"The sea, once it casts its spell, holds one in its net of wonder forever." - Jacques Yves Cousteau

## *Historical Background of Marine Biology*

"The inception of marine biology involved basic observations focused on the distribution and diversity of marine life."

For thousands of years, individuals living near the coast and fishing villages have developed a deep knowledge of the ocean's biology. Formal marine biology research dates back to an era in which there were few boundaries between scientific fields. The "natural philosophers," who before modern biologists, made extensive observations about anatomy and behaviour. Aristotle, along with his Greek peers, played a crucial part in creating the tradition of natural philosophy. They meticulously recorded their findings on the distribution and habits of shore life. Aristotle extensively studied the anatomy of marine animals, observing distinctive characteristics such as viviparity in certain sharks and the presence of bristle-like structures instead of teeth in certain whales (Levinton 2017).

During the 18th century, tremendous advancements took place as numerous Europeans actively observed and categorised live animals. One of the most prominent researchers in this field was Linnaeus (1707–1778), who was a pioneer in developing the contemporary method for classifying and identifying species. Linnaeus diligently documented numerous marine creatures and plant species, as well as establishing more comprehensive classifications. Georges Cuvier (1769–1832), a prominent French scientist, was an important researcher of that time. He classified all animals into four primary categories, namely Articulata, Radiata, Vertebrata, and Mollusca, based on their body structures. The classifications made a significant advancement in the systematic comprehension of marine life (Levinton 2017).

The eighteenth century marked a crucial period of oceanic exploration, with several expeditions undertaking global circumnavigation. Numerous of these excursions had a scientific purpose, and the mission of gathering both terrestrial and marine flora and animals assigned to specially trained scientific experts. Nicolas Thomas Baudin, a French captain, led a famous expedition that toured the tropical Pacific and brought back a large number of marine molluscs to France. Captain James Cook supervised the cartography of eastern Australia in 1770, and his scientific team gathered biological specimens across the Pacific Ocean, establishing the groundwork of enormous collections in Great Britain (Levinton 2017).

The field of marine biology changed during the nineteenth century, becoming a scientific field that included species descriptions, ecological principle research, hypothesis testing, and more. Edward Forbes, a marine scientist from the Isle of Man, gained recognition as a leading figure in the field of marine biology during the mid-19th century. As the naturalist on board the Mediterranean ship Beacon, Forbes saw a decrease in the variety of species at deeper depths. This led him to develop the azoic theory, which states that there is no life beyond 300 fathoms (1,800 feet) below the surface of the sea. Forbes made significant contributions to the field by identifying species that live at different depths. His findings show that species with a wider variety of depths also tend to have a bigger geographic distribution. Forbes developed maps that illustrate the regional distributions of organisms and a thorough natural history of European waters, which served as a source of inspiration for many other researchers in the field of biological research (Levinton 2017).

In this era, Forbes was joined by other notable marine biologists from other European countries. In 1850, Norwegian marine researcher Michael Sars challenged the azoic theory by meticulously documenting and identifying 19 species that were flourishing at depths exceeding 300 fathoms in Norwegian bays. Marine biology became a separate scientific field as a result of this discovery, which also happened to coincide with the first use of a plankton net and the creation of crude submersibles (Levinton 2017).

Charles Darwin (1809–1881) is widely recognised for his theory of evolution through natural selection, but he also made substantial contributions to the field of marine biology. In his early years, he worked as a naturalist on board the H.M.S. Beagle, which undertook a worldwide trip from 1831 to 1836. The author's experiences were subsequently recorded in "The Voyage of the Beagle," a widely acclaimed travel literature piece from the 19th century.

Darwin, as a naturalist, collected a large number of marine species and then focused his efforts on the organised categorization of barnacles (Levinton 2017).

### *The Vast Realms of Our Oceans and Seas*

The Earth's oceans can be classified into two main categories: open oceans and marginal seas. The Earth's surface is around 71% occupied by the water, and it has a coastline that spans about 1.6 million kilometres. The Southern Hemisphere displays a higher prevalence of oceanic areas in comparison to the Northern Hemisphere. Coastal and marine habitats are present in 123 nations, encompassing estuaries, lagoons, sand dunes, near shore coastal areas, and open marine areas (Venkatraman & Raghunathan 2015). The Pacific Ocean is the largest of all the oceans and is less affected by regional climate fluctuations or river inputs compared to the Atlantic Ocean. Known as the "Ring of Fire," the Pacific is known for its many island chains and intense volcanic activity around its edges. Examples of this activity include Mount St. Helens in Washington, Mount Fuji in Japan, and Krakatoa in the southwest Pacific (Levinton 2017).

In contrast, the Atlantic Ocean is comparatively narrower and is encompassed by vast peripheral seas, such as the Gulf of Mexico, Mediterranean Sea, Baltic Sea, and North Sea. The Atlantic Ocean is significantly impacted by the drainage of major rivers such as the Mississippi, Amazon, Nile, and Congo. This influence is due to the terrestrial climate and the introduction of dissolved and particulate compounds from these rivers (Levinton 2017). The Antarctic Ocean, sometimes referred to as the Southern Ocean, is distinct from other oceans in that it shares a border that is entirely aquatic. The northern boundary of this area is marked by the Subtropical Convergence, where colder and saltier water moves southward. A surface circulation circles eastward across Antarctica and is typified by a predominant west wind pattern between 40° and 60° S (Levinton 2017).

The oceanographic features of marginal seas are influenced by local climates and are characterised by insignificant depths and limited connections with the open ocean. In the Mediterranean Sea, for example, limited exchange occurs because of a local excess evaporation relative to precipitation, and the sea is isolated from the Atlantic by a shallow-water barrier or sill. Around five to six million years ago, a significant decrease in global sea level caused the separation from the Atlantic, resulting in widespread evaporation and the creation of huge salt deposits. According to Levinton (2017), the history of the majority of other marginal seas have been characterised by notable variations in their environment.

The Indian Ocean encompasses around 29% of the total area of the world's oceans, making it the third biggest ocean (Venkatraman & Raghunathan 2015). India is a country with a rich and diverse range of plant and animal species. It is a significant and prominent member of the central Indian ocean region, which also includes Bangladesh, Indonesia, Maldives, Malaysia, Myanmar, Thailand, and Sri Lanka (Gopi & Mishra 2015). India is surrounded by three discrete marine ecosystem zones in the central Indian Ocean marine region: the Arabian Sea to the west, the Bay of Bengal to the east, and the Indian Ocean to the south of India (Gopi & Mishra 2015). India possesses a coastal habitat of around 8000 km, which includes the Andaman-Nicobar and Lakshadweep Islands (Venkatraman & Raghunathan 2015).

