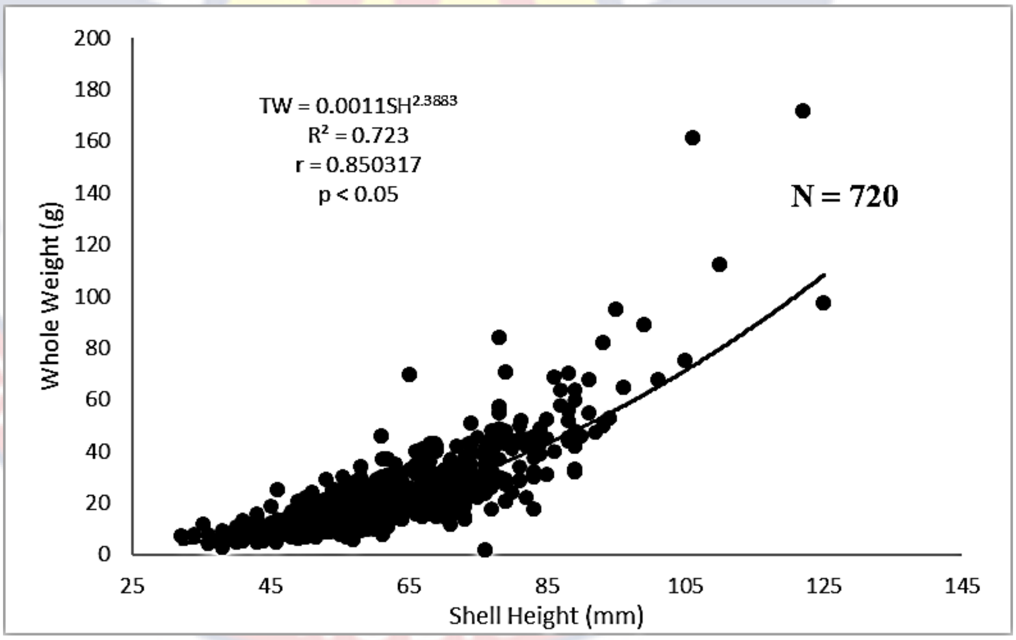

Figure 21: Length-weight relationship of mangrove oysters *Crassostrea tulipa* sampled from Allahein in The Gambia

Bullock Mangrove Area

Figure 22 shows the regression analysis between shell height (mm) and the corresponding total weight (g) of the mangrove oysters in Bullock. The shell height-total weight relationship has been defined by the equation: $TW = 0.0014SH^{2.3406}$, where Tw= total/whole weight in grams and L = shell height in millimetre. The coefficient of determination (R^2) of the regression analysis suggested a significant positive relationship (R^2 =0.670) between the shell height and total weight of the oysters. The slope value (b=2.34), significantly deviated from 3.0 ($p < 0.05$) indicated that total weight increased relatively less compared to the increase in shell height, showing a negative allometry.

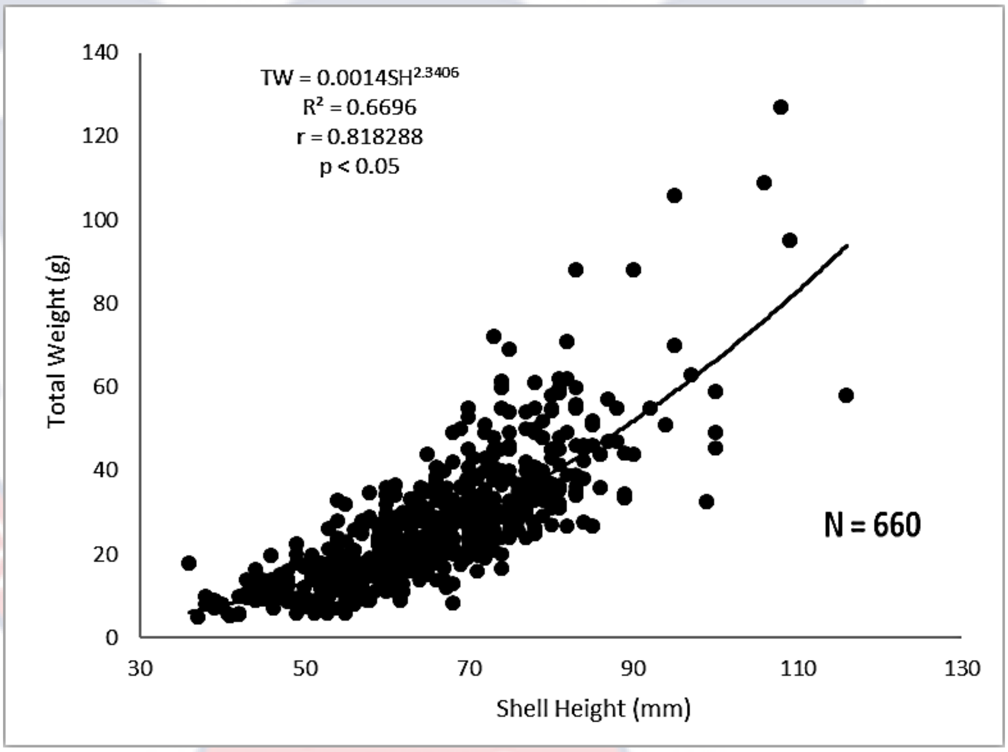

Figure 22: Length-weight relationship of mangrove oysters *Crassostrea tulipa* sampled from Bullock in The Gambia

Tanbi Wetland System

Figure 23 shows the regression analysis between shell height (mm) and the corresponding total weight (g) of the mangrove oysters at Tanbi. The shell height-total weight relationship has been defined by the equation: TW = $0.0039SH^{2.0802}$, where Tw= total/whole weight in grams and L = shell height in millimetre. The coefficient of determination (R^2) of the regression analysis suggested a positive relationship (R^2 =0.5909) between the shell height and total weight of the oysters. The slope value (b=2.08) significantly deviated from 3.0 ($p < 0.05$) which indicated that total weight increased relatively less compared with shell height, showing negative allometry.

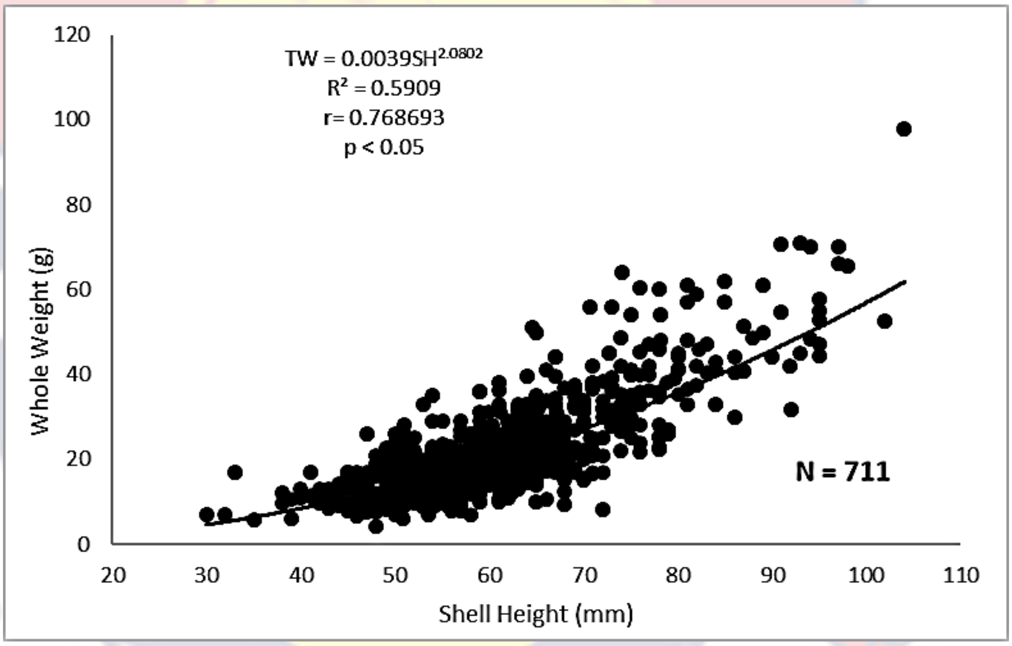

Figure 23: Length-weight relationship of mangrove oysters *Crassostrea tulipa* sampled from Tanbi in The Gambia.

Densu Estuary

Figure 24 shows the regression analysis between shell height (mm) and the corresponding total weight (g) of the mangrove oysters in Densu. The shell height-total weight relationship has been defined by the equation: TW = $0.0012SH^{2.409}$, where Tw= total/whole weight in grams and L = shell height in millimetre. The coefficient of determination (R^2) of the regression analysis suggested significant positive relationship (R^2 = 0.8426) between the shell height and total weight of the oysters. The slope value (b=2.41) also significantly deviated from 3.0 ($p < 0.05$) which indicated that total weight increased relatively less compared with shell height, showing negative allometry among the oyster populations in the Densu estuary.

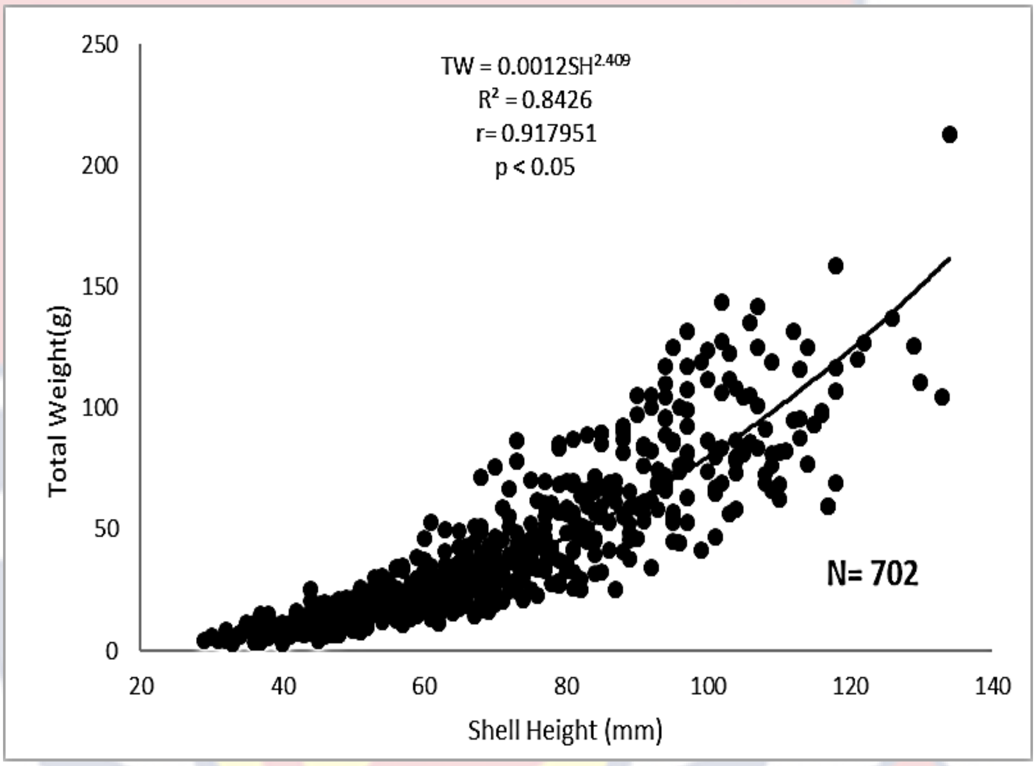

Figure 24: Length-weight relationship of mangrove oysters *Crassostrea tulipa* sampled from Densu in Ghana.

Narkwa Lagoon

Figure 25 presents the regression analysis between shell height (mm) and the corresponding total weight (g) of the mangrove oysters in Narkwa. The shell height-total weight relationship has been defined by the equation: $TW = 0.0021SH^{2.2444}$, where Tw= total/whole weight in grams and L = shell height in millimetre. The coefficient of determination (R^2) of the regression analysis suggested significant positive relationship ($R^2 = 0.7051$) between the shell height and total weight of the oysters. The slope value (b=2.244) also significantly deviated from 3.0 ($p < 0.05$) which indicated that total weight increased relatively less compared with shell height, showing negative allometry among the oyster populations in the Narkwa lagoon.

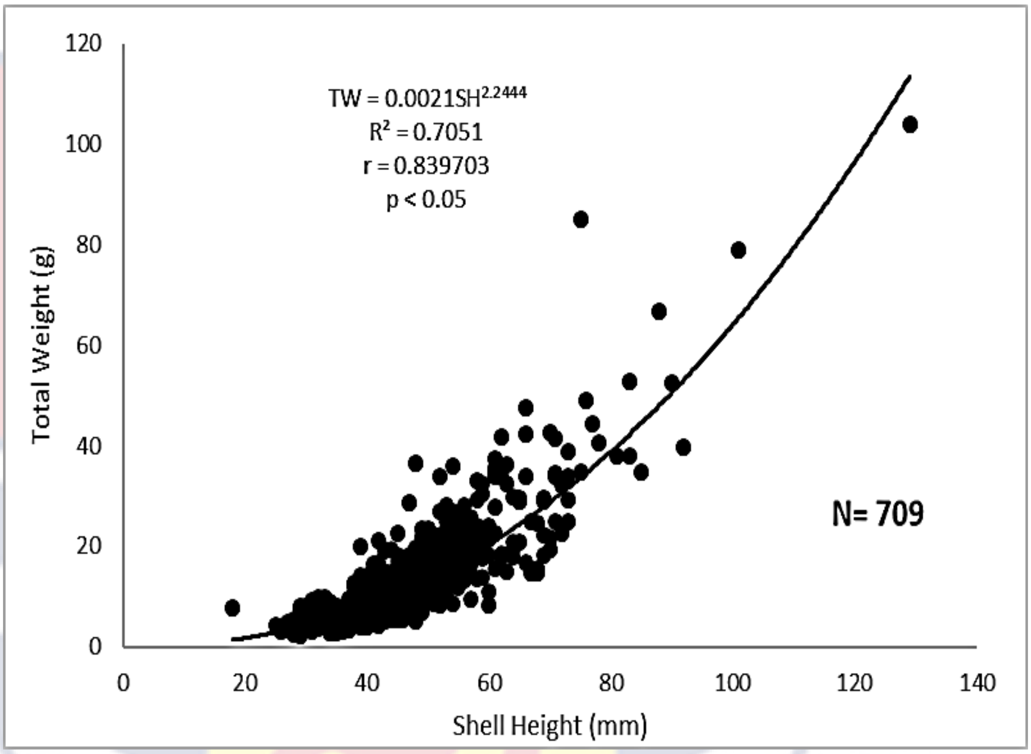

Figure 25: Length-weight relationship of mangrove oysters *Crassostrea tulipa* sampled from Narkwa in Ghana.

Whin Estuary

Figure 26 shows the regression analysis between shell height (mm) and the corresponding total weight (g) the mangrove oysters at Whin. The shell height-total weight relationship has been defined by the equation: $TW = 0.0026SH^{2.2124}$, where Tw= total/whole weight in grams and L = shell height in millimetre. The coefficient of determination (R^2) of the regression analysis suggested a positive relationship ($R^2 = 0.7262$) between the shell height and total weight of the oysters. The slope value (b=2.21) significantly deviated from 3.0 ($p < 0.05$) which indicated that total weight increased relatively less compared with shell height, showing negative allometry.

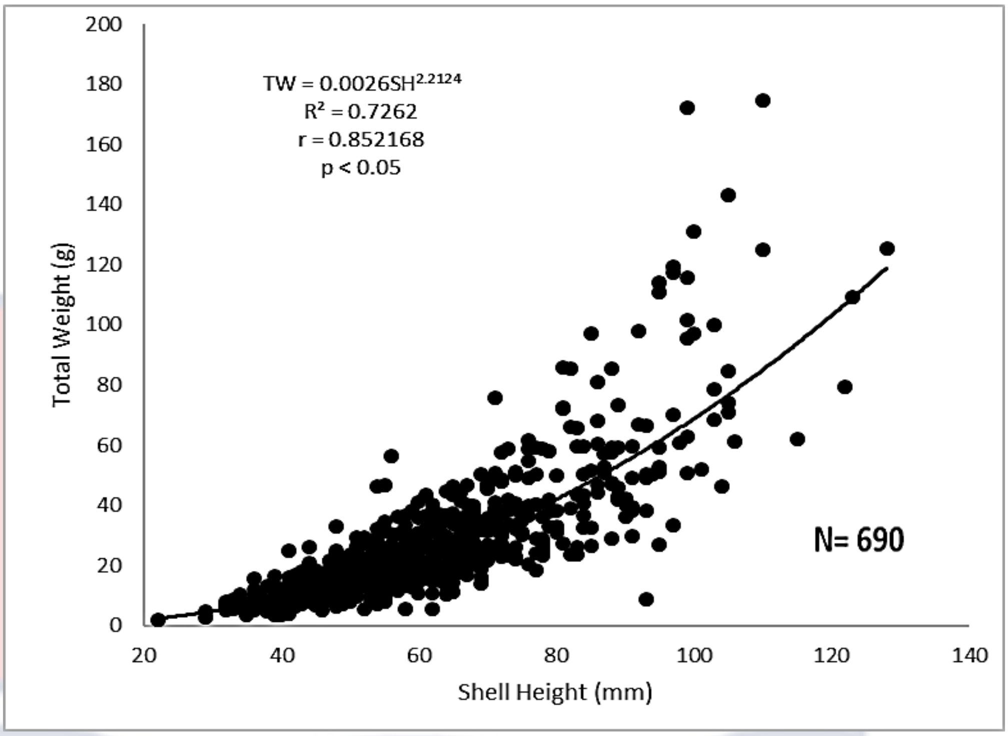

Figure 26: Length-weight relationship of mangrove oysters *Crassostrea tulipa* sampled from Whin in Ghana.

Condition Index of *Crassostrea tulipa.*

Figure 27 presents the monthly mean variations in condition index for the oyster populations sampled from all six waterbodies from March 2021 to Feb 2022. The grey lines represent the Gambian systems and the black lines, for easy comparison represent the Ghanaian systems. The very first observable difference is how the C. I. of the Ghanaian populations of oysters seem to fluctuate widely between themselves though higher than the C.I of the Gambian population. Between August to October 2021, the highest peak was recorded at 16 for Densu while at the same time, the lowest C. I was recorded for Whin at 2. All the systems in the Gambia recorded a high C. I between March to April 2021 but maintained a low but steady C. I for the rest of the year and the values ranged between 3 and 14.

