Assessing the Effects of Environmental Drivers on the Growth of Asian Sea Bass (*Lates calcarifer*) and Mapping Potential Growth Zones in the Bakkhali–Maheshkhali Estuary Using Generalized Additive Models (GAMs)

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Certificate

I hereby declare that this paper, entitled **"Assessing the Effects of Environmental Drivers on the Growth ofAsian Sea Bass (Lates calcarifer) and Mapping Potential Growth Zones in the Bakkhali–Maheshkhali Estuary Using Generalized Additive Models (GAMs)"** is an original work of mine. I also declare that no part of this work has been submitted elsewhere for the award of any degree.

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Reg. No.: 2022126008
Session: 2022–2023
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Throughout the study period, I found him sincere, dedicated, and honest in his work. I also certify that this thesis is an original submission and has not been submitted elsewhere previously for publication in any form.

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Md. Nazmus Sakib
The Author

Declaration

“The data presented in this thesis are original. To ensure transparency and foster scientific collaboration, the raw data used in this study are available from the author upon reasonable request.”

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Abstract:

The present study investigates the effects of environmental parameters on the weight gain of Asian sea bass *(Lates calcarifer)* using a Generalized Additive Model (GAM) to analyze data from Moheshkhali-Bakkhali estuary region. Five key environmental variables—salinity, temperature, alkalinity, Do and pH—were examined to determine the optimal conditions for the growth of Asian sea bass (*Lates calcarifer*). Our findings indicate that salinity (15–25 ppt) and temperature (25.5–28.5 °C) emerged as the primary drivers influencing weight gain in Asian sea bass across both hatchery and open-culture environments, aligning closely with previous research. Alkalinity levels ranging from 111 to 129 mg/L and pH values between 7.2 and 7.8 were also found to significantly influence growth performance. Similarly, dissolved oxygen concentrations of 5.5–7.1 mg/L enhanced the probability of improved growth in both environments, underscoring the importance of maintaining optimal water quality conditions. Using the GAM model, we identified the Moheshkhali and Bakkhali River estuary as a particularly favourable region for Asian sea bass growth, especially during the summer season when environmental conditions are most conducive. Overall, this study contributes to a deeper understanding of the ecological dynamics shaping Asian sea bass populations in relation to environmental variability. The identified region holds strong potential for sustainable aquaculture development, and by integrating environmental stewardship with economic opportunities, our results support initiatives aligned with the Sustainable Development Goals (SDGs).

Keywords: GAM model, *Lates calcarifer,* Moheshkhali-Bakkhali, Bay of Bengal.

1.Introduction

A dynamic exploration of how environmental parameters shape the growth rate of Asian sea bass and help pinpoint the most promising zones in the Bakkhali River, Cox's Bazar, using the adaptive power of GAM modeling. Bangladesh's aquaculture sector suffered over $140 million between 2011 and 2020 due to climate disasters, yet cultivating highly survivable species like Asian sea bass in geographically sheltered rivers like Moheshkhali-Bakkhali in Cox's Bazar offers a beacon for economic growth (Islam *et al.,* 2024). Primarily, its ability to adapt to varying salinities, along with high market demand, makes barramundi a prime species for aquaculture (Haque *et al.*, 2020). For instance, the worldwide production of vetki (the local name in Bangladesh) exceeds approximately 150,000 metric tons (FAO, 2022). However, for optimal growth, survival ,and reproduction, species require certain environmental conditions, referred to as habitat in ecological terms (Hall *et al.,* 1997). Encompassing both living and non-living components of the environment, along with their structured populations, is a major factor in defining habitat (Kearney, 2006). Moreover, for a sustainable marine environment, the protection of habitats is crucial, as species depend on them for food and survival throughout their life cycle. For this reason, assessing fish habitats is pivotal for sustainable fisheries management as well as aquaculture. Thus, it is necessary to study the interaction between biological processes and environmental factors for sustainable aquaculture development. Furthermore, in today's world, fish play a vital role in international trade and domestic nutrition as a key source of protein (Lindsay, 2022). The substantial size, high quality meat, rapid growth rate, and strong export potential make *Lates calcarifer* a favored aquaculture species globally (Yenmak, Joerakate, & Poompuang, 2018).

The export potential, contribution to socioeconomic development, and economic importance establishes Asian sea bass as a crucial aquatic species for aquaculture in Bangladesh (Hossain et al., 2025). Recent studies have documented a broad geographical distribution of barramundi , with the species predominantly found in coastal regions of Bangladesh, including Khulna, Satkhira, Bagerhat, Bhola, Patuakhali, and Cox's Bazar (Ali *et al*., 2023). One major reason why Asian sea bass is referred to as a potential species is that Bangladesh's expanding fish export market, which began in 1977 with an initial value of $2000, expanded to US$180.26 million by 1992–93, indicating broader potential for this species like Asian sea bass in the export market and aquaculture development (Kamal & Hussain, 1994). In recent years, the export of fish has surged to US$422.28 million, creating significant opportunities and positioning it as an ideal candidate for cultivation due to its nutritional value, excellent taste, and high flesh content compared to other species (Shamsuzzaman et al., 2020 ;Haque et al., 2020). Under ongoing climate change, adaptability, resilience, and rapid growth are essential which is why barramundi is favored worldwide for its fast growth rate (reaching up to 60 kg) and tolerance to varying environmental conditions (Asadollahi *et al.,* 2025). Mass production of Asian sea bass has been undertaken by several countries, including Southeast