### *Ecological Realms Unveiled: Defining Habitats and Life Habits*

The intertidal zone encompasses the entire extent between the maximum and minimum levels of the tides. A detailed classification of marine environments organised according to water depth is presented in Fig. 1. In areas with limited or absent tide movements, the vertical range of this coastal ecosystem is predominantly determined by wind. The subtidal zone includes the entire ocean floor, ranging from the point where the water level is at its lowest to the deepest part of the ocean. Continental shelf habitats, also known as neritic habitats, encompass the seafloor and open-water regions that lie between the high-water mark and the edge of the continental shelf. Adjacent to the shelf are oceanic or pelagic environments, which include the epipelagic zone (upper 200 m), mesopelagic zone (200 to 1,000 m), bathypelagic zone (1,000 to 4,000 m), and abyssopelagic zone (4,000 to 6,000 m). Bathyal benthic bottoms extend from a depth of 1,000 to 4,000 metres, while abyssobenthic bottoms cover a range of

4,000 to 6,000 metres. Hadal habitats include trench and seabed levels that are frequently greater than 6,000 metres; the Marianas Trench, for example, is approximately 11,000 metres deep (Levinton 2017).

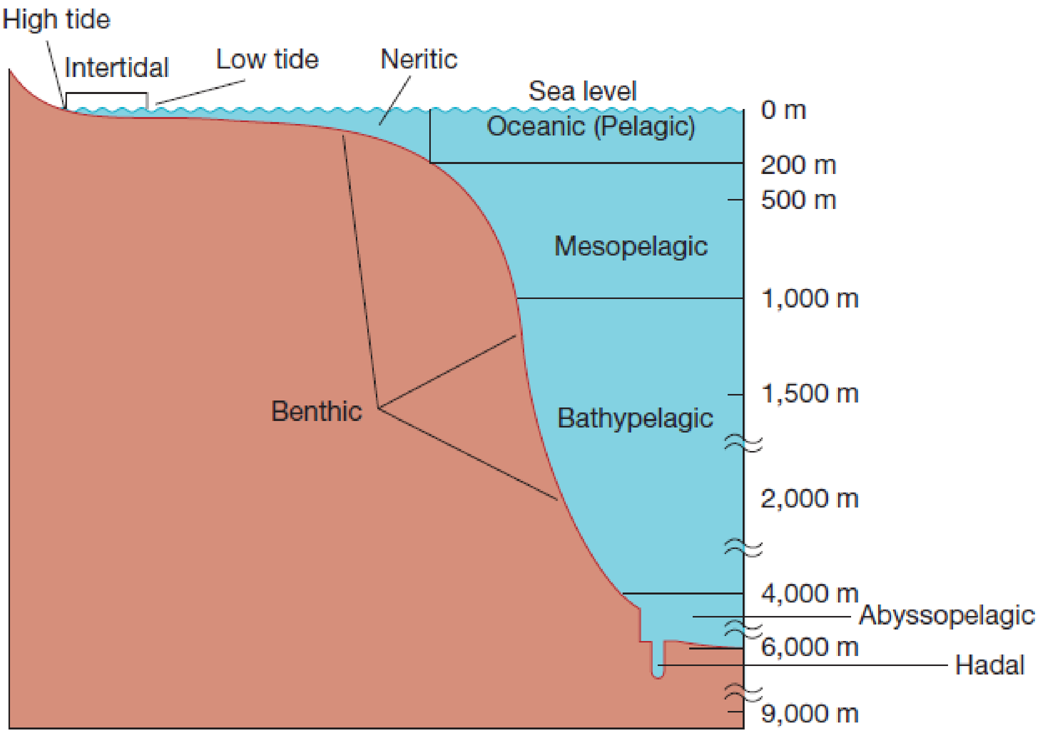


Figure 1: A cross section of the ocean from the shoreline to the deep sea, showing the location of major marine habitats. (Source: Levinton 2017)

"The richness of marine biodiversity is a testament to the intricate beauty of life beneath the waves." - Sylvia Earle

### *Decoding Marine Life: Neuston, Plankton, Nekton, Benthos*

An effective method is to categorise marine species according to their general environment. Plankton is made up of protists, animals, plants, and bacteria. It lives in the water column and is not sufficiently adaptable to oppose strong currents. Neuston refers to creatures that are associated with the surface of the sea, particularly bacteria that are attached to the surface slick. Nekton refers to the larger aquatic organisms that are capable of swimming in the water column and have the ability to move against the direction of currents. This category encompasses a wide range of marine creatures, including tiny prawns, crabs, and fish, as well as massive whales. Benthos refers to the organisms that are found in association with the seafloor. This includes infaunal species that burrow into the seabed and epifaunal species that reside on the surface of the seabed. Demersal is a term used to describe certain mobile species that live on or near the seafloor, such as bottom fish.

> "Fisheries research is the compass guiding us toward sustainable oceans, ensuring a legacy of abundance for generations to come." - Daniel Pauly

### *Historical Background of Fisheries Research*

During the 19th century, fisheries research became a significant and key area of attention in the field of marine biology. This event marks the beginning of applied marine biology, motivated by the necessity to understand and efficiently control fish populations. This research was inspired by the need to acquire knowledge on the identification and maintenance of fish populations. England took the lead in this undertaking, initiating these studies in 1863. Afterwards, many countries began comparable research initiatives in the latter part of the century. The Fish Commission in the United States performed a crucial role in establishing the relationship between the maritime environment and the life cycle of fishes. This comprehensive method attempted to understand the complex ecological factors that affect fish populations. Marine ecology and fisheries studies become closely associated, as they both include studying the relationship between marine ecosystems and the resources they provide for fishing. Canada established renowned laboratories on both the Atlantic and Pacific coasts, with a strong concentration on fisheries. These laboratories have made major contributions to the field of marine biology, particularly in relation to fisheries (Levinton 2017).

The H.M.S. Challenger's mission from 1872 to 1876 provided the first comprehensive understanding of marine biology and the diverse range of living organisms in the ocean from a global standpoint. Under the leadership of C. Wyville Thomson and the renowned naturalist John Murray, the Challenger conducted a thorough and precise examination of the waters and bottom in all seas, with the exception of the Arctic region. The enormous quantity of information required 50 volumes to record the variety of creatures that were collected (Levinton 2017).