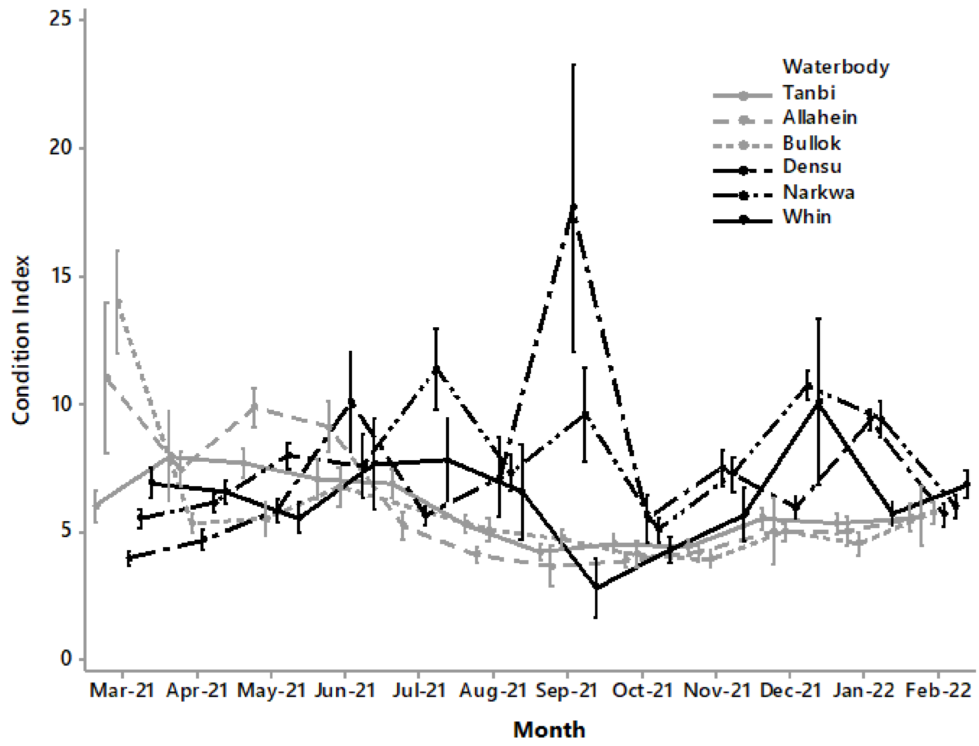

Figure 27: Monthly mean ± S.E (vertical bars) variations in condition index of oysters sampled from the six water bodies in The Gambia and Ghana.

Table 5 presents the correlation coefficients together with the estimated p-values at 95% confidence intervals between the condition indices of the oysters sampled from both Ghana and The Gambia against their hydrographic parameters. Generally, the hydrographic parameters measured did not have any direct relationship on the condition index of the oysters as depicted by the correlation coefficients in the table. In The Gambia, the relationships were generally positive but weak correlations, which were not significant with the exception of salinity. However, in Ghana, weak negative relationships were observed and were mostly not significant. Whin showed significant weak negative and positive correlations with dissolved oxygen and pH respectively.

Table 5*: Correlation coefficient (r) with p-value between the hydrographic parameters and C. I of* C. tulipa *in Ghana and The Gambia*

		Temp	D. O.	Salinity	pH	Depth	Turb.
C.I Allahein	**r**	-0.15	-0.30	0.64	0.16	0.12	-0.19
	p	0.64*	0.34*	0.03	0.61*	0.70*	0.56*
C.I Bullock	**r**	0.49	0.58	0.64	0.58	0.08	0.41
	p	0.10*	0.05*	0.02	0.05*	0.81*	0.19*
C.I Tanbi	**r**	-0.25	-0.69	0.77	-0.18	0.10	-0.26
	p	0.43*	0.01	0.00	0.60*	0.80*	0.41*
C. I.	**r**	-0.04	0.08	-0.40	-0.35	0.64	0.33
Densu	**p**	0.91*	0.82*	0.20*	0.27*	0.03	0.28*
C. I.	**r**	-0.39	-0.20	0.09	0.28	-0.16	0.13
Narkwa	**p**	0.21*	0.53*	0.79*	0.38*	0.62*	0.69*
C. I.	**r**	0.24	-0.68	0.23	0.62	-0.47	0.08
Whin	**p**	0.45*	0.02	0.48*	0.03	0.12*	0.80*

*= Not significant (α=0.05).

Whole weight-meat weight regression of *Crassostrea tulipa.*

Allahein Estuary

Figure 28 shows a linear regression to establish the relationship between the wet meat weights of the mangrove oysters to their whole weight. From the graph, oysters at the Allahein estuary followed a regression equation of MW = 0.1075TW and R^2 = 0.7873. The R^2 value shows a fairly strong but significant positive correlation between the meat weight and their total weight.

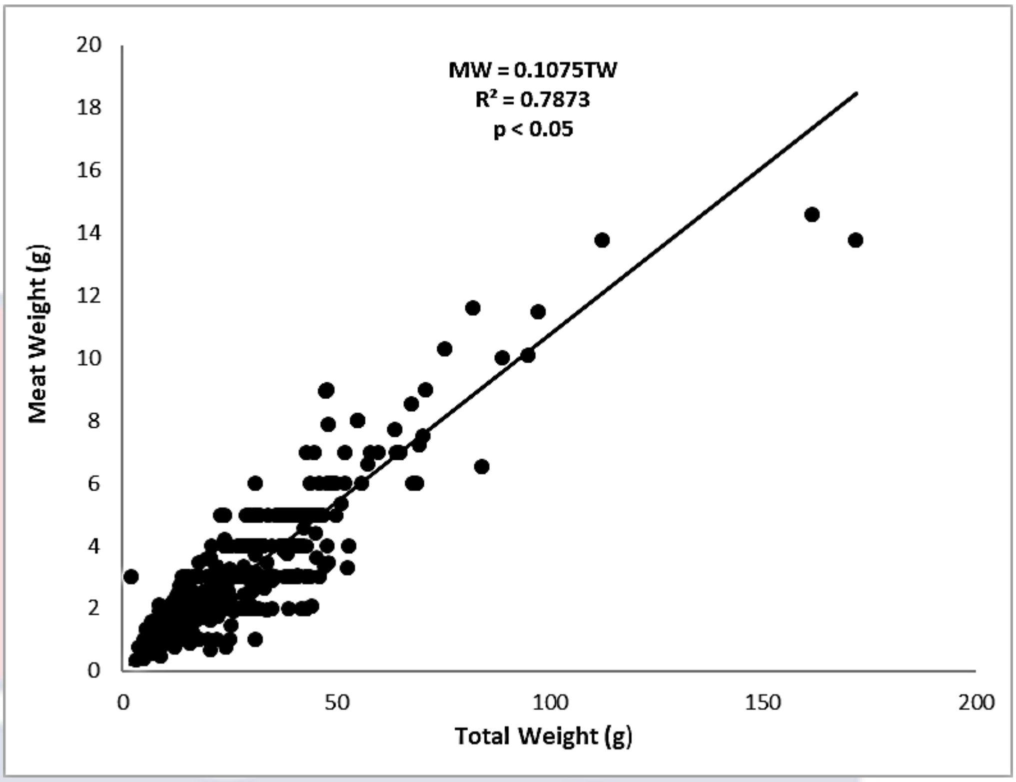

Figure 28: Whole weight-meat weight regression of mangrove oysters *Crassostrea tulipa* sampled from Allahein in The Gambia.

Bullock Mangrove Area

Figure 29 shows a linear regression to establish the relationship between the wet meat weights of the mangrove oysters to their whole weight in the Bullock waterbody. From the graph, oysters at the Bullock mangrove followed a regression equation of MW = 0.1106TW and $R^2 = 0.8009$. The R^2 value shows a fairly strong but significant positive correlation between the meat weight and their total weight.

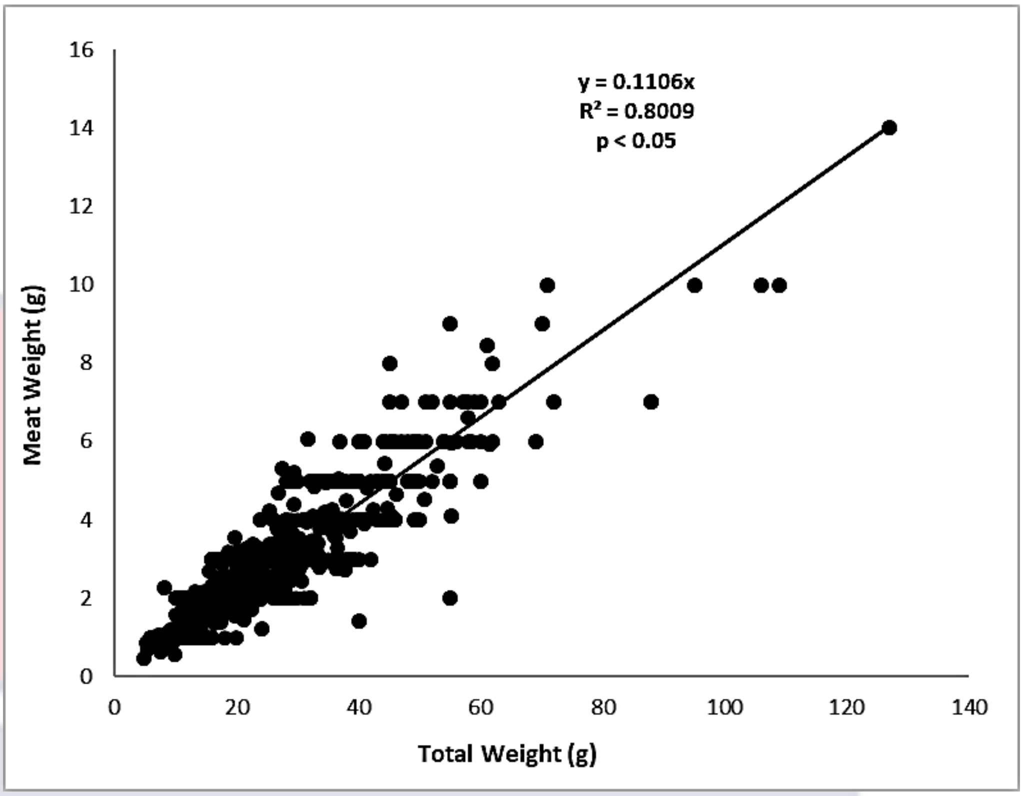

Figure 29: Whole weight-meat weight regression of mangrove oysters *Crassostrea tulipa* sampled from Bullock in The Gambia.

Tanbi Wetland System

In Figure 30, the relationship between meat weight and the total weight of oysters sampled at Tanbi was expressed through linear regression, MW = 0.1284TW and R^2 = 0.754. The R^2 value shows a fairly strong but significant positive correlation between the meat weight and their total weight.

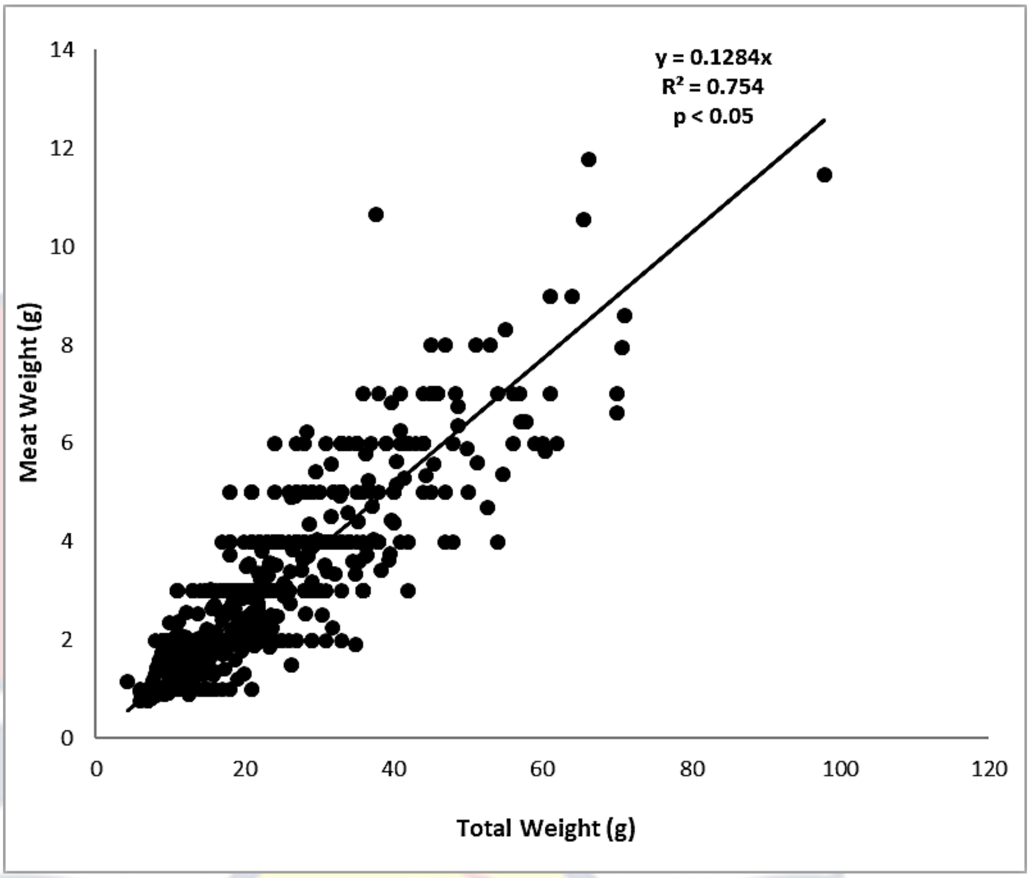

Figure 30: Whole weight-meat weight regression of mangrove oysters *Crassostrea tulipa* sampled from Tanbi in The Gambia.

Densu Estuary

In Figure 31, the relationship between meat weight and total weight of oysters sampled at Densu was expressed through a linear regression, MW = 0.1092TW and $R^2 = 0.6762$. The R^2 value shows a fairly strong but significant positive correlation between the meat weight and their total weight.

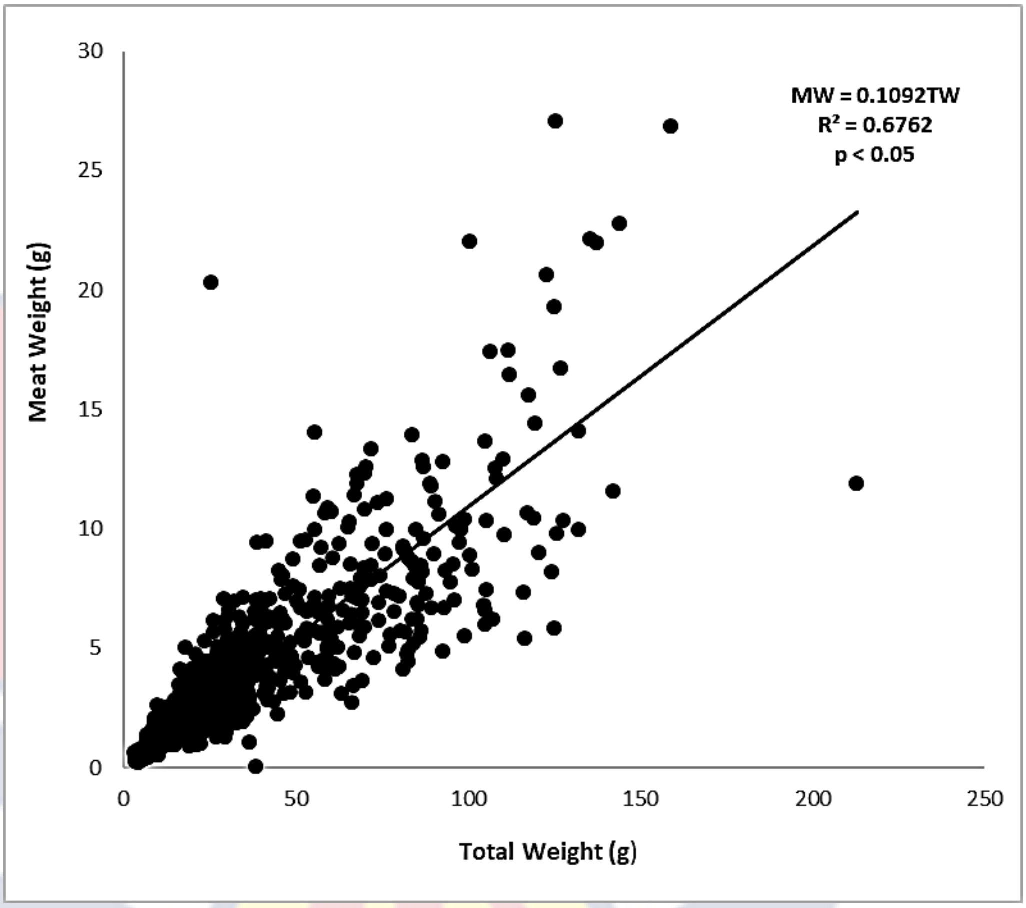

Figure 31: Whole weight-meat weight regression of mangrove oysters *Crassostrea tulipa* sampled from Densu in Ghana.

Narkwa Lagoon

Figure 32 shows a linear regression to establish the relationship between the wet meat weights of the mangrove oysters to their whole weight. From the graph, oysters at the Narkwa lagoon followed a regression equation of MW = 0.1333TW and R^2 = 0.7647. The R^2 value shows a fairly strong but significant positive correlation between the meat weight and their total weight.

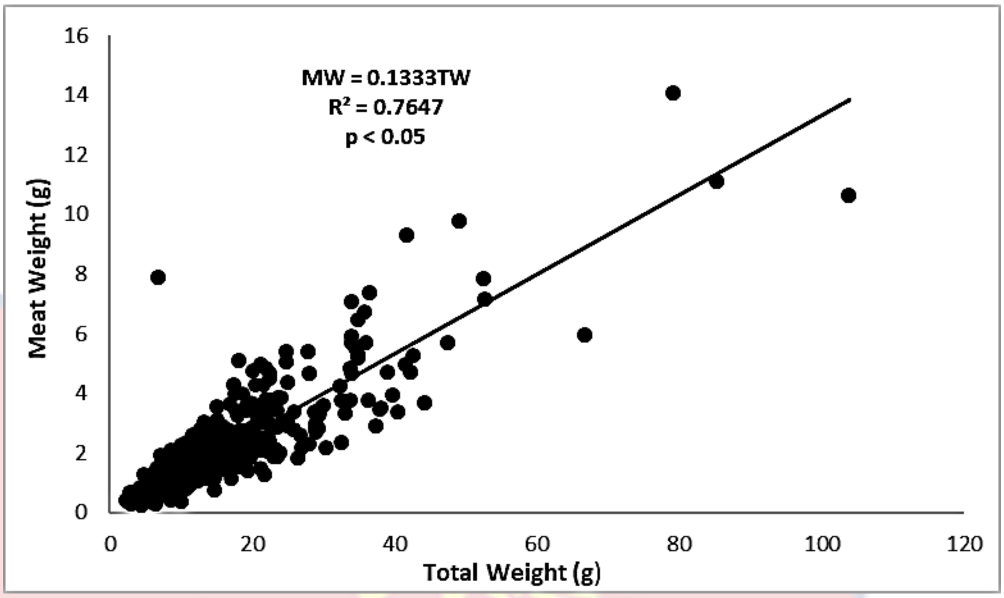

Figure 32: Whole weight-meat weight regression of mangrove oysters *Crassostrea tulipa* sampled from Narkwa in Ghana.