In the latter part of the nineteenth century, marine stations started to spread worldwide, starting with the creation of the "Stazione Zoologica" in Naples, Italy, in 1875. This station established a standard for worldwide collaboration among scientists. During the year 1880, marine stations were established in England and Scotland. Prince Albert I of Monaco equipped boats and larger vessels for the purpose of collecting samples from the ocean. This endeavour led to the creation of an oceanography institute and museum in Monaco in 1906. The institute was later managed by the distinguished inventor-oceanographer Jacques-Yves Cousteau, who died in 1998. Zoologist Alexander Agassiz undertook oceanographic expeditions in the United States, bringing forth improvements like lowering samplers with piano wire rather than rope and studying the embryology of starfish and similar species. The renowned Marine Biological Laboratory was established in Cape Cod in 1886, alongside the establishment of numerous European marine stations towards the end of the century. By the beginning of the 20th century, several European countries had established marine stations, and the United States also saw the emergence of such facilities, such as the Friday Harbour Laboratories in Washington State. Marine biology has undergone significant development as a scientific discipline, characterised by extensive investigation and valuable theoretical contributions throughout its history (Levinton 2017).

"Estuaries: Nature's poetry, written in the fluid script of mingling waters, where the dance of tides whispers tales of resilience and beauty."

### ***Exploring Nature's Nexus: Unveiling the Beauty and Vitality of Estuaries***

Estuaries have been periodically defined by different experts in the fields of geology, geography, hydrology, and biology. Unfortunately, there is still a lack of agreement throughout fields on a common set of terminology. Most often, a practical strategy is used, adapted to the needs of research studies or shown to be most advantageous in a particular nation. Digby *et al.* (1998) conducted a comprehensive categorization of 780 Australian estuaries by employing geographical, topographical, morphological, and climatic data. The ultimate categorization incorporated an actual model that explained a substantial amount of the variation in the ratio of salt marshes and mangroves in Australian estuaries. This model classified the climate into five distinct groups: tropical, tropical savannah, hot dry, subtropical, and temperate. Additionally, these areas were further separated into 15 subgroups depending on tidal ranges. According to scientists, Pritchard (1967), Dyer (1973), and Day (1981) are the definitions of an estuary that are most often accepted. These descriptions include comprehensive collections of features that help determine whether a particular body of water meets the criteria to be classified as an estuary. Pritchard (1967) provided the following definition for an estuary:

*'An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with freshwater derived from land drainage.'*

However, this definition excluded blind estuaries and those with hypersaline conditions. Day (1981) subsequently modified it as follows:

*'An estuary is a partially enclosed coastal body of water which is either permanently or periodically open to the sea and within which there is a measurable variation of salinity due to the mixture of sea water with freshwater derived from land drainage.'*

Blaber (2000) revised the term to include shallow coastal waters that are adjacent to estuaries and have lower salinities. In addition, he categorised estuaries into four main groups: open estuary, estuarine coastal waters, blind estuary, and coastal lake. The fact that the fish faunas in many tropical estuary locations extend onto the shallow shelf, where the transition to marine conditions is gradual, is reflected in this adaption. As a result, it is possible that there is no distinct demarcation between the estuary and the sea. Estuarine conditions, together with their associated fish species, can stretch several kilometres offshore, encompassing vast expanses in regions like Southeast Asia, South America, and West Africa. Therefore, when it comes to fish populations, there is really a greater expanse of estuary habitat outside of the conventional boundaries of recognised estuaries than within them.

According to Sarkar *et al*. (2012), India's hinterland spans over 20,000 $km^2$, with 228 minor and 14 large estuaries, as well as backwaters and coastal lagoons. The estuarine ecosystem in this region is highly productive on a global scale. It is characterised by a large number of autotrophs, high levels of oxygen due to tidal currents, the input of inorganic and organic detritus from rivers and coastal wetlands, and a complex food chain that allows for quick conversion and replenishment of nutrients (Acharya *et al.* 2019).

Estuaries, despite their geological transience caused by sea level fluctuations, are exceptionally abundant in nutrient availability and biological productivity. Estuaries are temporary because even little variations in sea level have the ability to fill or empty basins. Variations in sea level caused by things like glacial activity can cause these basins to flood or drain. The particular arrangement of an estuary is projected to last for approximately 10,000 years. However, rivers, which form the foundation of estuaries show very high antiquity and have the potential to endure for much longer. Estuaries, despite being temporary in nature, are notable for their high biological diversity. The introduction of nutrients from freshwater sources, together with nutrient recycling processes such as denitrification, promotes increased levels of primary production. As a result, this supports thriving communities of bottom-dwelling invertebrates, fish, vegetation, and avian species in the estuary.

### ***Unveiling the Rich Diversity of Tropical Estuaries***

Tropical estuary habitats vary in size, ranging from small, seasonally flowing systems that are one to two kilometres in length, to the vast estuaries of major rivers such as the Amazon and the Zaire. Furthermore, these habitats encompass vast coastal lakes in Africa and Asia, along with the brackish estuarine waters that have lower salt concentration found along the shores of certain regions in Southeast Asia, South America, and Africa. Tropical estuaries have a lack of homogeneity due to variances in size, depth, ecosystems, and physical regimes. The fish populations and fishing industry in tropical estuaries are greatly influenced by several factors, such as the specific traits of nearby marine and freshwater environments. In order to enhance comprehension, the tropical estuarine environment has been classified into four main types: open estuary, estuarine coastal waters, blind estuary, and coastal lake (Blaber 2000).

### *Ecology of Tropical Estuaries*

Tropical estuaries support a wide range of species, such as annelid worms, prawns, crocodiles, birds, hippos, and particularly fishes, which are closely interconnected and play important roles in the overall biological dynamics of the estuary community. Biologists tend to prefer projects in more appealing regions such as coral reefs due to the difficult and unpleasant conditions found in these settings, which are characterised by hostile muddy, and scorching weather, as well as the presence of many biting insects. Nevertheless, whereas estuarine research has traditionally focused on cold or temperate settings in developed countries, there has been a notable surge in research on tropical estuarine species in the past five years.

Two major imperatives are driving this surge: first, the difficulties inshore fisheries face in developing nations, where food security is threatened by shrinking catches, environmental degradation, and growing human populations; and second, international pressure, primarily from the developed world, to conserve and maintain biodiversity. Both matters require a thorough understanding of the ecology of tropical estuarine fishes, specifically their interactions with the environment and the degree to which they rely on estuaries or nearby environments for their survival.

### *Ecological Interactions: Exploring Nature's Interconnected Web*

Ecology investigates how organisms interact with their surroundings and how this affects their abundance and distribution. These interactions take the form of biological interactions between organisms and abiotic interactions, in which the functioning of the organism is impacted by nonbiological elements such as the chemistry of the saltwater. Indeed, the demarcation between these interactions is sometimes ambiguous. For example, a cold-blooded organism may be restricted in its movement due to low temperature, which in turn can impact its capacity to avoid predators, which is a biotic interaction.

### ***Estuarine Dynamics: Balancing Seaward Freshwater Flow and Tidal Mixing***

The arrival of freshwater from rivers triggers an estuary current, guiding the less dense surface water towards the sea. At the same time, a compensatory subterranean movement of marine water with higher salt content goes upstream beneath the less dense surface flow. Estuaries have strong stratification when there is a strong flow and minimal mixing with tides. This results in a clear separation of a layer with low salt that moves towards the sea, and a subsurface movement of higher salinity towards the river. Estuaries commonly undergo partial mixing as a result of tidal forces and wind. Although there is a specific area close to the mouth of the estuary where the process of mixing takes place, the salinity at the surface in this zone continuously remains lower than at deeper levels. In smaller and shallower estuaries, the wind tends to completely mix the water along the entire column, creating a homogenous environment in terms of water properties and characteristics (Levinton 2017).

"In the kaleidoscope of underwater wonders, fish diversity is nature's poetry, written by the currents, sung by the waves, and choreographed by the dance of fins."

### ***Dive into the Depths of Ichthyofauna Diversity***

With 36,718 confirmed fish species as of 2023, ichthyofaunal diversity accounts for over half of all known species within Vertebrata, making up a significant percentage of the vertebrate subphylum globally (Fricke *et al.* 2023). Among them, teleost fishes are an important group that show a variety of ecological preferences. Many species are found only in freshwater habitats, while the bulk of them live in marine areas. These specific ecological preferences classify them into stenohaline freshwater and stenohaline marine water groups, which include a substantial number of teleost fishes (Schultz & McCormick 2013). Less than 10% of teleost fishes exhibit exceptional adaptability, allowing them to travel between freshwater and marine settings. These fishes are classed as euryhaline fishes (Nordlie 2015). In India, the combined population of fish in both fresh and marine waters accounts for 9.7 percent of the global population. Specifically, marine fishes make up 7.4 percent of this total (Eschmeyer & Fong

2014). Day (1899 a, b) recorded a total of 1418 fish species belonging to 342 genera in British India. Talwar & Jhingran (1991) provided more information by documenting a total of 2546 species belonging to 969 genera, 254 families, and 40 orders. The number of legitimate fish species in India has increased to an estimated 3231 due to recent advances in ichthyological study. This number includes freshwater, brackish water, and marine species (Gopi & Mishra 2015). India's ichthyofaunal richness is characterised by a varied spectrum of species found in different types of water. Marine water alone supports 2443 species, freshwater supports 675 species, and brackish water accommodates approximately 113 species (Sarkar *et al.* 2012).

### *Estuarine Ichthyofauna*

Estuarine fish classification has gone through multiple revisions, reflecting the wide range of estuarine classifications (Day 1951; Gunter 1967; Green 1968; Perkins 1974). These taxonomy, physiological, and ecological classifications reflect characteristics including breeding, feeding, and migrating patterns, as well as salt tolerance. Research on estuary fishes has traditionally focused on salinity as a key factor influencing the composition of estuarine fish populations, primarily in temperate and warm temperate regions of Europe and North America. Blaber (2000) reports that from 1978 to the end of 1995, a search of the Aquatic Science and Fisheries Abstracts database turned up over 1800 publications about fishes in temperate estuaries, but only 600 about fishes in tropical estuaries. During the time span of 1995 to 2000, there was a notable shift in the numbers. Specifically, there were 630 articles on temperate estuary fishes and 338 on tropical estuarine fishes. This suggests a substantial rise in productivity in the tropical regions.

In estuary ecosystems, the number of different species may be lower compared to nearby aquatic environments. However, the populations of these species are very large. The composition of fish populations is determined by the complex interplay of multiple factors, with particular importance placed on the following:

1. The size, depth, and physical characteristics of estuaries, including salinity and turbidity levels, as well as the types of habitats present.

2. The features and extent of neighbouring oceanic seas, with minimal impact from sources of fresh water.

3. The physical location of the estuary, including factors such as latitude and its connection to marine features such as ocean currents, canyons, and reefs.

Species in temperate regions have been classified according to their ability to tolerate salt, which is categorised as either euryhaline or stenohaline. These categories can be further divided (Green, 1968). Estuarine fish distribution in these areas has been explained by their tolerance to salinity; a significant decline in species diversity from sea to estuary is suggestive of the salinity's dominant effect (Gunter, 1967). Nevertheless, the suitability of this phenomenon in subtropical and tropical settings remains uncertain. Salinity tolerance can affect the distribution of fish in tropical estuaries. However, these ecosystems frequently undergo significant changes in salinity, ranging from nearly 0% to 35%, on a daily and seasonal basis. Therefore, a significant level of euryhalinity is necessary for the organisms living in tropical estuaries, as well as for several species in marine regions that experience seasonal fluctuations in salinity. Due to the scarcity of experimental research on the salt tolerances of the majority of tropical estuarine species, it is not very feasible to categorise them primarily based on their salinity tolerances.

Recent progress in comprehending spawning behaviour has resulted in alternate categorization frameworks for subtropical and tropical estuary fishes (Day 1981; Blaber 1997), highlighting their use of estuaries and spawning sites. These strategies are supported by the classification scheme that follows:

1) Estuarine-adapted species, which may complete their whole life cycle inside estuaries, display unique features that vary across different regions. (a) In the subtropics, these species make up a substantial part of the fish population found in estuaries. These include different types of clupeids, gobies, engraulids, ambassids, atherinids, and syngnathids. (b) These species have a significant impact on the fish population in estuaries in tropical locations, especially in West Africa, Southeast Asia, and tropical South America. The estuarine environment contains a wide variety of species, both big and small, such as Clupeidae Cuvier, 1816, Mugilidae Jarocki, 1822, Sciaenidae Cuvier, 1829, Ariidae Bleeker, 1858, Polynemidae Rafinesque, 1815, and Haemulidae Gill, 1885, which reproduce in estuaries.