Whin Estuary

In Figure 33, the relationship between meat weight and the total weight of oysters sampled from Whin was expressed through linear regression, MW = 0.1297TW and $R^2 = 0.7027$. The R^2 value shows fairly strong but significant positive correlation between the meat weight and their total weight.

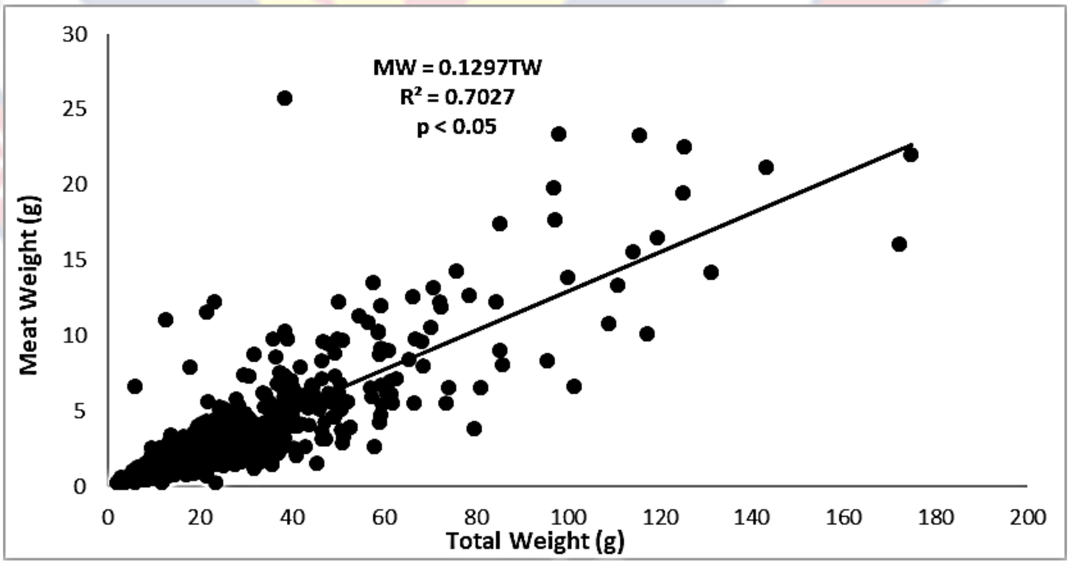

Figure 33: Whole weight-meat weight regression of mangrove oysters *Crassostrea tulipa* sampled from Whin in Ghana.

Assessment of growth parameters and mortality rates

Growth Parameters of *Crassostrea tulipa.*

Estimates of the growth parameters of the mangrove oysters were generated from the monthly length-frequency data collected from March 2021 to February 2022 using the TropFishR package in the R software. Figures 34 and 35 display the monthly length-frequency distributions alongside the restructured length-frequency distributions of the oysters from each of the six locations that were used to fit the von Bertalanffy growth curve. From the figures, it can be observed that most of the smallest-sized specimens with higher distributions occurred around 4 - 6cm for all the sites throughout the year. This can be inferred that there was the introduction of smaller-sized individuals into the populations the whole year.

Figures 36 - 39 describes the yearly plot of the VBGF growth curve with the parameters estimated using the ELEFAN_GA function installed in the TropFishR package in R-software. The population with the biggest maximum theoretical size were oysters from Whin ($SH\infty$ = 12.98 cm SH), with the Tanbi population having the smallest ($SH\infty$ = 10.70 cm SH). The species longevity, tmax was estimated as 3/K (Pauly, 1984). The parameters are summarised in Table 6.

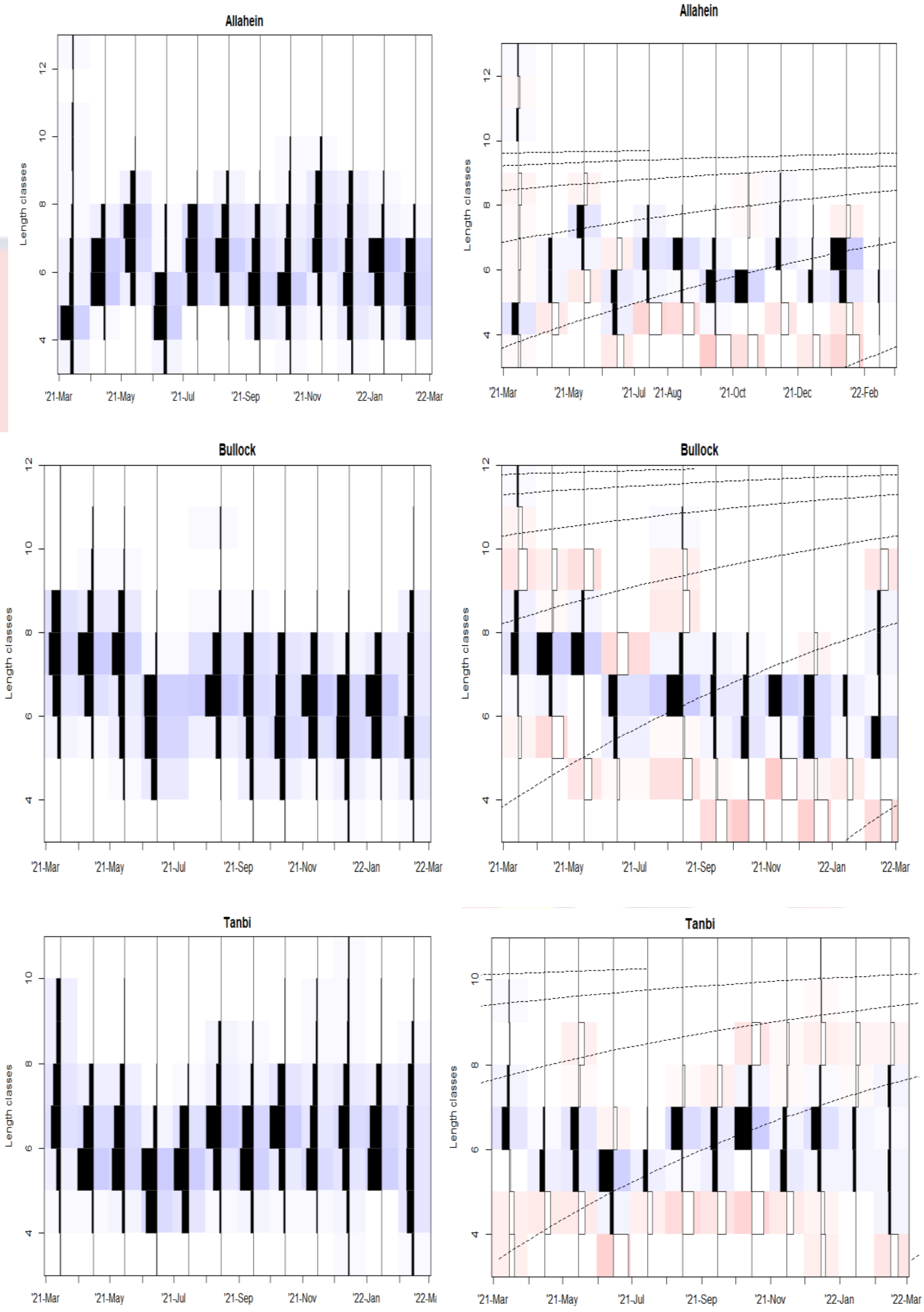

Figure 34: Monthly length-frequency and restructured length-frequency distributions of *Crassostrea tulipa* sampled from the three sites in The Gambia with growth curves superimposed.

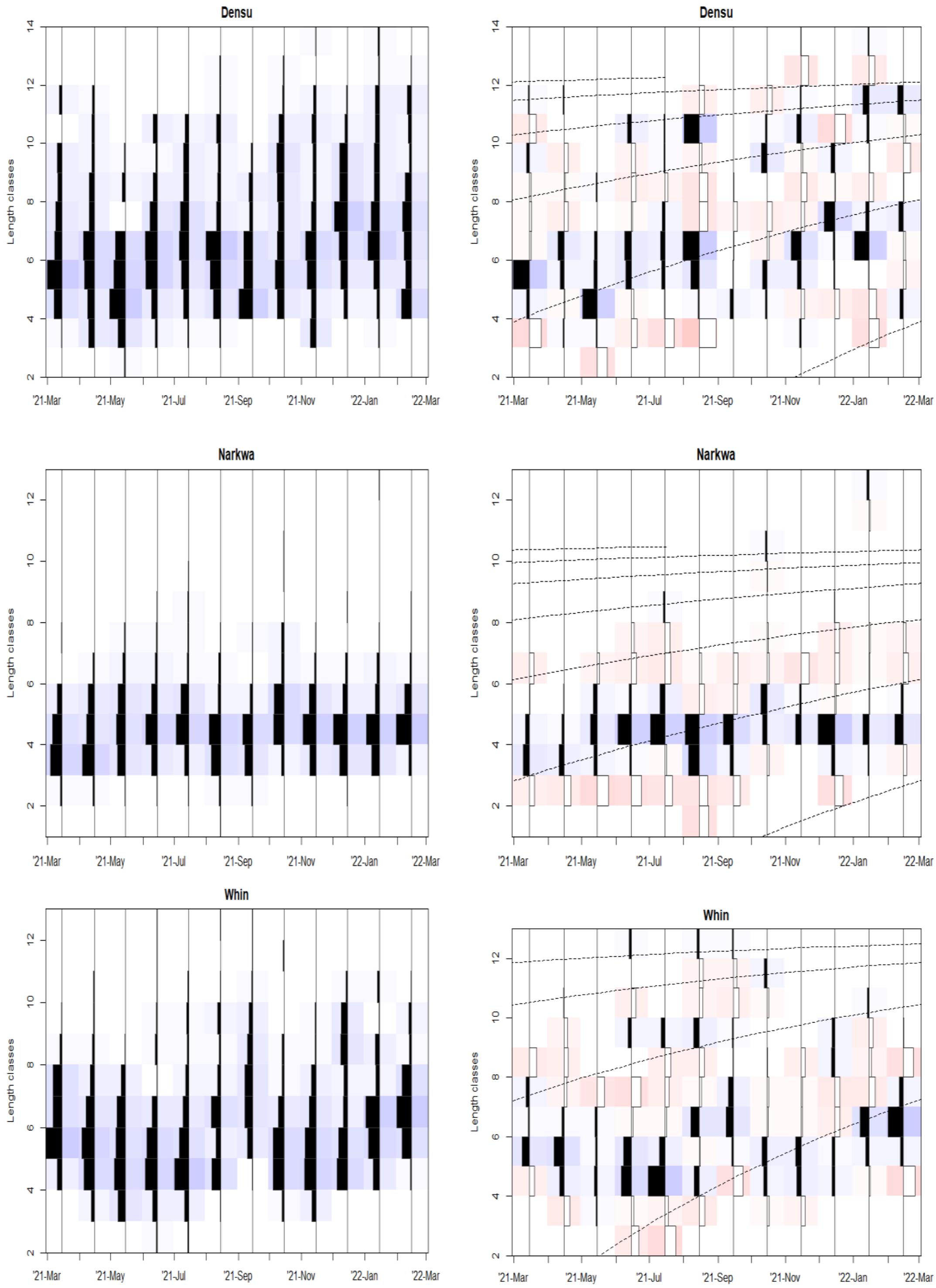

Figure 35: Monthly length-frequency and restructured length-frequency distributions of *Crassostrea tulipa* sampled from the three sites in Ghana with growth curves superimposed.

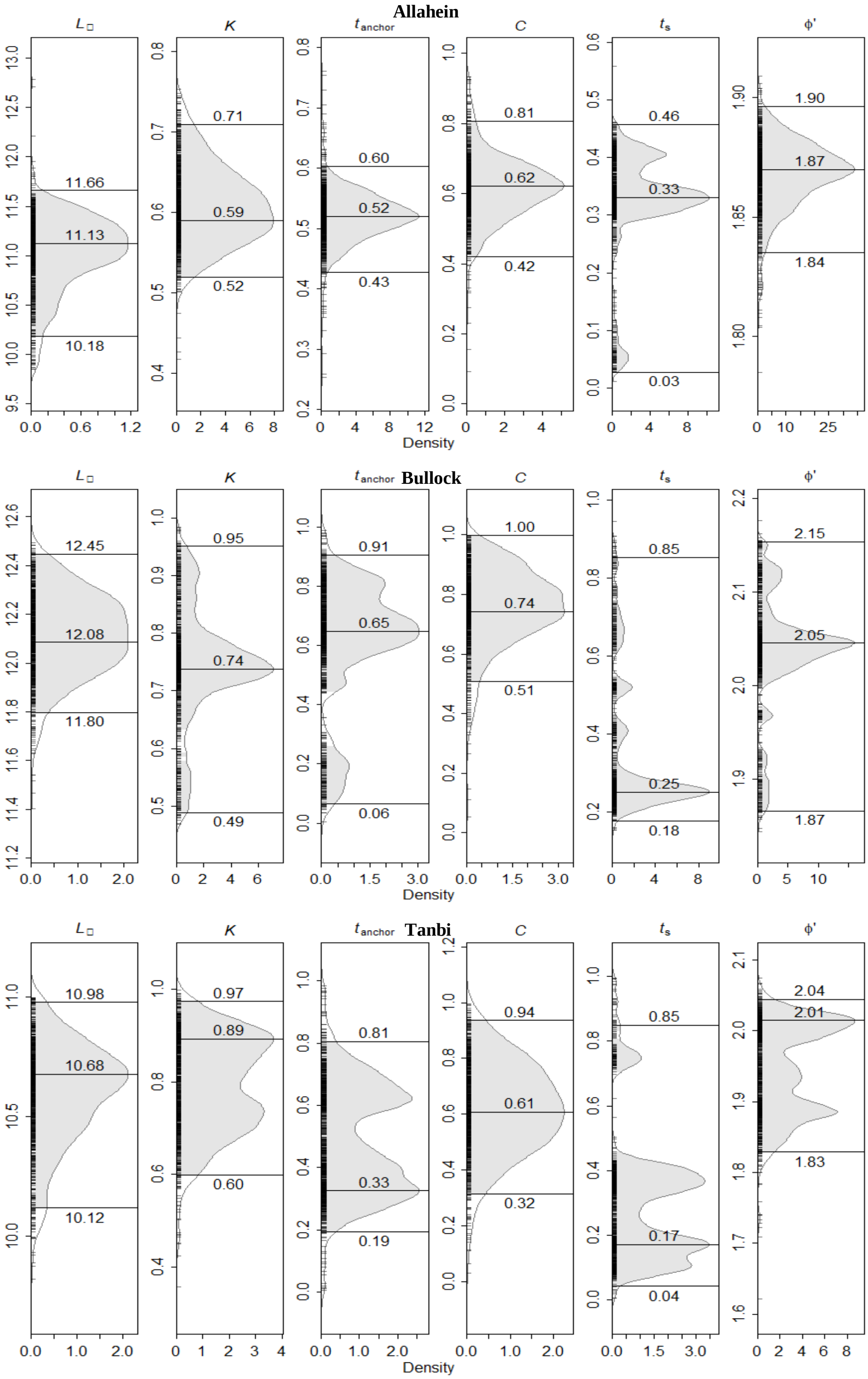

Figure 36: von Bertalanffy Growth parameters of *Crassostrea tulipa* sampled from the three sites in The Gambia.

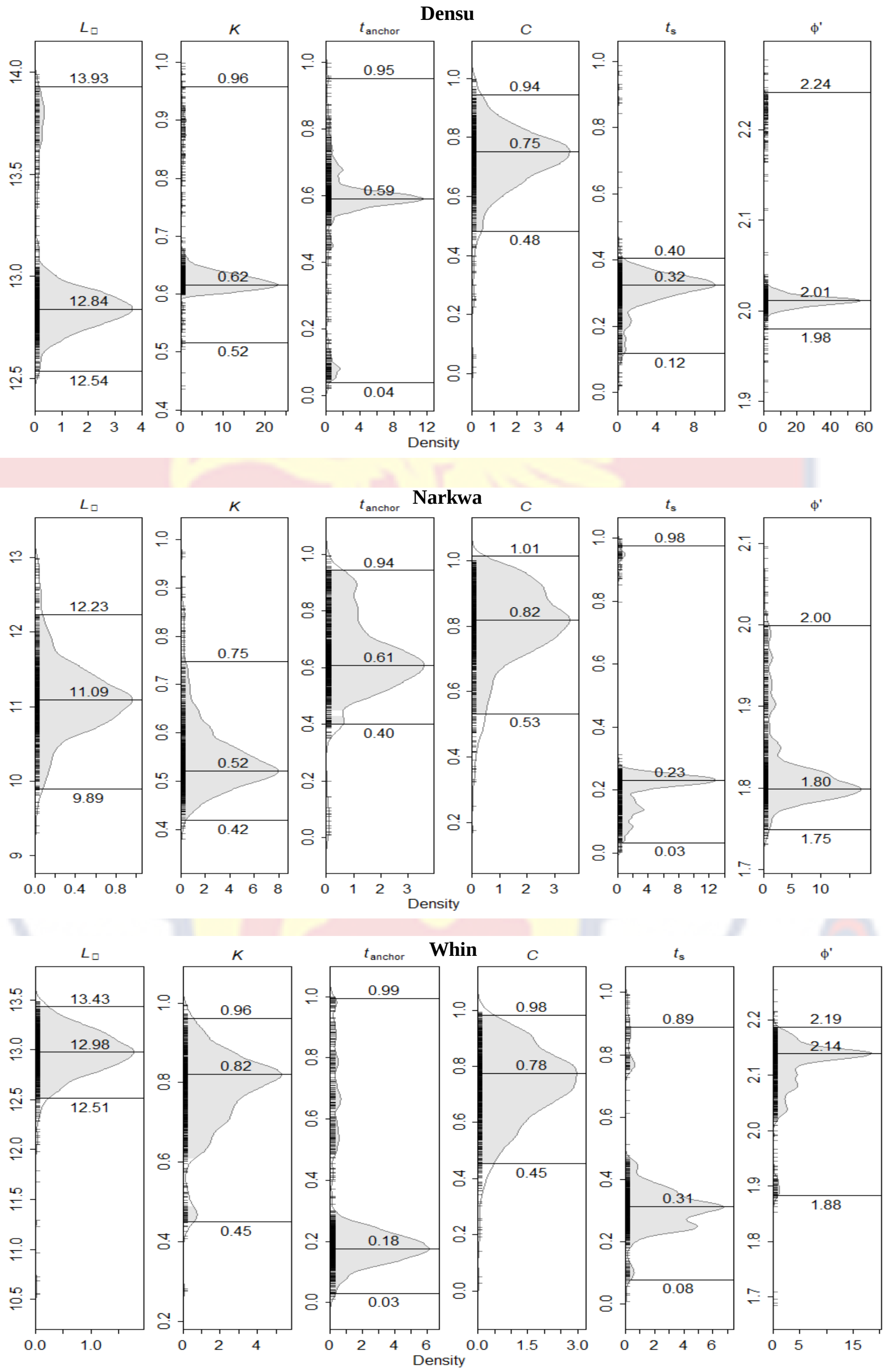

Figure 37: von Bertalanffy Growth parameters of *Crassostrea tulipa* sampled from the three sites in Ghana.