2) In subtropical and tropical estuaries, a significant population of marine migrants, generally referred to as marine spawners, arrive from the sea. These estuaries host migratory individuals of diverse species, such as *Lares calcarifer* in Southeast Asia and Australia, the circumtropical *Mugil cephalus* Linnaeus, 1758, as well as several species of Leiognathidae Gill, 1893 and Haemulidae Gill, 1885, in both adult and juvenile stages. Alternatively, certain species within the Mugilidae Jarocki, 1822, Carangidae Rafinesque, 1815, and Polynemidae Rafinesque, 1815 families may only exist in their juvenile stage, whereas certain species within the Ariidae Bleeker, 1858 family may only exist in their adult stage. The difficulty in classifying these species in tropical settings should be noted, since many that are classified as marine migrants in subtropical areas are also classified as "estuarine" in tropical environments (Blabber 2000).

The mullet species, *M. cephalus*, which is found in tropical regions around the world, has been the subject of thorough research by Thomson in 1966 and Odum in 1970. Similar to other Mugilidae species, they are iliophagous, meaning they eat on the top layer of the substratum, consuming both inorganic and organic matter, and expelling undigested sand particles. Adult individuals are commonly found in estuaries and coastal waterways, exhibiting a general absence of specialised environmental preferences. They spawn only in the sea, and their migrations are amazing, with big groups meeting at the mouth of estuaries and then migrating out into the open (Wallace 1975). Post-larvae are thought to be required to actively search for estuaries and shallow waters when they are small in size (10-20 mm) in order to undergo a series of intricate transformations in their diet and feeding habits, ultimately resulting in iliophagy.

3) Anadromous species are important to temperate estuaries because they reproduce in freshwater and travel through estuaries on their way to and from spawning grounds. Shad, lampreys, and salmon are prominent members of this group (Blabber 2000).

4) Freshwater migratory species, such as eleotrids, migrate different lengths along estuaries, sometimes for the purpose of spawning, and usually return to freshwater habitats for breeding. Within tropical climates, South and Central American estuaries are home to many species of pimelodid catfish, poeciliids, and characids that inhabit estuary waters (Cervigón 1985; Winemiller & Leslie 1992).

The majority of fish species found in subtropical and tropical estuaries possess a significant level of euryhalinity, which means they have the capacity to adapt to a broad spectrum of salinities, ranging from almost freshwater (<1%) to at least 35%. Curiously, tropical marine species appear to have a much simpler process of adapting to freshwater habitats compared to their temperate counterparts (Pauly 1985). The salinity ranges in which 100 Indo-West Pacific fishes have been recorded in Africa are listed in the publications of Whitfield *et al.* (1980) and Whitfield (1996). Out of the total number, 65 organisms are classified as marine migrants. Regarding their ability to tolerate low salt levels, 16 out of the 65 have been observed in freshwater environments, while another 31 have been found in salinities ranging from 1-3 ‰. Additionally, 14 organisms have been documented in salinities of 4-10‰. Only two elasmobranchs have been seen to possess a minimum tolerance of 17‰. Notable among the most tolerant species are *Elops machnata* (Forsskål, 1775) with a salinity range of 0–115‰, *Pomadasys commersonnii* (Lacepède, 1801) with a range of 0-90‰, *Monodactylus falciformis* Lacepède, 1801 with a range of 0–90‰, *M. cephalus* with a range of 0–90‰, *Rhabdosargus sarba* (Forsskål, 1775) with a range of 1-80‰, and *Liza macrolepis* (Smith, 1846) [now known as *Planiliza macrolepis* (Smith, 1846)] with a range of 1-75‰.

The task of precisely identifying tropical marine and estuarine fishes remains a major obstacle to doing thorough ecological study. The large number of species and the lack of adequate field keys frequently obstruct research activities, even in spite of the availability of several important new field guides (Allen 1997) and the appearance of new FAO guides. This is particularly evident in underdeveloped nations, where scientists often face a lack of access to adequately equipped library facilities. The fact that there is a noticeable drop in the number of fish taxonomists and a worldwide loss in financing for taxonomic study are worrying.

### *Conservation: Preserving Estuaries for Future Generations*

Even though fish only sometimes live in tropical estuaries, they nevertheless contribute to the complex ecosystem dynamics of these areas of exceptionally rich biodiversity. Beyond ethical and aesthetic concerns, the preservation and conservation of tropical estuary ecosystems is necessary to ensure their future viability for the production of fisheries. Ensuring the ecological functioning of estuarine habitats is crucial for the economic prosperity of fishers (Boisneau 1998). Fish populations and surrounding inhabitants' livelihoods can be negatively impacted by any changes to this functioning, whether they are direct (dredging, for example) or indirect (dam-induced flow variations, pollutants linked to catchment use, or sediment loads). Since individuals are essential to most tropical estuarine habitats, their presence and activities must be taken into consideration when planning conservation efforts. In various tropical areas, indigenous populations actively engage in the planning and administration of natural resources, questioning traditional discussions over the balance between aquaculture advancements and the conservation of mangroves. There are many instances, particularly in India, where local villages take the lead in restoring and replanting mangroves (Kathiresan *et al.* 1996). Other reasons to conserve tropical estuaries and their fish populations include the need to fulfil international agreements focused on preserving biodiversity and the growing economic importance of eco-tourism. Finally, it is important to consider any conservation efforts in the context of larger-scale processes, such as climate change and the rise in sea levels, which occur over long periods of time. Irrespective of their origins, the fact that human activities can make them worse is not a major issue, as they are mostly beyond our control.

### *Mugilidae*

The Mugilidae, known as grey mullets, are highly prevalent teleost families in coastal seas worldwide. The majority of temperate, sub-tropical, and tropical waters in both the northern and southern hemispheres are residence to them. This family demonstrates exceptional versatility, resulting in the presence of species that thrive in both the transparent and unspoiled waters of coral reefs, as well as those that prefer relatively turbid estuary and freshwater environments. Certain species belonging to the Mugilidae Jarocki, 1822 family have extraordinary resilience in the face of extreme pollution in global waterways. This is demonstrated by their existence in the port of Visakhapatnam, India (Blaber 2000).

The Mugilidae family, known for its tendency to maintain consistent physical characteristics, has often resulted in misidentifications and incorrect synonymies, especially when dealing with specimens from remote geographical areas. Several taxonomic matters are still under discussion and will probably contribute major changes in the taxonomy and name of the family in the near future. The most recent exhaustive examination of Mugilidae Jarocki, 1822 was conducted by Oren in 1981, which is more than 30 years ago. The book not only emphasised aquaculture but also consolidated a significant amount of the existing biological and ecological information during that period. Gautier & Hussenot (2005) published a subsequent work in French that offered vital insights into European grey mullets. Whitfield *et al.* (2012) released a current comprehensive analysis of the biology, genetics, ecology, and fisheries of *M. cephalus*.

Mugilidae Jarocki, 1822 is the specific family of grey mullets under the class Actinopterygii and order Mugiliformes (Fricke *et al.* 2023). Formerly, grey mullets were classified inside the order Perciformes, but currently they are the sole representative of the Mugiliformes order (Nelson 1984). The maximum normal length of mullets is 120 cm, although they tend to grow over 30 cm; they have a subcylindrical body; the head is frequently large and flattened dorsally (rounded in the taxa *Joturus* Poey, 1860, and *Agonostomus* Bennett, 1832) (Harrison & Howes 1991). The Mugilidae family, first described by Jarocki in 1822, consists of medium to large-sized fish that are found in maritime environments worldwide (Harrison & Howes 1991). The majority of the species are euryhaline, meaning they can tolerate a wide range of salinity levels. They are typically found in coastal marine waters, as well as hypersaline to brackish water lagoons, estuaries, and freshwater environments. These species thrive in sediments that are enriched with organic matter. Certain species are capable of inhabiting extremely contaminated waterways, such as the harbour in Visakhapatnam, India (Blaber 2000). Mullets hold a relatively low position in the food web, which makes them highly efficient secondary providers of protein. Their diet consists of small organic particles, decaying debris, and microalgae found on the ocean floor. Within the group Pisces, no members depend as heavily on microphytobenthos as mullets, as these microorganisms are a significant source of food in their diet. Mullets thus provide apex predators with access to high-quality fish protein (Whitefield *et al.* 2012).

Grey mullets commonly establish dominance over the fish population in any location they inhabit, and their feeding habits, which mostly involve consuming detritus, give them a distinct role in the food chain. The St. Lucia coastal lake system in South-East Africa is known for its significant species variety, with a minimum of 10 coexisting species (Blaber 1976). Not unexpectedly, these fish have economic importance in different countries, with the species *M. cephalus* being widely spread over the world and forming the basis for important commercial fisheries in developed areas such as Australia and the U.S.A. Additionally, it plays a crucial role in artisanal and subsistence fisheries inside poor nations. Grey mullets are often raised through aquaculture in many regions worldwide. This includes vast systems, such as the relatively restricted coastal lagoon areas in the Mediterranean region, as well as semi-intensive and intense systems that often involve polyculture with other species. However, it's noteworthy that mullet aquaculture still relies on the collection of wild fries, as commercial-level induced spawning is not widely practiced. Egypt has become the primary producer of farmed grey mullets, accounting for 84% of the worldwide mullet aquaculture production, which amounted to 138,143 tonnes in 2013 according to FAO (2020) data.

The need for a new comprehensive review of Mugilidae Jarocki, 1822 was created due to recent advancements in knowledge. These advancements include substantial progress in ecological and biological information from tropical developing countries, more rigorous taxonomic investigations, biogeographical studies, advancements in genetic techniques, and significant strides in applied aquaculture.

The euryhaline ecosystem experiences varying environmental conditions, which create favourable conditions for the thriving of different kinds of fish such as mullets. Environmental factors such as pH, temperature, salinity, dissolved oxygen, and others can significantly influence the growth and development of estuarine fishes (Fig. 2). EMECS (2007) identifies BOD, salinity, pH, and DO as the primary water quality metrics for water bodies. Temperature, while not specifically stated, is equally vital as it impacts parameters like pH. The rise in water temperatures is occasionally associated with the release of heated water from industrial and power plants that utilise water for cooling purposes. The temperature of water has a substantial impact on the metabolic rate and numerous activities, such as the reproduction of marine life. It also plays a vital role in monitoring the dispersion of marine creatures and plants (Levinton 2017). It is crucial to maintain an ideal pH level for marine fauna, often ranging from 7.5 to 8.5. Marine species are less tolerant of pH changes compared to freshwater creatures (Boyd *et al.* 2000). Decreased pH levels can have an impact on the ability of organisms to maintain a proper balance of salt and can also affect their ability to reproduce (Lloyd 1992).

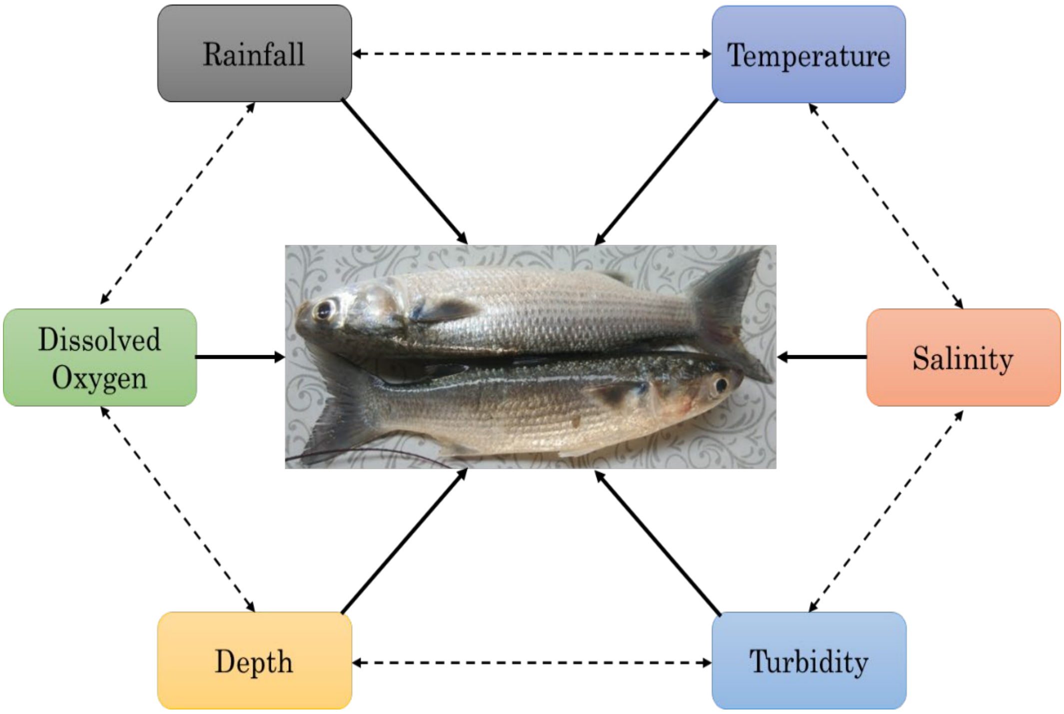


Figure 2: Physicochemical parameters influencing the occurrence, distribution and movements of fish – *Mugil cephalus* in tropical and subtropical estuaries