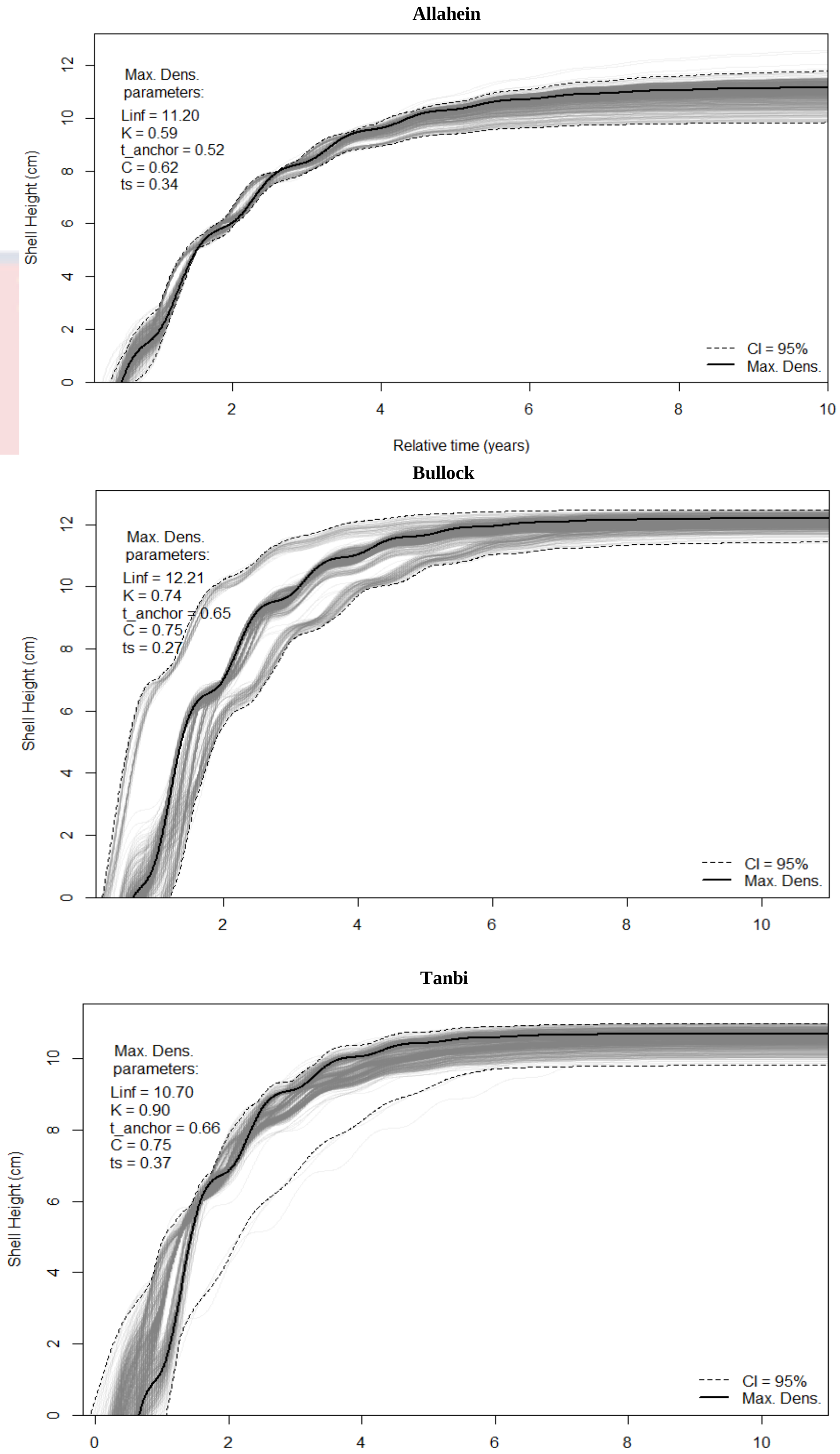

Figure 38: A plot of the von Bertalanffy growth curve with growth parameters estimated (at 95% confidence interval) for sites in The Gambia.

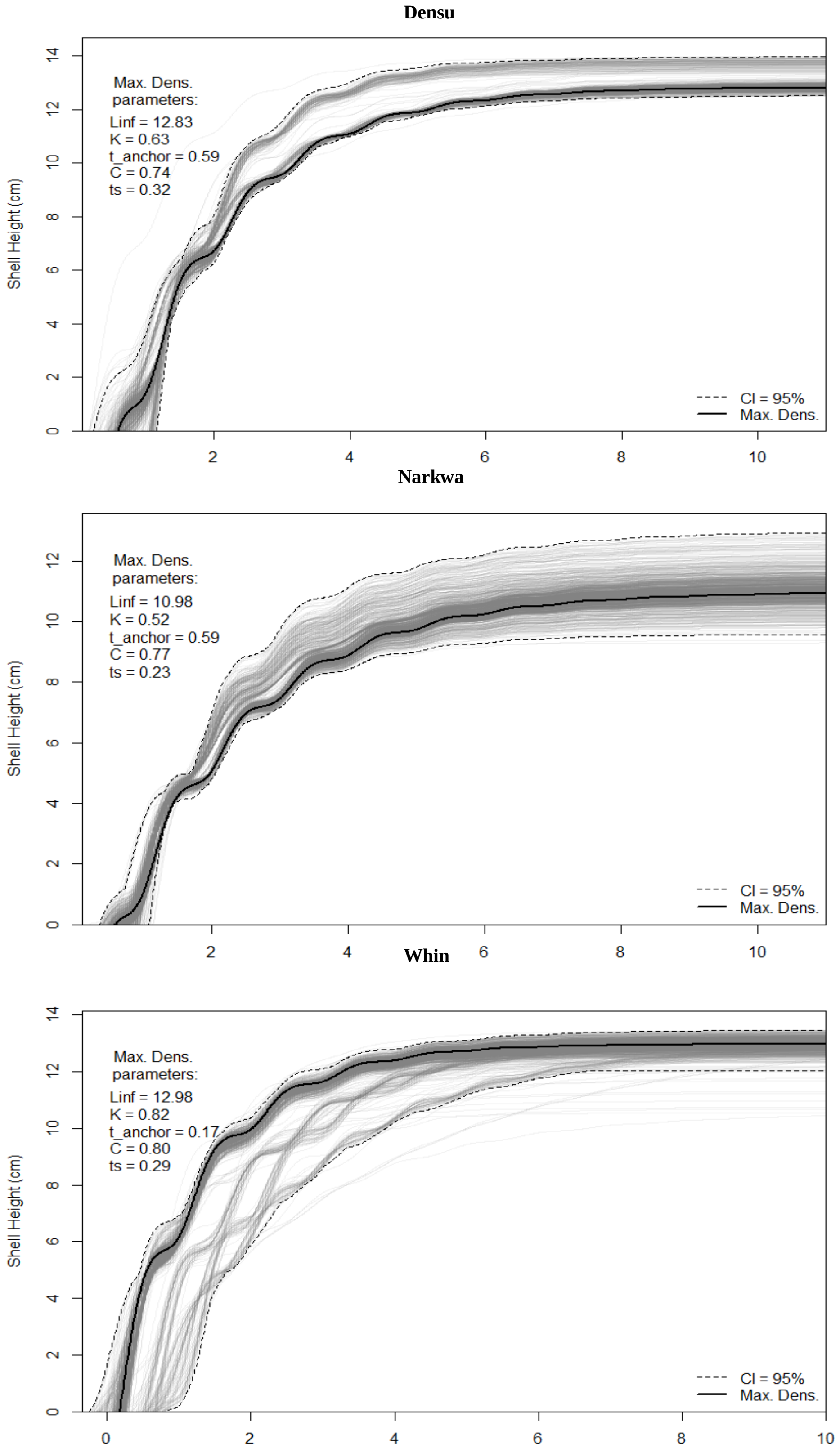

Figure 39: A plot of the von Bertalanffy growth curve with growth parameters estimated (at 95% confidence interval) for sites in Ghana.

Table 6: *Estimates of growth and derived parameters of C. tulipa population in Ghana and The Gambia*

Sites	SH_{∞}/cm	K/yr	t_anchor/yr	φ'	Tmax/yr
Allahein	11.20	0.59	0.52	1.87	5.08
Bullock	12.21	0.74	0.65	2.05	4.05
Tanbi	10.70	0.90	0.66	2.01	3.33
Densu	12.83	0.63	0.59	2.02	4.76
Narkwa	10.98	0.52	0.59	1.80	5.77
Whin	12.98	0.82	0.17	2.1	3.66

Von Bertalanffy growth equation describing growth of *Crassostrea tulipa* populations at each waterbody is estimated as follows:

Allahein: $SH_t = SH_{\infty}$ (1-k^(t-t_0)), t = 1

SH_1 = 11.20 (1-0.59^(1-0.52)) = 7.30cm (At age 1, the oyster grows to 7.3 cm at a monthly height increment of 0.61cm).

Bullock: $SH_t = SH_{\infty}$ (1-k^(t-t_0)), t = 1

SH_1 = 12.21 (1-0.74^(1-0.65)) = 7.62cm (At age 1, the oyster grows to 7.62 cm at a monthly height increment of 0.64cm).

Tanbi: $SH_t = SH_{\infty}$ (1-k^(t-t_0)), t = 1

SH_1 = 10.70 (1-0.90^(1-0.0.66)) = 4.89 cm (At age 1, the oyster grows to 4.89 cm at a monthly height increment of 0.41 cm).

Densu: $SH_t = SH_{\infty}$ (1-k^(t-t_0)), t = 1

SH_1 = 12.83 (1-0.63^(1-0.59)) = 10.62cm (At age 1, the oyster grows to 10.62 cm at a monthly height increment of 0.88 cm).

Narkwa: $SH_t = SH_\infty$ (1-k^(t-t_0)), t = 1

SH_1 = 10.98 (1-0.52^(1-0.59)) = 8.13 cm (At age 1, the oyster grows to 8.13 cm at a monthly height increment of 0.68 cm).

Whin: $SH_t = SH_\infty$ (1-k^(t-t_0)), t = 1

SH_1 = 12.98 (1-0.82^(1-0.17)) = 3.13 cm (At age 1, the oyster grows to 3.13 cm at a monthly height increment of 0.26 cm).

Mortality Rates of *Crassostrea tulipa.*

Figures 40 and 41 present results of the length-converted catch curves of the oyster stocks in Ghana and The Gambia generated from the TropFishR package in R-software showing a detailed comparison of the mortality and exploitation parameters estimated for the populations across the six sites. It estimated the total mortality rate (Z) of the populations based on oysters that were fully exploited. The annual mean sea surface temperature during the sampling period at each site was integrated into the function. The total mortality (Z), natural mortality (M), and fishing mortality (F) of the oysters were estimated. The current exploitation rate (E=F/Z) was estimated which indicated the oyster populations at most of the sites were optimally exploited or underexploited. A summarised interpretation is presented in Table 7. The Z/K ratio estimated are all greater than 1 indicating a mortality induced populations at all the sites.

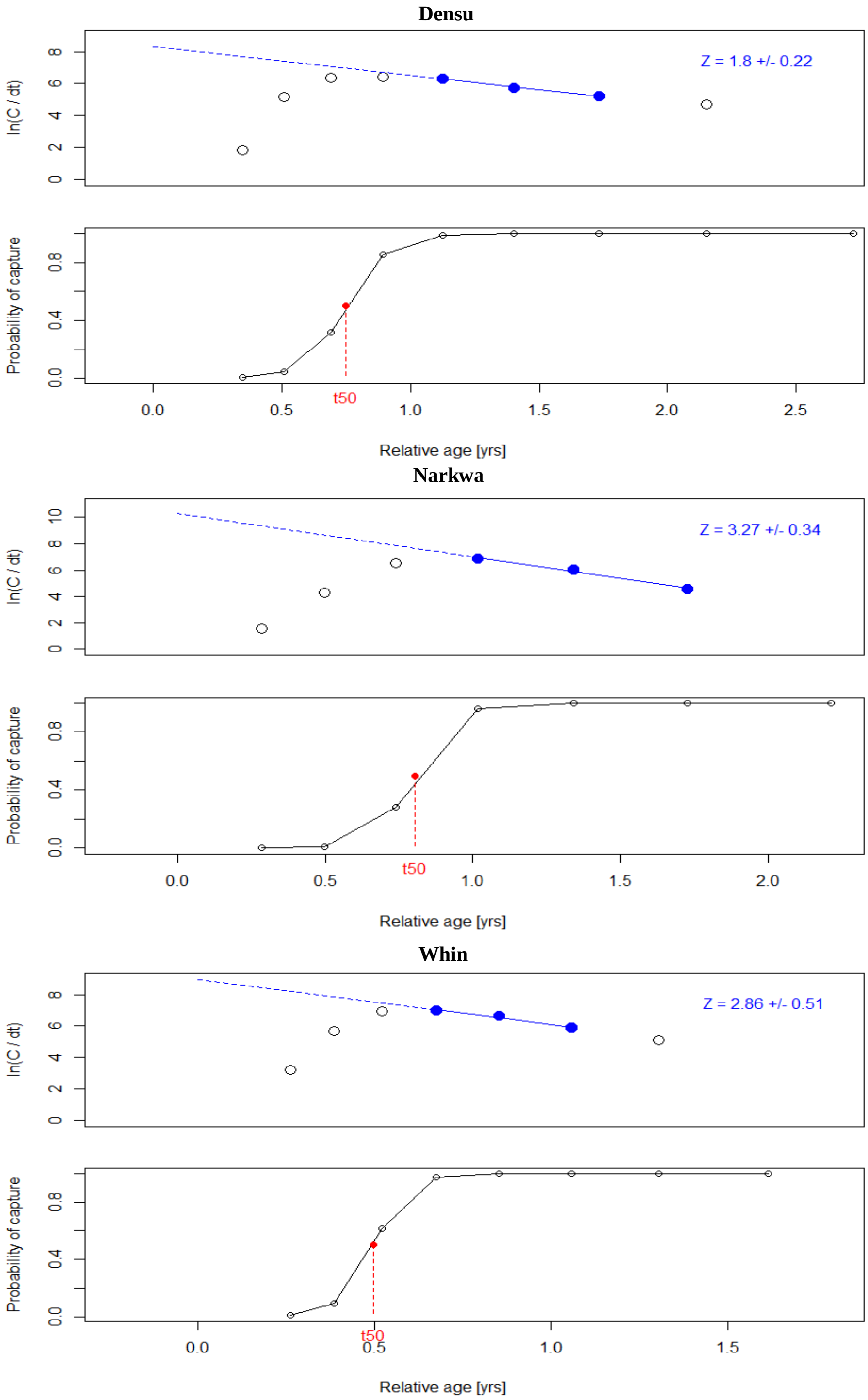

Figure 40: Catch-curve distribution and probability of capture for oyster populations at the three sites in Ghana.

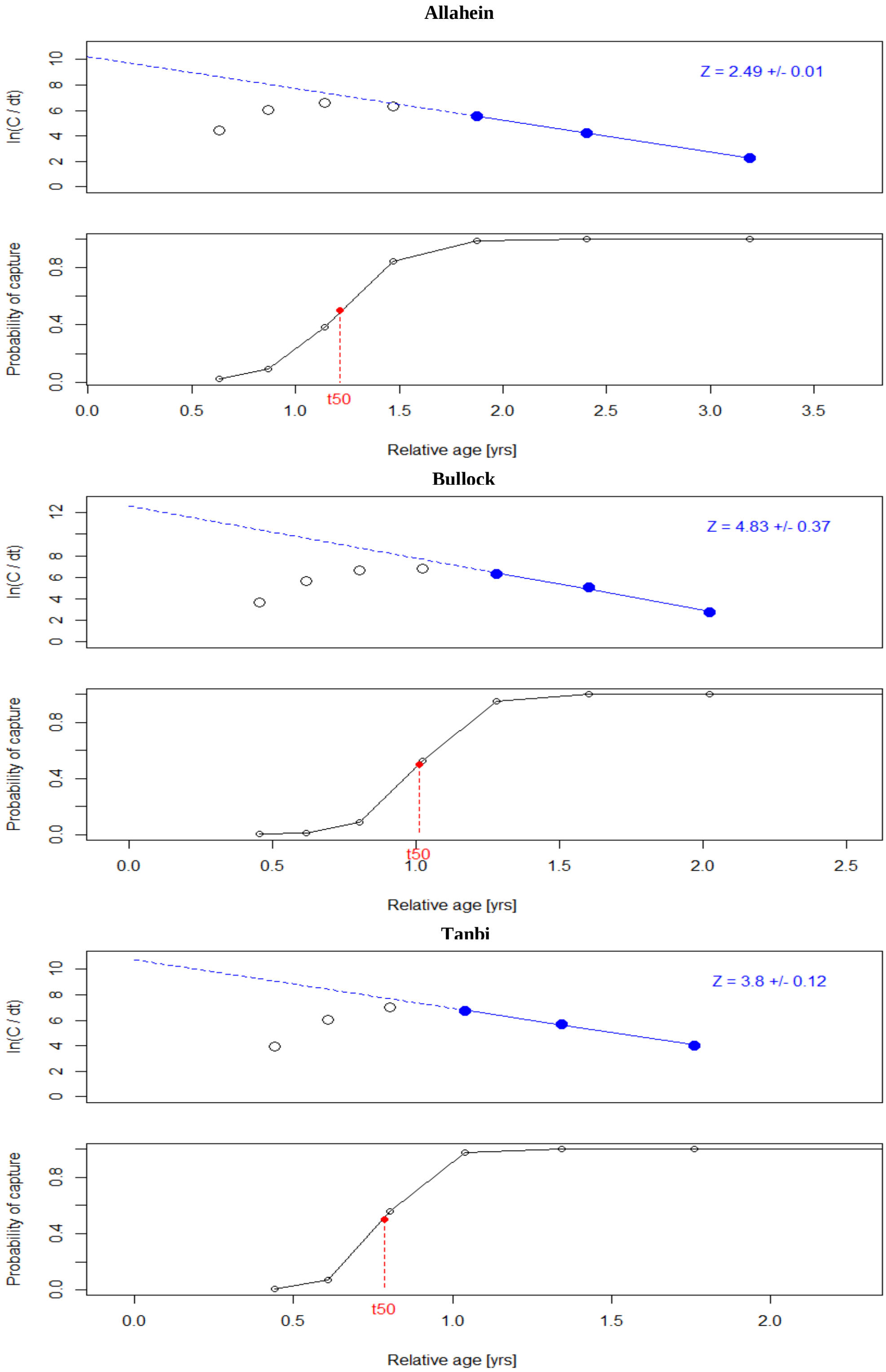

Figure 41: Catch-curve distribution and probability of capture for oyster populations at the three sites in The Gambia.