### *Length-Weight Relationship, Condition Factor, Gonadosomatic Index and Hepatosomatic Index*

The history of the condition factor and weight–length relationship is intricately connected. The concept can be traced back to the 'square cube law' formulated by Galileo Galilei (1564–1642), who was one of the first to propose that volume increases in proportion to the cube of linear dimensions, whereas strength (such as the diameter of legs) increases solely in proportion to the square. Herbert Spencer, in his Principles of Biology published between 1864 and 1867 (referenced from the 1966 reprint of the 1898 version), restated the first portion of Galileo's statement, which later became known as the 'cube law.' According to this law, in bodies that have similar shapes, the masses and weights change proportionally to the cubes of their dimensions. For instance, if a fish were to double its length, its weight would increase by a factor of eight.

Fulton (1904) conducted a study on 5675 individuals belonging to 19 fish species from the Scottish North Sea and observed that the cube law did not accurately apply to fishes. He noticed that the majority of species experience a greater rise in weight compared to what the law would predict based on the growth in length. Fulton observed substantial discrepancies in the mass for a certain length across various species. Within a given species, he discovered that the ratio varies at various sites and during different periods of the year. In addition, he saw a significant decrease in weight immediately after spawning, which appeared to be quickly recovered. Fulton determined that fish, particularly prior to reproductive incidents, depart from the cube law, and seasonal variations impact fish of varying sizes.

Fulton noted that during the initial phases of fish development, their length increases at a higher proportion compared to their other dimensions. This results in a difference in the length-to-weight ratio when compared to larger individuals. He emphasised that the weight variation within the same species increases significantly as the fish grows longer. The concepts of allometric growth, form factor, spatial, seasonal, and reproductive variations in condition, growth differences between juveniles and adults, changes in condition with size, and the exponential nature of the variation in weight-at-length data were essentially established by Fulton.

On the other hand, he provided tables that allow for the determination of weight by using length measurements in accordance with a predetermined weight-to-length ratio. Duncker (1923) stated that Fulton determined this ratio based on the smallest length class with enough specimens and then applied it to all subsequent length classes. surprisingly, Fulton (1904) did not clearly mention the equation that is currently acknowledged as Fulton's condition factor.

$$K = 100\frac{W}{L^3}$$

Here, W represents the whole body wet weight in grams, and L represents the length in centimetres. The multiplication by 100 is applied to normalize K to be close to unity.

Le Cren (1951) provided a comprehensive assessment of water-related organisms (WLRs) and their condition factor. The development of a formula designed to express the relationship between length and weight, and to simplify the conversion of measures, revealed the complex interaction between length, weight, and condition. Additionally, associations between seasonal fluctuations in gonad growth and development and the condition evaluation were found. Furthermore, as Le Cern explained (1951), it became vital to assess the impact of stomach contents on weight.

Examining data on the dimensions and mass of fish is a widespread method for extracting biological knowledge. Undoubtedly, these studies have now become conventional techniques in the field of fishery biology. Nevertheless, the analysis of length-weight data has occasionally become excessively standardised, resulting in unclear understandings of its goals, the utilised techniques, and its successful outcomes. This discussion does not try to extensively explore the literature, but rather present an overview of the main approaches used to analyse length-weight data (Le Cern 1951).

The examination of length-weight data often fulfils two separate objectives. First and foremost, its objective is to quantitatively articulate the correlation between length and weight, so simplifying the process of conversion among these two variables. Additionally, it aims to measure the discrepancy between the actual weight of individual fish or particular groups of individuals and the expected weight based on their length. This variance functions as an indicator of things such as adiposity, general health, gonadogenesis, and other related aspects. Within this discourse, the phrase "length-weight relationship" is specifically used to refer to the initial category, whereas the term "condition" is employed as a precise and inclusive term to incorporate length-weight analyses of the second category (Le Cern 1951).

The weight (W) of fishes, as well as other organisms, follows an exponential relationship with their length (L), expressed by the equation $W = aL^b$. In this equation, 'a' represents the intercept, and 'b' is the slope when the relation is log-transformed (Le Cren 1951; Froese 2006). The slope 'b' plays a crucial role in determining the growth characteristics of a fish species. If 'b' equals 3, it indicates isometric growth, where all fish dimensions increase at the same rate. For 'b' less than 3, the growth is hypoallometric, meaning the fish increases less in weight than predicted by its increase in length, leading to a more elongated form. Conversely, if 'b' is greater than 3, it signifies hyper allometric growth, where the fish increases more in weight than predicted by its increase in length, resulting in a less elongated or more roundish form (Le Cern 1951).

Weight–length relations (WLRs) have various practical uses, including the conversion of lengths into biomass, the evaluation of fish condition, the comparison of fish growth in different regions, and the support of species-specific research on reproduction and feeding (Petrakis & Stergiou 1995; Koutrakis & Tsikliras 2003; Froese 2006). Therefore, these relationships are an essential element of fisheries biology, and when precisely computed, they provide substantial benefits for fisheries management.

Similarly, the mullet gonadosomatic index is employed to determine the spawning season. The term "GSI" was introduced by Meien in 1927, and since then, many researchers have utilised it as a measure of gonad growth. The gonadosomatic index (GSI) offers valuable insights on the monthly changes in gonadal development of a species, making it a valuable tool for managing the fishery and aquaculture sectors. The hepatosomatic index is calculated in connection to the development of the gonads. As the gonad size increases, the liver size decreases. The hepatosomatic index is strongly associated with the gonadosomatic index, indicating that vitellogenesis utilises hepatic energy during reproduction (Albieri & Araújo 2010).