Table 7*: Estimates of mortality and exploitation rates of C. tulipa population in Ghana and The Gambia*

Sites	Z/yr	M/yr	F/yr	$E_{currrent}$	L_{c50}/cm	Z/K
Allahein	2.49	1.69	0.79	0.32	5.74	4.2
Bullock	4.83	1.93	2.91	0.61	6.47	6.5
Tanbi	3.80	2.26	1.55	0.407	5.42	4.2
Densu	1.80	1.58	0.22	0.12	4.81	2.86
Narkwa	3.27	1.57	1.70	0.52	3.74	6.29
Whin	2.86	2.03	0.84	0.29	4.34	3.49

Table 8*: Parameters of von Bertalanffy growth function of some bivalves from different countries*

Location	Species	Source	L_∞/cm	K/yr	φ'	T_{max}-/yr	Z/yr	M/yr	F/yr
The Gambia (Allahein)	*C. tulipa*	Present study	11.20	0.59	1.87	5.08	2.49	1.69	0.79
The Gambia (Bullock)	*C. tulipa*	Present study	12.21	0.74	2.05	4.05	4.83	1.93	2.91
The Gambia (Tanbi)	*C. tulipa*	Present study	10.70	0.90	2.01	3.33	3.80	2.26	1.55
Ghana (Densu)	*C. tulipa*	Present study	12.83	0.63	2.02	4.76	1.80	1.58	0.22

Location	Species	Source	L_{∞}/cm	K/yr	φ'	T_{max}-/yr	Z/yr	M/yr	F/yr
Ghana (Narkwa)	*C. tulipa*	Present study	10.98	0.52	1.80	5.77	3.27	1.57	1.70
Ghana (Whin)	*C. tulipa*	Present study	12.98	0.82	2.1	3.66	2.86	2.03	0.84
Ghana (Densu)	*C. tulipa*	Osei *et al.* (2021)	16.86	0.44	-	6.82	1.92	1.20	0.72
Benin	*E. elliptica*	Akele *et al.* (2015)	4.75	0.38	1.92	-	2.90	1.16	1.74
Bangladesh	*C. virginica*	Amin *et al.* (2006)	13.65	0.63	2.07	-	1.87	1.66	0.21
Bangladesh	*C. maderensis*	Amin *et al.* (2008)	20.88	0.35	2.18	-	1.78	1.01	0.77
Korea	*C. gigas*	Vakily (1992)	10.37	2.35	4.40	-	-	-	-

Assessment of the reproductive capacities of *Crassostrea tulipa*.

Examination of gonads of *C. tulipa* showed that the gonad was part of the visceral region and not a separate organ and observed as a whitish (for males) or cream-colored fluid (for females). A sample is shown in Figure 42A. Under the microscope, the mature female specimen showed oval-shaped figures

(Figure 42B) and the male mature specimen showed highly condensed dotted shapes (Figure 42C).

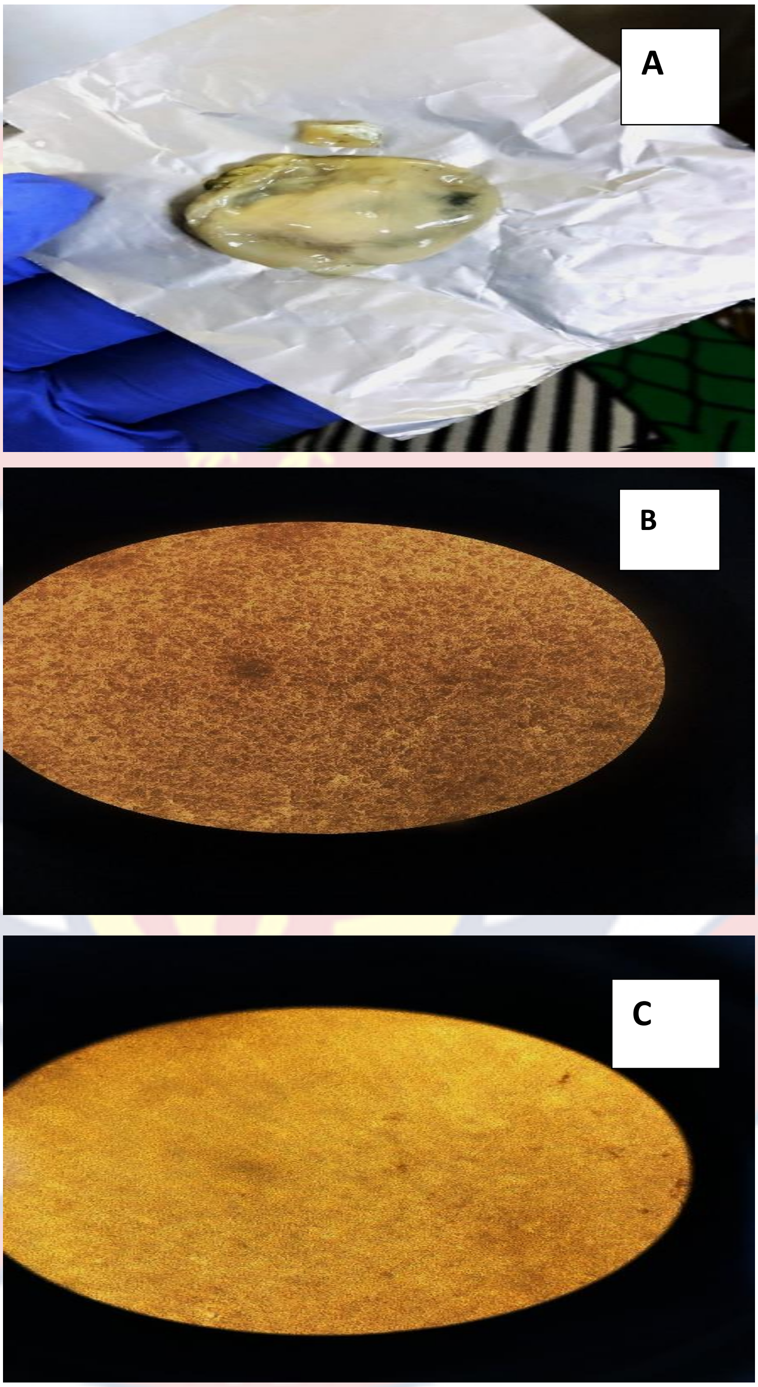

Figure 42: Mature oyster specimen showing ripe gonads (A), mature female oyster (B) and mature male oyster (C) as viewed under the microscope. (Magnification = x10).

Sex ratio

Table 9 and Figure 43 presents a tabular record of the sex ratios of mangrove oysters and the graphical representation of their monthly percentage compositions respectively. Generally, there appeared to be a significantly higher number of females at each of the six sites in both countries although Densu recorded a fairly higher percentage of males whiles Tanbi recorded more females. However, it can be observed that, there were gradual shifts in male and female percentages across the months. For instance, at Densu, Narkwa and Whin, there were more males observed than females in the periods between March 2021 and October 2021 before the female populace took over. Although around February 2022, the male population appeared to shoot up again, especially in Narkwa and Densu. The reverse to this is true for the Gambian systems.

The monthly occurrence of indeterminate individuals suggests a continuous happening of spent oysters as well as entry of smaller oysters into the population and it occurred throughout the year, which could be inferred to as a continuous spawning habit in the oysters. The highest proportion of individuals of indeterminate sex were recorded in March 2021 at the sites in The Gambia while the populations in Ghana had most of these between July and September of 2021. Further analysis was done on the sex ratio to check the deviation from 1:1 at all six sampling locations (Table 9). It can be observed that most of the sites with the exception of Allahein and Narkwa significantly deviated from the 1:1 sex ratio.

Table 9: *Summary of oyster sex ratio encountered at each of the six study sites*

Country	Sites	No. of males	No. of females	Indeterminate	M:F	χ2	P
The Gambia	Allahein	240	262	94	1:1.09	0.96	0.33*
	Bullock	163	322	62	1:1.98	52.31	0
	Tanbi	300	223	47	1:1.66	32.06	0
Ghana	Densu	247	279	34	1.35:1	11.34	0.001
	Narkwa	195	324	62	1:1.11	1.95	0.16*
	Whin	192	258	79	1:1.34	9.68	0.002

*= Not significant (α=0.05).

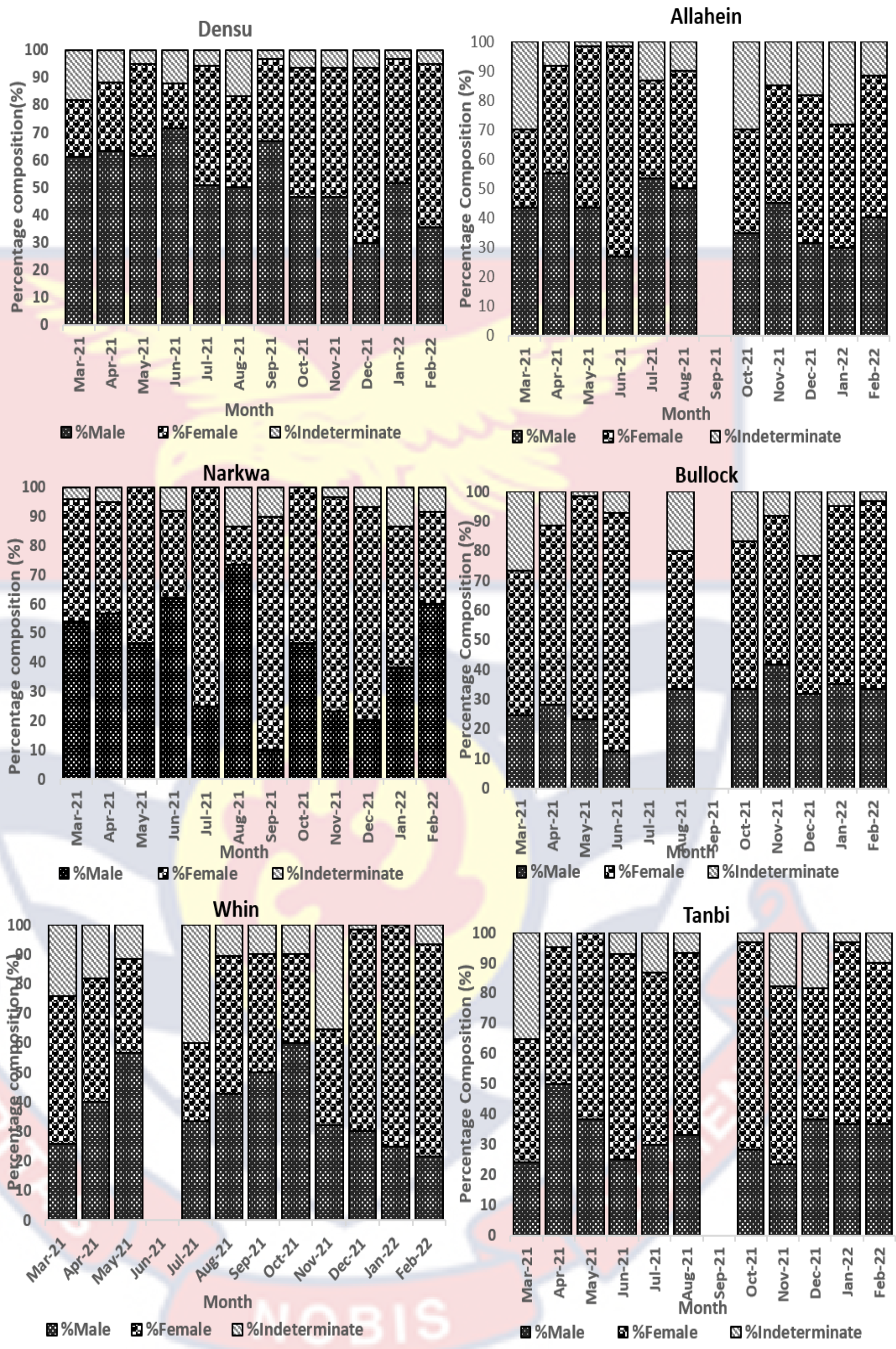

Figure 43: Percentage composition of the sex ratios for mangrove oysters sampled from the six water bodies in Ghana and The Gambia.

Maturity Size

Table 10 presents a summary of the smallest mature sizes of oyster species encountered at each of the six study sites. Narkwa recorded the smallest sized mature individuals for both male and female individuals (M= 26 mm, F= 27 mm). Generally, the males has smaller maturity sizes than the females. An estimation of the length at which 50% of the oysters have matured (Lm_{50}) is presented as graphs in Figures 44 and 45. Here, Densu recorded the highest Lm_{50} (56 mm), followed closely by Bullock (55.24 mm), then Allahein (52 mm), Tanbi (51.8 mm), Whin (51 mm) and Narkwa (35.6 mm). Table 11 gives a summarised description of the exploitation status of the populations at each site.

Table 10: *Smallest mature sizes of oysters encountered at each of the six study sites*

Country	**Site**	**Smallest mature specimen [SH (mm)]**	
		Male	**Female**
The Gambia	Allahein	34	34
	Bullock	36	37
	Tanbi	32	35
Ghana	Densu	29	32
	Narkwa	26	27
	Whin	29	34

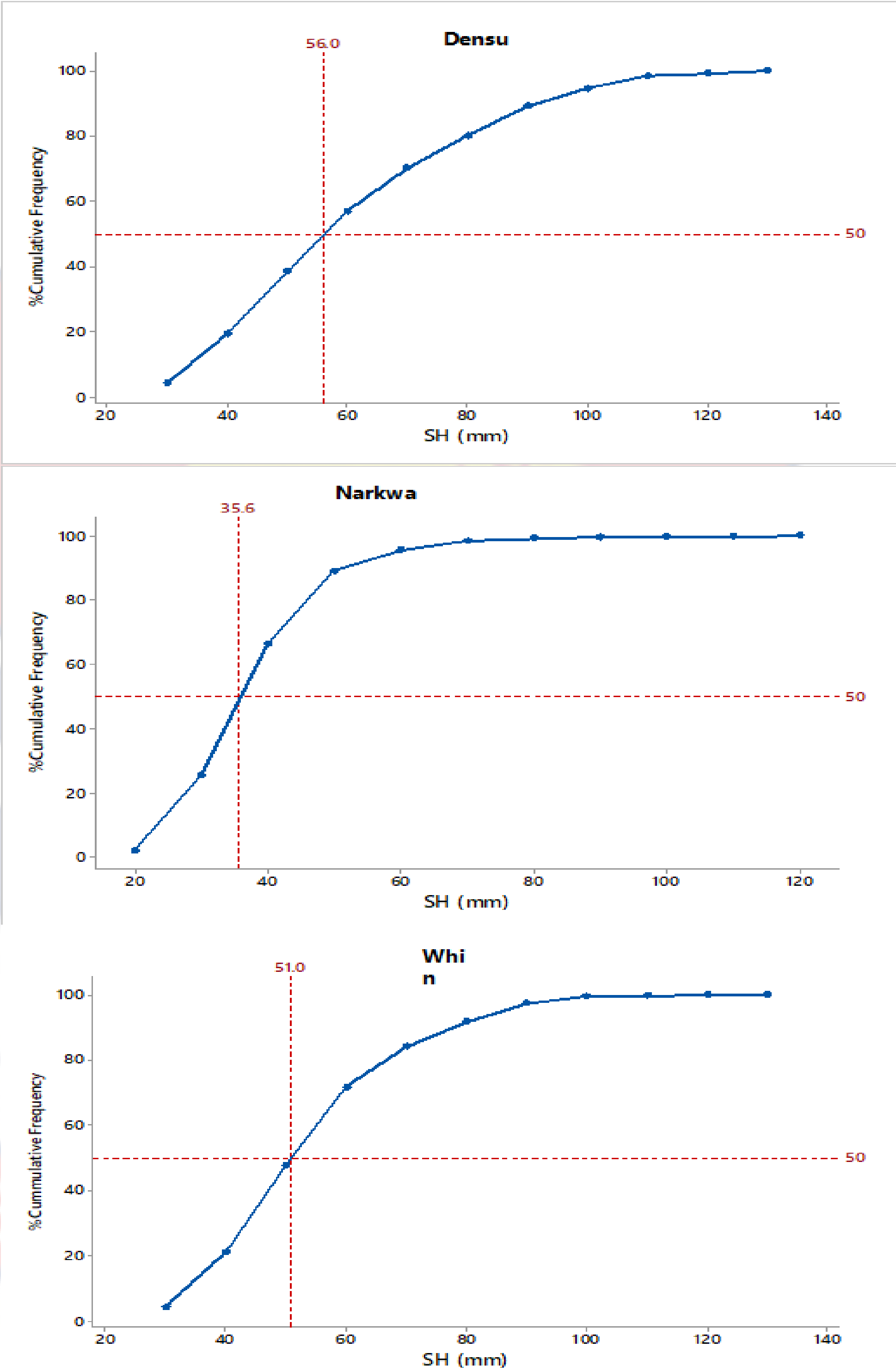

Figure 44: Maturity size (Lm_{50}) of the mangrove oysters sampled from the six water bodies in Ghana.

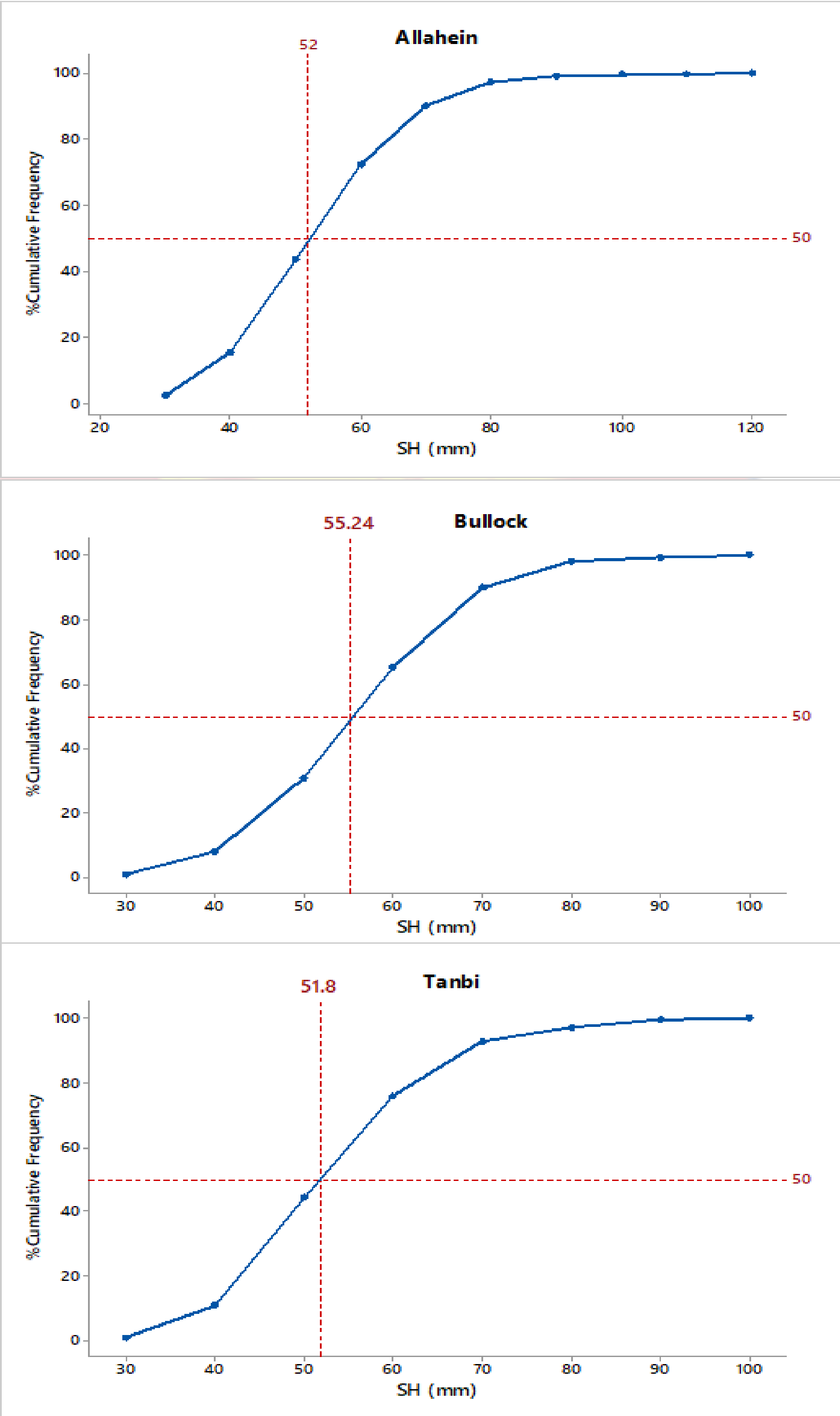

Figure 45: Maturity size (Lm_{50}) of the mangrove oysters sampled from the six water bodies in The Gambia.

Table 11: *Estimating exploitation status of C. tulipa at the six study areas*

Country	Sites	Lm_{50} (cm)	Lc_{50} (cm)	$L\infty$/cm	$Lc_{50}/L\infty$	$E_{currrent}$
The Gambia	**Allahein**	5.2	5.74	11.20	0.51	0.32
	Bullock	5.5	6.47	12.21	0.53	0.61
	Tanbi	5.2	5.42	10.70	0.51	0.407
Ghana	**Densu**	5.6	4.81	12.83	0.40	0.12
	Narkwa	3.6	3.74	10.98	0.34	0.52
	Whin	5.1	4.34	12.98	0.33	0.29

Assessment of Catch per Unit Effort, Exploitation and Scale of Fishery

Trends of Catch per Unit Effort and Exploitation.

Figures 46 and 47 represent graphs showing the average monthly CPUE; estimated as catch per shellfisher per hour. Continuous monthly data collection could not be carried out at all the sites because of the closed harvesting season for some of them as part of their management practices. In Tanbi and Bullock, data collection was carried out from March to June 2021. The CPUE was estimated as a monthly average of the daily catch of a fisher per hour. Bullock had a higher CPUE ranging between (15-20) kg/person/hour and Tanbi, which recorded between (7-9) kg/person/hour in March, had increased to 10kg/person/hour.

The scenario is not different from what was observed in Ghana. Data collection began in February 2022 and ended in August 2022. Densu was closed until April 2022. However, when data harvesting resumed, Densu fishers reported higher CPUE values in comparison to the other sites in Ghana ranging between (17-23) kg/person/hour. Over the months, Narkwa recorded the lowest

CPUE values falling between (7.5 – 16.5)kg/person/hour. A summary of the oyster harvesting activities is presented in Table 12.

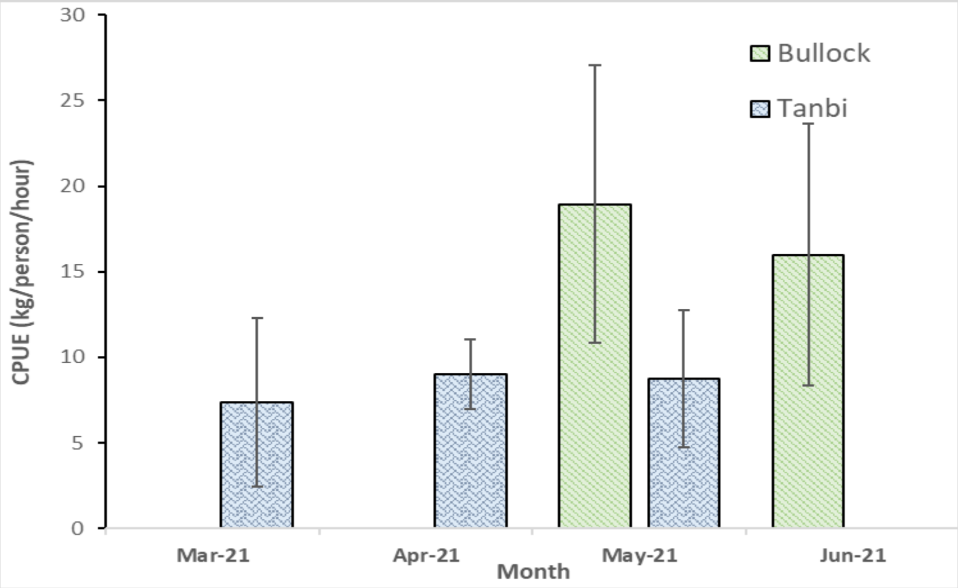

Figure 46: Monthly average Catch per Unit Effort ± S.E (vertical bars) of the mangrove oysters *(Crassostrea tulipa)* harvested from the study sites in The Gambia from March to June 2021.

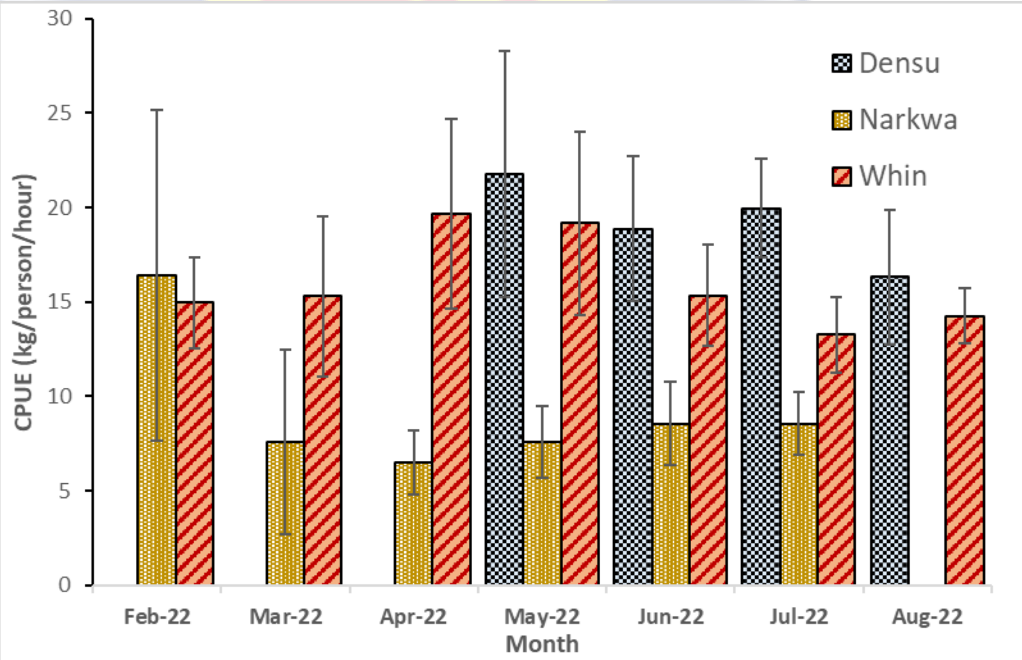

Figure 47: Monthly average Catch per Unit Effort ± S.E (vertical bars) of the mangrove oysters *(Crassostrea tulipa)* harvested from the study sites in Ghana from February to August 2022.

Table 12: *A summary of the oyster harvesting activities at the six study sites in Ghana and The Gambia*

Country	Sites	Communities exploiting waterbody	Frequency of harvest	Harvesting time/person/hours
The Gambia	**Allahein**	5	Everyday in a season	Not estimated
	Bullock	12	Everyday in a season	5 - 6
	Tanbi	9	Everyday in a season	>8
Ghana	**Densu**	4	Twice a week	2 - 3
	Narkwa	1	Everyday in a season	5 - 7
	Whin	4	Everyday in a season	7 - 10

Comparative assessment of the scale of the fishery in Ghana and The Gambia and management modalities.

Harvest Value and Income

An estimation of the income value based on the daily catch of the shellfish harvesters are presented in Table 13. This was derived from the regression analysis of the whole weight-meat weight relationship in Figures 28 to 33. The USD equivalent value was derived using standardized local prices. At the time of the study, the USD rate to Ghana cedis was GHc 13.10 (Bank of Ghana) and was 61.5GMD to the Gambian Dalasi. The whole weight-meat weight relationships for all six sites are described. By comparison, Gambia placed a higher value on the price of oyster meat as compared to Ghanaian oyster markets. From all the four sites assessed, Whin appears to have a lower value for the prices of their oyster meat even though the amount of harvest they make is much higher than the rest of the sites.

Allahein - MW = 0.1075TW

Bullock - MW = 0.1106TW

Tanbi - MW = 0.1284TW

Densu - MW = 0.1092TW

Narkwa - MW = 0.1333TW

Whin - MW = 0.1297TW

Average daily Income per person for the sale of only oyster meat was estimated using the formula;

Average daily Income per person (USD) = Average daily catch /person x Price/kg (USD)

Table 13: *Summary of the income value of oyster meat per daily catch in Ghana and The Gambia*

Sites	Daily Average Catch/person/kg (Meat weight)	Price/kg (local currency)	Daily Income per person (local currency)	Average daily Income per person (USD)
The Gambia (Bullock)	9.65	690GMD	6658.5GMD	108.27
Ghana (Densu)	4.25	GHc20	GHc85	6.50
Ghana (Narkwa)	3.52	GHc9.00	GHc31.68	2.42
Ghana (Whin)	11.95	GHc7.71	GHc92.15	7.03

Management modalities in Ghana and The Gambia.

From the focus group discussions (FGDs) carried out as part of the research with key informants, in both Ghana and The Gambia on the structure of the fishery and the management operations at each of the locations, the following observations were noted.

1. Majority of the women engaged in shellfishing in Ghana and The Gambia are found in the Densu estuary (200 women) and Allahein (125 women), respectively.

2. There were varying levels of governance structures and management regimes at four sites which ranged from a formal co-management approach giving exclusive use rights to the fishers (Tanbi and Densu) to a mostly community-led management approach (Allahein and Bullock). Whin and Narkwa had no existing structures.

3. The management strategies at these sites with modalities in place include, among other things, seasonal closures, size restrictions, mangrove preservation, and regeneration. Unfortunately, there are no catch quotas or restrictions on human effort or entry.

4. At sites with management and governance regimes, the women shellfishers are strongly integrated into all decision-making processes, unlike the other Whin and Narkwa, where the traditional authority takes all decisions on their behalf.

5. Fishers at all the six sites studied affirmed that the mangroves were protected and prohibited from being harvested.

CHAPTER FIVE

DISCUSSION

This chapter discusses the outcomes from Chapter 4. The discussion gives interpretations to findings from this study, which covers the hydrographic parameters of the water bodies studied, and how they affect the development and survival of the oyster populations. It also describes the growth and mortality parameters of the population in comparison to findings from other relevant literature. The harvest and income value of the shellfish industry and management regimes in place to protect the resource are discussed in this chapter.

Hydrographic trends

The survival of organisms in the marine environment; especially bivalves, is highly influenced by the prevailing environmental conditions (Villarroel *et al.*, 2004). Thus, it is imperative that these hydrographic factors are constantly checked to assess how they affect population growth. It has been evidenced by research that, the hydrographic factors that impact the survival of bivalves the most is temperature, salinity, and turbidity; due to the filter-feeding habit of bivalves. (Obodai *et al.*, 1996; Buitrago *et al.*, 2009; Efiuvwevwere and Amadi 2015; Krampah *et al.*, 2019; Chuku *et al*,. 2020a; Osei *et al.*, 2020b).

The presence of oxidizable minerals or higher biological breakdown of organic (eutrophication) from the surroundings are two possible explanations for the establishment of a dissolved oxygen deficit, which leads to deoxygenation in waterbodies (Efiuvwevwere and Amadi, 2015) and having adverse impacts on the survival of fauna in that system. Research has shown that oyster species are able to thrive in low threshold levels of dissolved oxygen, sometimes below 1 mg/L (Mahu *et al.*, 2022). The D.O range that was measured was between (2.3 – 10.34) mg/L for all the waterbodies with significant variations among the water bodies and the two countries, which is within acceptable range. pH levels conducive for their growth range between 6 – 8.5. Extremely low or elevated concentrations of D.O. and pH may be fatal to the organisms or prevent their existence by having significant detrimental effects on their shell development (Bhatnagar *et al.*, 2004; Mahu *et al.*, 2022). Waterbodies in Ghana recorded pH levels of 6.5 and peaking at 10 and those in The Gambia recorded pH levels of 6.7 – 10.02. The low levels of D.O and pH measure in the months of June/July and December/January could be ascribed to putrefaction of organic matter because of increased precipitation in those months (Osei *et al.*, 2020b).

Although increased temperatures that remain inside the acceptable range can still maintain the growth of larval and adult oysters, provided food is available, temperature influences several physiological processes in oysters, including eating (Angell 1986; Arakawa 1990; Gosling, 2015). Temperature is also acknowledged as one of the key elements influencing the respiration rates and energy balance of poikilothermic marine organisms (Resgalla *et al.*, 2007). In Figure 10, there is a very distinct difference in the recorded observations for the waterbodies in the two countries, which is statistically significant. The West African mangrove oyster grow well within temperatures of 23– 31 °C (Atindana *et al.*, 2020) and temperatures lower than 10°C and higher than 35°C could be lethal. Findings from this study showed that the measured temperature readings for the waterbodies ranged between (24.0 ± 0.07) ºC and (34.0 ± 0.37) ºC showing that the condition was optimal for the growth and reproduction of the organisms.

Brackish mangrove swamps and protected waters with a depth of 2 to 5 meters are ideal habitats for oysters (Kamara, 1982; Yankson, 1990; Obodai, 1999; Yankson and Obodai, 1999; Ansa and Bashir, 2007). Salinity is one of the key elements for oyster growth and other physiological processes. Although the species are euryhaline, very low salinity levels might be detrimental to oyster development and survival because of diminished or unavailable nutrition as well as physiological stressors. (Obodai, 1997; Asare *et al.*, 2019; Osei *et al.*, 2020b). Mahu *et al.* (2022) propounds that the organisms cope well between 4 ‰ and 50 ppt salinity. Salinities outside of that band have the potential to be harmful to development and survival. Mortality/deaths are triggered from prolonged exposure to 0 ppt salinity. Salinity readings in The Gambia were generally higher and with steady trends throughout the year, ranging between 20-42 ppt. However, Ghanaian waterbodies fluctuated widely. In months where there was a lot of precipitation, salinity readings approached freshwater level of 0 ppt and the highest reading was recorded in May 2021 at 30 ppt.

Crassostrea tulipa is mostly found in sheltered aquatic areas and nearshore intertidal areas with depths of about 2-5 m. It is usually attached to mangrove stilt roots, (specifically red mangroves) or rocky substrate or simply lying on the sandy/muddy bed of the waterbody they inhabit (Kamara, 1982; Yankson, 1990; Yankson and Obodai, 1999; Obodai, 1999; Ansa and Bashir 2007; Mahu *et al.*, 2022). According to the outcomes of the physio-chemical study, the Gambian systems were generally deeper (1.5 – 4 m) with the Tanbi

Wetlands being the deepest, than Ghanaian waters (0 - 1.5 m) and Whin Estuary being the shallowest. Food resources for the species in the form of phytoplankton have their growth inhibited as a result of reduced water depth from the accumulation of organic waste and silt (Atindana *et al.*, 2020) and may be extremely damaging to the oyster community. Oyster life activities is highly impacted by turbidity, which measures the extent of suspended particles or silt in the water column. High levels of suspended silt have a detrimental effect on their survival. Because there is little light penetration in the water column, the primary production of the estuaries is decreased (Lloyd *et al.*, 1987; Asare *et al.*, 2019; Atindana *et al.*, 2020; Chuku *et al.*, 2020b; Osei *et al.*, 2020b; Mahu *et al.*, 2022). Moreover, Blay (1990) and Bayne (2017) indicate that, bivalves may seal their shells if there is a significant amount of silt present. This can prevent them from feeding and breathing, which can limit growth and increase mortality. This is because bivalves are filter feeders, and when turbidity levels rise, their gills may become clogged and they may experience irritation. Lloyd *et al.* (1987) reported that, turbidity values outside the range of 5–25 NTU could negatively affect their population.

Ghana's turbidity readings were highly fluctuating (20-150 NTU) and higher than The Gambia's readings which was lower and more stable (0-15 NTU). The highest turbidity readings for Ghana was recorded in June-July 2021 where there was increased levels of precipitation and land runoff carrying silt and other nutrients. The United States Environmental Protection Agency (USEPA) claims that rising ocean temperatures, together with high nutrient levels and climate-related changes, may also lead to an increase in the severity and frequency of harmful algal blooms (HABs), which limit sunlight absorption and lower oxygen levels required by other organisms, which include those that directly or indirectly provide food resources for oysters (USEPA, 2013).

The amount or levels of nitrogen and phosphorus in the water column as documented in reports, strongly correlate with primary production in estuarine and coastal aquatic systems (Smith *et al.*, 2006) by causing a rapid increase of phytoplankton abundance which serve as food for the species under study (National Research Council, 2000). Nitrate and phosphate concentrations reported in this study for both countries were significantly higher than what was recommended (1.0 mg/l for nitrates and 0.1 mg/L for phosphates) by NOAA/EPA. Again, Ghana's EPA dictates that the maximum permissible value for nitrates is 0.1 mg/L and for phosphate is 2.0 mg/L in aquatic systems (Nartey *et al.*, 2012) and eventually, this might cause the proliferation of harmful algal blooms (HABs), which are also a source of food for the oysters. They are harmful algae because they make the oysters toxic for human consumption.