### *Proximate Content*

Marine fish are often consumed as a food source in coastal regions. The rising population and the recognised nutritional advantages have resulted in a higher market demand for fish. The nutritional and therapeutic properties of fish products depend on their proteins, lipids, minerals, and vitamins. The superior biological value of fish proteins is derived from their ideal ratios of essential amino acids, as stated by Njinkoue *et al.* (2016). Fish are also significant repositories of ω3 polyunsaturated fatty acids. Multiple studies have shown that fish tissues contain significant amounts of eicosapentaenoic acid (EPA or 20:5ω3) and docosahexaenoic acid (DHA or 22:6ω3). Polyunsaturated fatty acids have a significant impact on human nutrition and can be used therapeutically and preventively to combat diseases like cardiovascular diseases, malignancies, rheumatoid arthritis, and inflammation (Njinkoue *et al.* 2016). Minerals have a crucial role in sustaining several body functions, such as regulating acid-base balance, forming haemoglobin, managing water balance, supporting bone and teeth structure, and facilitating metabolic responses. Beyond their physiological and nutritional functions, minerals have an impact on food texture, flavour, and the activation or inhibition of enzyme-catalyzed activities. The skeletal structure of fish, specifically the vertebrae, contains a significant amount of essential minerals, including around 65% of the total minerals found in fish muscles and bones (Njinkoue *et al.* 2016).

Proximate analysis in fish involves identifying the fundamental chemical composition or proximate components of fish tissue. The primary constituents typically examined in fish are moisture content, protein content, lipid (fat) content, ash content, and occasionally carbohydrate content (Kumaran *et al.* 2012). These investigations offer crucial data on the nutritional composition of fish, which assists in the management of fisheries, aquaculture, and decision-making for human consumption.

### *Organoleptic Study and Aquaculture*

An organoleptic study of fish entails the sensory assessment and analysis of its detectable attributes, specifically taste, smell, texture, and appearance. This evaluation seeks to evaluate and characterise the comprehensive sensory attributes of fish, offering vital information about its freshness, flavour, and general palatability. These evaluations aid in assessing the fish's calibre, detecting any unpleasant tastes or disagreeable smells, and evaluating its overall appeal to consumers. The organoleptic study is of utmost importance in the seafood and aquaculture sectors, as it aids in quality assurance, product innovation, and ensuring that consumers are provided with fish products that satisfy their sensory preferences. Moreover, it offers crucial data for regulatory compliance and ensures uniformity in the sensory characteristics of fish in the marketplace.

Grey mullets are widely harvested and play a significant role in small-scale fishing and large-scale aquaculture in many developing countries (FAO

2020). The introduction of mullet fish into aquaculture presents numerous potential advantages and prospects. Mullet fish are highly esteemed in several cultures for their delectable flavour and pleasing consistency. The introduction of mullet into aquaculture can offer a sustainable supply of this culturally important seafood, satisfying consumer demand and safeguarding culinary traditions. Integrating mullet into aquaculture broadens the variety of species being grown. This diversification can enhance the resilience of the aquaculture industry by reducing dependence on a limited number of species and providing alternatives in case of fluctuations in market demand or environmental factors affecting other species. Aquaculture of mullet can offer lucrative prospects for pisciculturists. Engaging in mullet cultivation can create opportunities for expanding markets and generating additional income, so enhancing the overall development and profitability of the aquaculture industry. Wild populations of mullet are occasionally vulnerable to overfishing (Crosetti & Blaber 2016). The introduction of mullet into aquaculture can mitigate the strain on wild stocks, hence aiding in the preservation of natural habitats and promoting sustainable fisheries management.

Research and development potential in fields including nutrition, disease control, and breeding are made possible by mullet aquaculture. This research has the potential to enhance aquaculture activities, develop disease-resistant strains, and optimise production systems. Mullet provide a substantial amount of protein and vital minerals. Aquaculture can enhance food security by offering a dependable and sustained supply of mullet, particularly in areas where natural populations are excessively exploited or confronted with environmental obstacles. Mullet are renowned for their capacity to adjust to a wide range of environmental circumstances. By incorporating them into aquaculture systems that replicate their natural environment, it is possible to achieve environmentally conscious and sustainable aquaculture methods. Nevertheless, it is imperative to approach mullet aquaculture with meticulous evaluation of its environmental consequences, disease control, and strict adherence to sustainable methodologies. The long-term viability of mullet aquaculture depends on industry monitoring and regulation to avoid unfavourable outcomes like the introduction of invasive species or habitat destruction.

Gujarat being a state of India having largest coastline with diverse coastal habitats. At present, Gujarat is the largest fish producing state in India (Handbook on Fisheries Statistics India 2018). Gulf of Cambay, Gulf of Katch and Saurashtra peninsula have many major and minor fish landing centres. Out of total fishery resource of the Gujarat, total mullet production was reported approximately 8000 metric tonnes in 2000 which includes marine and inland production (FAO 2000). This is quite less compared to the other coastal states Andhra Pradesh, Tamil Nadu and West-Bengal. In Gujarat, many estuarine forming rivers, large coastal wetlands and lagoons are present where aquaculture of mullets can be proposed. At present, human consumption increases every day, thus need of quality food also increases. Mullet fish can be a potential fishmeal which can compensate the demand of nutrient reach food. In Gujarat, very few studies have been carried out on diversity (Rao & Shashtri 2005; Saravanakumar *et al.* 2009; Gohil & Mankodi 2013; Brahmane *et al.* 2014; Parmar *et al.* 2015; Bhakta *et al.* 2017; Raval *et al.* 2017; Sarma & Mankodi 2017; Joshi *et al.* 2018; Bhakta *et al.* 2018; Bhatt & Mankodi 2020) and biology of mullets. Hence, there is a need of detail investigation on diversity and biology of mullets in the state to find out possible management measures in capture fisheries as well as to explore aquaculture potential. The present study will be useful in the context of diversity status, biology and aquaculture management and potential development in Gujarat state, India.

## ❖ OBJECTIVES

1) **Species Diversity and Distribution of Mullets - [Family: Mugilidae Jarocki, 1822] from Coastal Waters of Gujarat, India.**
    a. Taxonomy based on Morphology, Morphometry and Meristic analysis.
    b. Molecular taxonomy and Phylogenetics.
    c. Present Distribution status of Mullets in Gujarat.
2) **Environmental (Water Parameters) and Biological Aspects of *Mugil cephalus* (Linnaeus 1758) from selected Coastal and Estuarine Zone of Gujarat.**
    a. Physico-Chemical parameters of selected stations of Marine and Estuarine Zones of Gujarat.
    b. Length-Weight Relationship and Fulton's Condition Factor of *Mugil cephalus* (Linnaeus, 1758).
    c. Gonadosomatic Index and Hepatosomatic Index of *Mugil cephalus* (Linnaeus, 1758).
3) **Status and Potential assessment of Mullet culture in Gujarat, India.**
    a. A proximate analysis - Moisture, Total Ash, Total Fat, Total Protein and Carbohydrate content of *Mugil cephalus* (Linnaeus, 1758).
    b. Organoleptic study of *Mugil cephalus* (Linnaeus, 1758).