By inference, it can be said that, the species in the Gambian waters were doing better with larger size ranges (50– 70 mm) shell height than the Ghanaian counterparts which had larger frequency of oysters with smaller size ranges (3 5 cm). This could be due to increased primary productivity and food abundance with the increased light penetration into the water, easier filtration and assimilation of food because of less turbid/silty water bodies in comparison to the waterbodies in Ghana. The assessment carried out also confirms the marine nature of the systems in The Gambia in comparison with the Ghanaian systems which were more estuarine with the influx of freshwater along with mud and silt, thereby increasing the turbidity levels and reducing the salinity levels in the waterbodies. Principal Component Analysis carried out on the waterbodies (APPENDIX C) showed the combined effects of the hydrographic parameters in the systems in both countries. In The Gambian systems, salinity had the highest effect/contributions, as seen in Figure 16 and this has greatly aided reproduction and population growth within The Gambian systems. The one-way ANOVA analysis conducted overall (APPENDICES A and B) confirm there were significant differences among the parameters for the waterbodies in the two countries, although there were no significant differences between the stations sampled at each site.

Size assessment and growth variations

In bivalves, shell height, length, width and weight can be used to estimate growth among the populations using various relationships (Punt *et al.*, 2013; Akele *et al.*, 2015; Krampah *et al.*, 2019; Osei *et al* 2020a; Chuku *et al.*, 2021; Osei *et al.*, 2021). The monthly size variations and size distributions of *C. tulipa* population in the six water bodies that were studied (Figures 19 and 20) show that the population in The Gambia were growing bigger with larger class sizes than the population in Ghana, except the Densu population, which fell within the same range as what was recorded in The Gambia. Based on the overall length-frequency data, the sizes of the mangrove oysters in The Gambia ranged from 30 – 120 mm shell height with the modal height falling within the range of 50 – 70 mm. In Ghana, the overall length-frequency was between 20 – 140 mm shell height, while the modal lengths were found between 40-60 mm shell height. For the monthly shell height variations in Figure 19, the oysters from The Gambian waters maintained a uniform steady shell height average of

65 mm. The shell height for the oyster stock in Ghana, however were fluctuating widely in the aquatic systems which could be as a result of the differing physicochemical parameters in each of the systems in Ghana, which were more of estuarine in nature. The influx of freshwater into the systems introduces silt causing the water to be more turbid. This forces the species to stop feeding and may affect their growth. Again, it can also be assumed that the fishers picked the bigger sized oysters in the systems leaving behind the smaller ones at the time of data collection. At the time of this research, the Densu oyster fishery was closed in late 2020 and opened in May 2021. It was then closed again in November 2021 and opened on 30th April 2022 for fishing to resume. That could explain why Densu recorded larger sized oysters in the period of sampling and smaller sizes were recorded in the months after the site was opened. Similar trends were observed at the sites in The Gambia around the season. Tanbi and Bullock in The Gambia had a season that was open for only two to three months between March and June, but Allahein had a season that was closed the entire year.

It is interesting to note that between May and June, mean sizes significantly dropped not just at Bullock and Tanbi, where fishing pressure was likely to be blamed, but also at Allahein, where harvesting was not taking place at the time. This tendency was also seen in the Whin Estuary between March and May, despite there being no season closure or opening at the time. Going by this, the narrative may then change from it being attributed to increased fishing pressure only but also maybe the active introduction of younger oysters into the population around those periods. A study conducted by Osei *et al.* (2021) in the Densu estuary alone, reported that frequency distribution for the oysters fell between 20 – 146 mm SH and the modal class was between 40 - 49 mm. In Benin, Akele *et al*. (2015) also found the shell height range of freshwater oysters, *E elliptica* were between 17 mm to 138 mm and these findings were at variance with what was observed in this study. It can also be observed that the sizes of the oysters have some relationship with the hydrographic parameters recorded at each site; particularly, salinity and turbidity. In the months (Jun-Jul and Dec-Jan) where there was increased rainfall resulting in lower salinity levels and increased turbidity due to runoff, the shell heights recorded were lower and this affirms the earlier inference.

Individual wellbeing and potential differences between different unit stocks or the same species of mangrove oysters can be assessed using morphometric analysis based on the shell dimensions and length-weight relationships (King, 2007; Thejasvi *et al.*, 2014). The length–weight relationship analysis of a species is an important element of its productivity (Le Cren, 1951; Lalèyè, 2006; Tah *et.al.*, 2012). As stated by Vakily (1989), its objective is to determine the essential variables that enable the conversion of length into weight, a parameter that growth studies typically find more complex to quantify. Relationships between the length and weight of organisms can used to estimate the weights from their lengths, condition indices as well as ontogenic morphometric changes (Teixeira de Mello *et al.*, 2006). The constant b, sometimes referred to as the coefficient of allometry/isometry, is used in growth research to express the degree with which an animal's body form changes as it grows (Thejasvi *et al.*, 2014).

In this study, the data for the shell height-total weight relationship were nonlinear and were log transformed to be able to define the relationship.

Crassostrea tulipa at all the six sites studies exhibited various strengths of significant relationships between the shell height and total weight. However, all the six sites had their populations significantly deviating from 3, where the growth coefficient, b, was less than 3 indicating a negative allometric growth among the species. This means that the shell height was growing at a faster rate than the total weight of the organism. This finding is in agreement with the findings of Akele *et al.* (2015); b = 2.214 and Osei *et al.*, (2021), b = 2.54.

Condition index reflects the relative degree of the bivalves' viability or robustness. It depicts the level of nutritional quality or the extent to which the flesh fills the shell (Quayle, 1980). Condition index, C. I., is founded on the assumption that oysters in better condition weigh more. A higher C. I would indicate a well-fed bivalve, while a low C.I. may indicate a poorly-fed bivalve of the same shell height. Farmers of bivalves can benefit from knowing this information since it shows how well the animals are suited for commercialization. (Davenport and Chen, 1987). In this study, the very first observable difference is the mean C. I. of the Ghanaian population fluctuates widely among the systems throughout the year although they recorded higher values between 2 and 16 than was obtained for the populations in The Gambia. The Gambian population maintained a steady but lower condition index across the months (Figure 27). This could be alluded to occurrence of continuous reproductive activities in The Gambian waterbodies as result of the high salinity levels. In the Ghanaian waterbodies, salinity levels were low and sometimes approaching freshwater conditions, which might halt reproduction. Hence, the oysters retain their weight, which is largely the gonad weight and record higher condition indices than the species in The Gambia. All the condition indices were greater than 1 (Pauly, 1984; Outa *et.al.*, 2014) indicating all the populations from both countries were in sound condition. The variations across the month give an indication of the best time to harvest the species for increased commercial values. However, seasonal variations in C. I. has been reported to be affected by factors such as hydrographic parameters, feeding intensity, sex and sexual maturity habitat, etc (Bagenal and Tesch, 1978; Oni *et.al.*, 1983; Anyanwu *et.al.*, 2007). A correlation was done to identify the relationship between the mean C. I. at all six sites and some hygrographic factors (Table 5).

Generally, there were positive and negative correlations between hydrographic factors and the C.I at each of the six sites. However, all the sites in The Gambia had a positive correlation with salinity and depth and some other variations, while the Ghanaian sites had very weak but positive correlations with turbidity, which were all statistically insignificant. A total weight-meat weight regression analysis was done to establish the relationship for the weights of meat that can be obtained from a known weight of whole oysters as was illustrated by Chuku *et al.* (2022). The relationships established showed they were all positive and significant correlations ($p<0.05$). This regression was useful in determining the amount of oyster meat that was obtained by harvesters from their daily catch per unit effort and estimating their daily earnings from the market value of the oyster meat.

Estimated growth parameters

The von Bertalanffy growth parameters estimated were derived from the ELEFAN_GA function in TropFishR. The estimated values have been summarised in Table 6. From the table, it can be seen that the estimated SH_∞ for all the sites ranged between 10.70 cm at Tanbi and 12.98 cm in Whin. The growth constants (K) was also recorded as a range between 0.52 in Narkwa and 0.90 in Tanbi. Bullock had the highest growth performance index at 2.05 and Narkwa recorded the lowest growth performance index, φ' of 1.80. These findings are at a slight variance with similar studies carried out on oyster species in Ghana and The Gambia. Osei *et al.* (2021) conducted a similar study on oysters at the Densu estuary and his findings showed that oysters in Densu had SH∞ of 16.86 cm, K= 0.44/yr . Akele *et al. (* 2015) whose study was situated in Benin also recorded SH∞ of 14.75 cm, K=0.38/yr and φ'= 1.92. Sparre and Venema (1992) and Yongo and Outa (2016) proposed that k = 1.0 $year^{-1}$ indicates fast growth, k = 0.5 $year^{-1}$ moderate growth and k = 0.2 $year^{-1}$ indicates slow growth.

From the above results, it can be inferred that, the oyster species from all six waterbodies studied approached their theoretical maximum length at a faster rate than what was reported by the authors whose findings indicated moderate growth rate. Different factors, such as changes in water quality, food availability, metabolic rate, fishing pressure and pollution, can be used to explain the variations in SH∞ and K. Hence, the growth performance index (φ') indicates estimation reliability since it has been suggested that φ' values are similar for the same species and genera (Santos *et al.*, 2022) or similar taxonomic family (Wehye *et al.*, 2017). Within related taxa, the growth performance index (φ') is typically determined to be generally dispersed around 3 and similar (Pauly & Munro, 1984). Additionally, extrinsic factors like temperature and food availability may stimulate or inhibit growth, influencing individual size, it is expected that the φ' will vary between species and within populations of the same species (Costa, 2020). Estimated growth performance index for all the populations for the six sites were within ranges of (1.8 – 2.1), which is significantly less than 3. The variations could be attributed to environmental factors within the habitats they grow in. These findings agree with studies by Amin *et al. (*2006) who estimated φ' as 2.07 for *C. virginica* in Bangladesh and Akele *et al.* (2015) estimated for *E. elliptica* in Benin as 1.92.

The length at which the oysters aged 1 with their monthly growth rate was estimated together with their longevity (tmax). All the oysters were confirmed to be fast growers, although their life span differed. Populations from Tanbi and Whin had shorter life spans 3.33 yrs and 3.66 yrs, respectively. This could be as a result of fishing pressure at these sites compared to the other locations.

A comparison of the growth and mortality paramters obtained in other studies to show differences and similarities in the oyster population dynamics in different parts of the world was made in Table 8.

Estimated mortality rates

Helm and Bourne (2004) postulate that the death of larval, juvenile, and adult bivalves can result from a variety of environmental or biological factors. Bivalves, as has been already established, serve as an important delicacy for humans just as they serve as food for larger organisms in higher hierarchy of the marine food chain, which includes; fish, birds, crustaceans and even other molluscs. As such, they are susceptible to deaths, which could be fishing mortality or natural mortality because of predation. Predation is said to have the ability to have an impact on population size structure, overall abundance, and regional distribution patterns. Predation is likely the most significant source of natural death in bivalve molluscs (Seed and Suchanek, 1992; Gosling, 2003). Common predators within the study sites are mostly other fish species, crabs and snails found in the waterbodies.

Estimated mortality parameters and exploitation rates of *Crassostrea tulipa* studied in Ghana and The Gambia were documented. A summary of the findings were presented in Table 7. All six sites studied had natural mortalities being higher than the fishing mortalities except Bullock and Narkwa whose fishing mortalities remained lower and were estimated at F=2.91 yr^{-1} and 1.70 yr^{-1} respectively. As a consequence, the estimated current exploitation, $E_{current}$ rate for these two sites reported overexploitation. According to Gulland (1969), the yield is optimized when F =M; therefore, when E is more than 0.5, the stock is overfished. The values recorded for $E_{current}$ at Bullock and Narkwa were 0.61 and 0.52, respectively.

Zhang and Megrey, (2006) proposed that there may be an empirically meaningful correlation between growth and mortality, with fast-growing fish generally having higher mortality rates due to the relationship between K and the species' longevity and mortality. Zhang and Megrey (2006) continued by asserting in general that, whereas short-lived species grow quickly, long-lived creatures reach their limiting size relatively slowly. Thus, species with high K values usually have high M values (Hordyk *et al.*, 2015). A slow-growing species can therefore not withstand a high natural mortality rate since, in such case, it would never fully mature and eventually go extinct.. The calculated individual Z/K ratio; prior total mortality relative to somatic growth ratio in Table 7 for *C. tulipa* at all six sites was greater than 1, suggesting that the stock is highly subjected to mortality. In general, if the Z/K ratio is less than 1, the population is dominated by growth; if it is more than 1, the population is dominated by mortality; and if it is equal to 1, the population is in an equilibrium condition where growth and mortality are balanced. (Barry and Tegner, 1989; Ahmed *et al.*, 2018). The table further highlights that the higher mortalities were because of natural causes in 4 of the sites (Allahein, Tanbi, Densu and Whin) than fishing. This observation is consistent with what was reported by Amin *et al.* (2006; 2008) in Bangladesh for *C. virginica* and *C. maderensis*, respectively.

However, the study by Akele *et al.* (2015) showed that although the population of oysters in Benin were mortality induced, they were more of fishing mortalities than natural mortalities (Table 8). The M and t_{max} values from this study indicate that population of oysters in Ghana and the Gambia are reasonably short-lived species. The estimate of t_{max} was below 5 years, suggesting that the species have a short life span. The estimated values for length at capture for the species (L_{c50}) showed that the populations enter exploitation phase after age 1, except for the population at Whin; where (SH_1 = 3.33cm, Lc_{50} = 4.34cm). As Table 8 illustrated, findings from this study is at a slight variance from what other authors have reported but what is very clear is that, all the locations confirmed that oyster populations are mortality induced which is mostly a natural mortality. Only a few locations reported have higher fishing mortality.

Sex ratio and maturity size

The male: female sex ratio summarised in Table 9 shows that *C. tulipa* at all six sites significantly deviated from the 1:1 ideal ratio, with the exceptions of the populations at Allahein and Narkwa, which did not significantly deviate. Studies have shown that oysters are oviparous. Findings from the study conducted by Yankson (1996) on *C. tulipa* suggested that most of the oysters sexually differentiated and spawned first as males and with increase in size, they re-differentiated into females in order to approach the 1:1 ratio. This form of development is referred to as protandry. However, the same study and others also suggest that there is a small number of hermaphroditism experienced among the population. Galtsoff (1964) 1% hermaphroditism in *C. virginica*, while Yankson (1996) also recorded 0.7% in the population from his study. The present study has revealed that *C. tulipa* has more females in the population.

When Figure 43 is closely examined, it can be noted that there was the presence of more males at some point in the population before the presence of females increased and took over. There was also a group of undifferentiated individuals that have been assumed to be spent or new members that have been recruited into the group throughout the year of data collection at all the sites. In the previous discussion, it was noted that smaller sized oysters have been recorded despite the fact that fishing pressure was low or even non-existent at some areas. The period/months where these observations were made coincided with the months in which a lot more undifferentiated individuals were encountered. Allahein (Mar- May/ Oct-Nov), Bullock (Jun-Sep), Tanbi (Jun-Jul), Densu (May and Sep), Narkwa (Aug-Sep) and Tanbi (Jul/Nov). Also, the Condition indices were found to be highest for all the systems especially in the period between Jun-Sep which infers that the species were spawning or preparing to spawn in subsequent months. The narrative could also be spun around the possibility that oysters reproduce more than once in a year. In Table 10, the smallest differentiated/ mature sizes of oysters were presented. Narkwa recorded the least sizes. The Gambian waterbodies had bigger sizes of oysters compared to the Ghanaian systems. This gives evidence to the success of the management measures put in place at each of the sites as well as better hydrographic conditions. In Ghana, only Densu employs some form of management regime and it clearly shows that the species in that waterbody are doing better than their counterparts in the other systems. The maturity size, Lm_{50} denotes the length at which 50% of the species have mature. Here, Densu recorded the highest Lm_{50} (5.6 cm), followed closely by Bullock (5.52 cm), then Allahein (5.2 cm), Tanbi (5.2 cm), Whin (5.1 cm) and Narkwa (3.6 mm). Narkwa recording the lowest Lm_{50} corroborates earlier findings in this study where the oysters at Narkwa reach sexual maturity the earliest.

Comparing Lc_{50} to the values recorded for Lm_{50} of these species, it is evident that, the species at all the sites enter the exploitation phase after they have attained sexual maturity; although it is a different narrative at Densu. They are able to spawn at least once in their life cycle before they become vulnerable to fishing impacts. To accurately analyse the population, the status of exploited stocks was evaluated using the estimated values of the asymptotic length ($L\infty$) and the length at first capture (Lc or L50). When the ratio ($Lc/L\infty$) values are less than 0.5, according to Pauly and Moreau (1997), the juveniles of the targeted species are more likely to be caught. This was illustrated in Table 8.

The Gambian oyster population are being exploited optimally as has been described in Table 11. Densu is doing well to reach optimum exploitation although Narkwa and Whin are having lower values. This could explain why locations such as Narkwa are recording smaller sized species and the $E_{current}$ estimated was above 0.5 pointing to growth overfishing. The situation of overexploited stocks at Bullock and underexploited stocks at Whin are rather unclear to explain, especially as the biggest oysters, biggest maturity size and biggest oysters at Lc/L50 were all recorded at Bullock while Whin oysters were mostly next smallest to Narkwa

Scale of shellfisheries in Ghana and The Gambia.

This study exposed the living condition and income made from oyster harvesting by the fishers who are mainly women. As explained in chapter 4, the very first difference between the oyster fishery in Ghana and The Gambia is the existence of good management regimes, which put restrictions of size limit, and fishing periods and ensure the welfare and wellbeing of the fishers in The Gambia. Densu estuary in Ghana has employed some management modalities and it is evidenced by how well their oyster fishery is doing compared to those of Whin and Narkwa. Delving further, a general trend of better living conditions/income and an empowered women community of oyster harvesters was found for the Tanbi among all the communities surveyed, further establishing the benefits of co-management of shellfisheries. When compared to the poverty index, wealth measured by household structure, and household income conducted as part of this study, Tanbi's female shellfish harvesters are comparably wealthier over their counterparts in both Ghana and The Gambia.

This can be said to be strongly anchored to their governance structures and management methodology where the women have been strongly involved in the decision-making process, while taking responsibility for the resource and its management. Compliance to these modalities is very high among the fishers as they are the same beneficiaries to the good arising from these interventions. Again, as most of the fishers are into the industry because it is the only source of livelihood available to them, they do well to comply in order to protect the resource and ensure its sustainability. This is very exemplary and worth replicating in other parts of West Africa as it would lead to an improved livelihood for the people plying the trade.

Chuku *et al.* (2022) estimated a yield of about 300,000 MT and over USD 300 million to be realised annually from the West African sub-region. Osei *et al.* (2021) also valued the gross annual income for oyster fishers in Densu at GHS 174,867 (USD 39,993) .The shellfish industry in itself has proven to be quite lucrative for the locals. In The Gambia, daily minimum wage for an income earning person is estimated to be around 50 Gambian Dalasi or $1.25 (https://www.minimum-wage.org/international/the-gambia-2022), while for Ghana it is estimated around 14.88 Ghana cedis or $1.03 (Minimum Wages in Ghana, 2022). From the estimations derived in Table 13, fishers at all the sites were making more than the estimated minimum wages for both countries daily per person. According to .Asare *et al.* (2019) study, the price of oysters in the Narkwa village was relatively cheaper, and individuals boost their income by harvesting more oysters. Narkwa had the lowest daily earning valued at $2.42, but this can be explained to be a result of lower sizes of whole oysters they harvest and lower catch per unit effort recorded among fishers in that community. Oyster meat is sold after it has been processed traditionally by sun-drying, salting, roasting, boiling and smoking as has been been reported by Crow and Carney (2012).

The other sites in The Gambia and in Ghana-Densu are doing better concerning pricing and income probably because they have management systems that ensure that the oysters thrive and grow well in their habitat so fishers can harvest them at the most appropriate sizes in order to fetch a welldeserved price for the meat. Currently, oyster harvesting in these communities look small-scale with very little income realised by some of the fishers. However, with the projections researchers (Chuku *et al*., 2022; Osei *et al.*, 2021) have made in current times, the industry looks promising.

CHAPTER SIX

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This chapter offers an overview of the study, its and objectives. Key findings made are outlined from which sound conclusions and recommendations are drawn.

Summary

This study sought to assess comparatively, the shellfish fishery in Ghana and The Gambia by investigating some ecological and biological characteristics of the West African mangrove oyster, *Crassostrea tulipa* populations in six water bodies from both countries. The research aimed at providing useful and crucial biological information on the species of concern, while describing the hydrographic factors of the waterbodies the populations of oysters inhabit for sustainable management interventions and successful culture methods. The waterbodies assessed for the study were Densu estuary, Narkwa lagoon and Whin estuary located in Ghana and Allahein estuary, Bullock mangrove area and Tanbi wetland area located in The Gambia.

By the end of the study, data garnered from the one-year period of data collection in both countries, described the physicochemical parameters of the water bodies and how each factor significantly affected the growth and survival of the species. Population parameters of the stock encountered at each location were also described. It described the monthly size variations, length frequency distributions, length-weight relationships and the co-efficient of growth for each population were described. These were done using Excel and Minitab data analysis software. For the VBGF growth parameters and mortality rates, the

TropFishR package in R-software was employed. The function used to describe the growth parameters was a bootstrapped approach and the genetic algorithm ELEFAN_GA_boot, while the length-converted catch curve function was used to estimate the mortality and exploitation rates of the populations.

The sexual capacities of the population were assessed by describing their sex ratios and maturity sizes. These gave an inference to their breeding patterns and how environmental factors influence their activities.

Lastly, daily catch per unit effort of the fishers was estimated and areas with higher CPUE were identified. The present study also sought to estimate the daily income of the fishers from their daily total catch and compare with each country's minimum wage to assess the scale of fishery. Management regimes at each location were investigated and compared to see which country has the better management practices evidenced by the state of the fishery in that location. At the end, this study unveiled the dynamism in the West African mangrove oyster fishery from both countries.

Conclusions

The following conclusions are made from the present study:

Hydrographic conditions.

- The hydrographic parameters of the waterbodies in The Gambia were all within range and suitable for growth and reproduction except pH which recorded higher concentrations in some months. Concentrations of nitrates and phosphates also exceeded the recommended threshold for the organisms.

- The hydrographic conditions in Ghana were not so stable. Parameters such as temperature, dissolved oxygen and water depth were withn range. However, pH readings were exceedingly high in some months and salinity concentrations were very low in other months. The water bodies in Ghana recorded very high turbidity readings up to 150 NTU.

Size and growth

- In general, the water bodies in The Gambia recorded individuals with bigger sizes and modal distributions around bigger sized frequencies (>60mm). The correlation between the shell height and total weights of the oysters were also significantly strong. However, all the organisms significantly deviated from isometry and displayed negative allometry at all the stations. The estimated condition indices showed that the organisms are in good physiological wellbeing.
- Water bodies in Ghana recorded big sizes of oysters but not as big, as was recorded in The Gambia. Oysters in Narkwa recorded the smallest sizes among all six sites studied. Correlation between the shell height and total weights of the oysters were also significantly strong ($p < 0.05$), although they all significantly deviated from isometry to negative allometry at all the stations. The estimated condition indices showed that the organisms are in good physiological wellbeing.

Growth parameters and mortality rates

- Estimated growth performance index, φ’, suggested that the oyster populations in Gambia are doing well. The species were found to be short-lived as they recorded higher K values (> 0.5); indicating fast growth with higher M values (Natural mortality). The ratio of Lc_{50} to $L\infty$ revealed that the harvested or targeted individuals were not juveniles. The Z/K ratio also re-affirmed that the population were mortality induced and natural mortality was prevalent. The exploitation status further indicated that the populations were under-fished except at Bullock, which showed more of a fishing induced mortality and an over-fished stock.

– In Ghana, the growth performance index φ', also showed the populations were doing well. They were also found to be short-lived as they had higher K values (> 0.5) and higher M values. However, the Lc_{50}/ $L\infty$ ratio revealed that harvested/targeted individuals were juveniles confirming the incidence of growth overfishing. As the Z/K and exploitation ratios confirmed that the populations in Ghana were natural mortality induced and under-fished, respectively, Narkwa differed by having a fishing induced mortality and an overfished population.

Sex ratio and maturity size

– In The Gambia, all the populations significantly deviated from the 1:1 sex ratio with more females in the population, except Allahein whose population did not significantly deviate. The maturity sizes estimated revealed that all the species attained maturity before they were captured. The occurrence of undifferentiated individuals suggested spent or immature/young recruits, which gives an indication of yearlong spawning activities.

- In Ghana, Narkwa and Whin populations showed a significant deviation from a 1:1 sex ratio with the exception of Densu. At Densu, it was noted that the species there were harvested before they reached their maturity sizes but that was not the case at the other locations. There was an indication of yearlong spawning activities just as in The Gambia.

Scale of shellfish fisheries and management structures

- It was established that in The Gambia, fishers are doing better in the business as a result of the co-management approach they adopted to protect the fisheries and in decision-making. As a result, the oysters from The Gambia fetched better prices than what was reported for Ghana. It was also found that the Tanbi shellfishers made higher income overall.
- In Ghana, only Densu has employed some form of co-management approach with support from The Development Action Association NGO and this was evidenced by the income level of the fishers as compared to those in Narkwa and Whin where all decision-making concerning the fisheries was done by the traditional council. This has resulted in the poor state of the resources itself and the users who utilized them.

Recommendation

The subsequent recommendations are offered in light of this study's findings:

1. As was enumerated in most of the waterbodies in both Ghana and The Gambia, the natural mortality, M was higher than the fishing mortality, F, and so, any additional level of pollution could distort the population.

Hence assessment of the water quality should be conducted periodically and sources of pollution be curtailed.

2. The Ghanaian government should include bivalve fishing in its fishery policies and facilitate more co-management policies as is being done in The Gambia. This would make it easier to manage and exploit this fishery in a sustainable manner and increase income for the fishers.
3. The Gambian and Ghanaian oyster fisheries should implement a quota system. By doing this, the overexploitation of the oyster species may be reduced.

Suggestions for Further Studies

1. To better understand the growth variations seen in the various water bodies, there should be an evaluation of the genetic diversity of oyster populations in Ghana and The Gambia’s coastal water bodies.
2. The promising potential of the fishery in terms of revenue and income establishes the need to investigate the value chain of the industry and maximizing benefits obtained from oysters to the industrial level aside its artisanal uses.
3. To provide data to validate the need for implementing quota systems, studies should be done to estimate the Total Allowable Catch (TAC) by collecting catch-effort data and frame surveys.

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APPENDICES

APPENDIX A: Analysis of Variance test conducted for all parameters between stations.

Source	DF	Adj SS	Adj MS	F-Value	P-Value (95%)
Date	12	1471.07	122.590	29.63	0.000
station	4	5.17	1.292	0.14	0.965*
water_body(station)	25	237.37	9.495	2.30	0.000
Error	958	3963.21	4.137		
Total	1047	6000.49			

*= Not significant (α=0.05).

APPENDIX B: Analysis of Variance and Tukey tests conducted for each parameter for all waterbodies.

B.1 Analysis of Variance for Dissolved Oxygen

Source	DF	Adj SS	Adj MS	F-Value	P-Value
water_body	5	255.8	51.161	9.28	0.000
Error	1042	5744.7	5.513		
Total	1047	6000.5			

Grouping Information Using the Tukey Method and 95% Confidence

Water_body	N	Mean	Grouping	
Narkwa	193	6.443	A	
Whin	180	6.335	A	
Densu	195	6.117	A	
Allahein	165	5.751	A	B
Tanbi	165	5.2493		B
Bullock	150	5.159		B

Means that do not share a letter are significantly different.

B.2 Analysis of Variance for Temperature

Source	DF	Adj SS	Adj MS	F-Value	P-Value
water_body	5	389.3	77.863	14.85	0.000
Error	1147	6014.9	5.244		
Total	1152	6404.2			

Grouping Information Using the Tukey Method and 95% Confidence

Water_body	N	Mean	Grouping		
Whin	195	29.515	A		
Densu	195	29.090	A	B	
Narkwa	193	28.813		B	
Bullock	180	28.799		B	
Tanbi	195	28.106			C
Allahein	195	27.801			C

Means that do not share a letter are significantly different.

B.3 Analysis of Variance for Salinity

Source	DF	Adj SS	Adj MS	F-Value	P-Value
water_body	5	57431	11486.2	100.01	0.000
Error	1141	131039	114.8		
Total	1146	188470			

Grouping Information Using the Tukey Method and 95% Confidence

Water_body	N	Mean	Grouping		
Allahein	195	34.827	A		
Tanbi	195	34.205	A		
Bullock	180	30.316		B	
Whin	189	19.861			C
Narkwa	193	19.597			C
Densu	195	18.57			C

Means that do not share a letter are significantly different.

B.4 Analysis of Variance for pH

Source	DF	Adj SS	Adj MS	F-Value	P-Value
water_body	5	229.4	45.8801	63.50	0.000
Error	1133	818.6	0.7225		
Total	1138	1048.0			

Grouping Information Using the Tukey Method and 95% Confidence

Water_body	N	Mean	Grouping		
Whin	195	8.5602	A		
Narkwa	193	8.5248	A		
Densu	195	8.3968	A		
Allahein	181	7.7918		B	
Bullock	180	7.5576		B	C
Tanbi	195	7.5127			C

Means that do not share a letter are significantly different.

B.5 Analysis of Variance for Depth

Source	DF	Adj SS	Adj MS	F-Value	P-Value
water_body	5	1211	242.269	192.71	0.000
Error	1147	1442	1.257		
Total	1152	2653			

Grouping Information Using the Tukey Method and 95% Confidence

Water_body	N	Mean	Grouping		
Tanbi	195	2.972	A		
Bullock	180	2.928	A		
Allahein	195	2.2705		B	
Narkwa	193	0.8348			C
Densu	195	0.7035			C
Whin	195	0.6301			C

Means that do not share a letter are significantly different.

B.6 Analysis of Variance for turbidity

Source	DF	Adj SS	Adj MS	F-Value	P-Value
water_body	5	149949	29989.9	61.00	0.000
Error	998	490688	491.7		
Total	1003	640638			

Grouping Information Using the Tukey Method and 95% Confidence

Water_body	N	Mean	Grouping			
Whin	165	38.63	A			
Narkwa	180	27.41		B		
Densu	180	19.461			C	
Allahein	165	7.673				D
Bullock	150	5.927				D
Tanbi	164	5.915				D

Means that do not share a letter are significantly different.

APPENDIX C: Principal Component Analysis tests conducted for waterbodies in Ghana and The Gambia

C. 1: Eigenvectors for the variables in Ghanaian waterbodies

Variable	PC1	PC2	PC3
Temperature (°C)	0.309	0.529	0.317
DO (mg/L)	0.011	0.717	0.086
Salinity	0.570	-0.311	-0.229
pH	0.416	-0.135	0.327
Depth (m)	-0.019	0.283	-0.835
Turbidity (NTU)	-0.637	-0.106	0.188

C. 2: Eigenvectors for the variables in The Gambian waterbodies

Variable	PC1	PC2	PC3
Temperature (°C)	-0.597	0.260	-0.061
DO (mg/L)	0.362	0.231	0.057
Salinity	0.633	0.039	0.185
pH	0.096	0.627	0.488
Depth (m)	-0.300	-0.193	0.818
Turbidity (NTU)	-0.108	0.669	-0.227

APPENDIX D: Summary of the number of differentiated individuals, males and females of *C. tulipa* sampled

D.1: Summary of the number of differentiated individuals, males and females of *C. tulipa* sampled from Allahein, with their monthly sex ratio.

Month	No. of Males	No. of Females	M:F	X^2	P
Mar-21	26	16	1.63:1	2.38	0.12*
Apr-21	33	22	1.5:1	2.2	0.14*
May-21	26	33	1:1.27	0.84	0.36*
Jun-21	15	40	1:2.67	11.36	0.0007
Jul-21	16	10	1.6:1	1.38	0.24*
Aug-21	15	12	1.25:1	0.33	0.56*
Sep-21	0	0	-	0	0
Oct-21	21	21	1:1	0	1*
Nov-21	27	24	1.13:1	0.18	0.67*
Dec-21	19	30	1:1.58	2.47	0.12*
Jan-22	18	25	1:1.39	1.14	0.29*
Feb-22	24	29	1:1.21	0.47	0.49*
Total	**240**	**262**	**1:1.09**	**0.96**	**0.33***

*= Not significant (α=0.05).

D.2: Summary of the number of differentiated individuals, males and females of *C. tulipa* sampled from Bullock, with their monthly sex ratio.

Month	No. of Males	No. of Females	M:F	X^2	P
Mar-21	10	20	1:2	3.33	0.07*
Apr-21	17	36	1:2.18	6.81	0.009
May-21	14	45	1:3.21	16.29	0.00005
Jun-21	7	45	1:6.43	27.77	0.00000014
Jul-21	0	0	-	0	0
Aug-21	10	14	1:1.4	0.67	0.41*
Sep-21	0	0	-	0	0
Oct-21	20	30	1:1.5	2	0.16*
Nov-21	25	30	1:1.2	0.45	0.5*
Dec-21	19	28	1:1.47	1.72	0.19*
Jan-22	21	36	1:1.71	3.95	0.05
Feb-22	20	38	1:1.9	5.59	0.02
Total	**163**	**322**	**1:1.98**	**52.13**	**0**

*= Not significant (α=0.05).

D.3: Summary of number of differentiated individuals, males and females of *C. tulipa* sampled from Tanbi, with their monthly sex ratio.

Month	No. of Males	No. of Females	M:F	X^2	P
Mar-21	13	22	1:1.69	2.31	0.13*
Apr-21	30	27	1.11:1	0.16	0.69*
May-21	23	37	1:1.61	3.27	0.07*
Jun-21	14	38	1:2.71	11.08	0.0009
Jul-21	9	17	1:1.89	2.46	0.12*
Aug-21	10	18	1:1.8	2.26	0.13*
Sep-21	0	0	-	0	0
Oct-21	17	41	1:2.41	9.93	0.002
Nov-21	12	30	1:2.5	7.71	0.005
Dec-21	23	26	1:1.13	0.18	0.67*
Jan-22	22	36	1:1.64	3.38	0.07*
Feb-22	22	32	1:1.45	1.85	0.17*
Total	**195**	**324**	**1:1.66**	**32.06**	**0**

*= Not significant (α=0.05).

D.4: Summary of number of differentiated individuals, males and females of *C. tulipa* sampled from Densu, with their monthly sex ratio.

Month	No. of Males	No. of Females	M:F	X^2	P
Mar-21	30	10	3:1	10	0.002
Apr-21	38	15	2.5:1	9.98	0.002
May-21	37	20	1.85:1	5.07	0.02
Jun-21	35	8	4.38:1	19.95	0.00004
Jul-21	27	23	1.17:1	0.32	0.57*
Aug-21	15	10	1.5:1	1	0.32*
Sep-21	20	9	2.22:1	4.17	0.04
Oct-21	14	14	1:1	0	1*
Nov-21	14	14	1:1	0	1*
Dec-21	18	38	1:2.11	7.14	0.008
Jan-22	31	27	1.15:1	0.28	0.6*
Feb-22	21	35	1:1.67	3.5	0.06*
Total	**300**	**223**	**1.35:1**	**11.34**	**0.001**

*= Not significant (α=0.05).

D.5: Summary of number of differentiated individuals, males and females of *C. tulipa* sampled from Narkwa, with their monthly sex ratio.

Month	No. of Males	No. of Females	M:F	X^2	P
Mar-21	27	21	1.3:1	0.75	0.39*
Apr-21	34	23	1.5:1	2.12	0.15*
May-21	28	32	1:1.1	0.27	0.61*
Jun-21	31	15	2.1:1	5.57	0.18*
Jul-21	10	30	1:3	10	0.002
Aug-21	22	4	5.5:1	12.46	0
Sep-21	3	24	1:8	16.33	0
Oct-21	14	16	1:1.1	0.13	0.72*
Nov-21	7	22	1:3.1	7.76	0.01
Dec-21	12	44	1:3.6	18.29	0
Jan-22	23	29	1:1.3	0.69	0.41*
Feb-22	36	19	1.9:1	5.25	0.02
Total	**247**	**279**	**1:1.1**	**1.95**	**0.16***

*= Not significant (α=0.05).

D.6: Summary of number of differentiated individuals, males and females of *C. tulipa* sampled from Whin with their monthly sex ratio

Month	No. of Males	No. of Females	M:F	X^2	P
Mar-21	13	25	1:1.9	3.79	0.05
Apr-21	24	25	1:1.04	0.02	0.89*
May-21	34	19	1.8:1	4.25	0.03
Jun-21	0	0	0	0	0
Jul-21	20	16	1.3:1	0.44	0.5*
Aug-21	12	13	1:1.1	0.04	0.84*
Sep-21	15	12	1.3:1	0.33	0.56*
Oct-21	18	9	2:1	3	0.08*
Nov-21	10	10	1:1	0	1*
Dec-21	18	41	1:2.3	8.97	0.003
Jan-22	15	45	1:3	15	0.0001
Feb-22	13	43	1:3.3	16	0.00006
Total	**192**	**258**	**1:1.34**	**9.68**	**0.002**

*= Not significant (α=0.05).