Asian nations, Australia, Iran, and Israel, which has serving as a weke-up call for Bangladesh to promote this species for large- scale cultivation (FAO, 2005). Indeed, barramundi can be cultured using the polyculture method (Chaitanawisuti *et al.*, 2001). For example, according to Joffre *et.al.*(2010), shrimp, crab, and tilapia can be cultured together with this species. Rearing with the high-fecundity tilapia *(Oreochromis niloticus)* represents an effective feeding strategy for barramundi, as this species naturally preys on tilapia larvae (Haque, Hossain, Uddin, & Dey, 2020). As a result, coastal communities of Bangladesh are more likely to cultivate *Lates calcarifer* as a highly preferred aquaculture species due to its high market value (approximately 2.05-4.52 per kilogram) (Farhaduzzaman *et al.,* 2023).
Various aquaculture techniques can be employed for this species, including intensive, semi-intensive , and cage culture systems (Ayson *et al.*, 2013). A notable example can be found in the Moheshkhali-Bakkhali region of Bangladesh, where an open-water culture method for barramundi was introduced by the Bangladesh Fisheries Research Institute (BFRI) (Mostofa *et al.*, 2024). Therefore, the application of proper aquaculture techniques for *barramundi* can help reduce the overexploitation of wild fishery resources. Conversely, a key factor for successful aquaculture is the collection of high-quality fry (Mely *et al.,* 2025). To maintain healthy fry, the Greenhouse hatchery in Cox's Bazar, Bangladesh, can serve as an alternative source(Greenhouse Mariculture, 2023). However, to reduce seasonal scarcity, most fry are collected from natural sources, mainly from the Sundarbans region, Sonadia, Hashimchor, Choufaldandi, Moheshkhali (Rahman *et al.*, 2017; Huq & Tareq, 2003).
Rich biodiversity, with 54 fin-finish species and 10 shellfish species, makes the southeastern coast one of the marine biodiversity hotspots of Bangladesh (Akter et al., 2017). Several anthropogenic and environmental factors are responsible for the decline of wild fish resources, including overfishing (Myers & Worm, 2003), destructive fishing practices (Pusceddu et al., 2014), climate change (Cheung et al., 2009), invasive species (Latini & Petrere, 2004), and illegal, unreported, and unregulated (IUU) fishing (Agnew et al., 2009). Hence, aquaculture is increasingly recognized as a strategy for sustaining ecosystems and conserving biodiversity.
Environmental parameters govern the distribution and diversity of species (Gizachew, 2022). Although studies on predicting the spatial distribution of aquatic species have been published worldwide, there is a significant lack of research employing geospatial models to identify optimal environmental parameters and suitable growth zones for aquatic species such as *Lates calcarifer* (Boyra *et al.,* 2016; Loots *et al.,* 2011; Sarker *et al.,* 2021). In the present study, we applied both Generalized Additive Models (GAMs) and integrated with geospatial tools to examine the complex relationships between environmental parameters and the growth rate of *Lates calcarifer* as well as identify their optimal growth zones in Bakkhali-Moheshkhali region, Cox's Bazar Bangladesh. Also, the identification of suitable growth zones for fish has not been extensively conducted in this region, leading to a significant gap in aquaculture management.

1.2Objectives

1. To identify and analyze the key environmental factors affecting the growth of Asian Sea Bass.
2. To apply and evaluate the effectiveness of Generalized Additive models (GAM) in predicting the Fish growth.
3. To visualize the spatial variations in predicted fish growth rates.
4. To understand the hatchery environment of Lates calcarifer.

2. Literature Review

2.1 Global Distribution:

The *Latidae* family is an extensively distributed perch-like family to which *Lates calcarifer* belongs known worldwide as the Asian sea bass and exhibits catadromous migration and protandrous hermaphroditism (Animal Diversity Web,2008). *Barramundi* exhibits the ability to inhabit a wide range of environmental conditions, including temperate, semi-temperate and warm regions, as a native species distributed across the Indo-Wast pacific, Southeast Asia, and the Middle East (Balston, 2009). For instance, Asian sea bass is either naturally occurs or cultivated in countries such as India, Thailand, Indonesia, Malaysia, Vietnam, the Philippines, Papua New Guinea, Sri Lanka, southern China, Iran and the Persian Gulf region (FAO, 2009).

2.2 Regional Distribution

Known locally as Bhetki or Koral, Asian sea bass is predominantly found throughout the coastal regions of Bangladesh. Several studies have shown that in the coastal region of Bangladesh, including Patuakhali, Sundarbans, Bakkhali, and other estuary areas, *barramundi* is predominantly found (Rahman, 1989; Chakraborty *et al.*, 2021; Haque *et al.,* 2019; Haque *et al.,* 2021; Farhaduzzaman & Hossain, 2023). Additionally, in India, Asian sea bass (*Lates calcarifer*) is mainly found in Vembanad Estuary and lower Ganges, Godavari and Mahanandi Rivers (Rimmer &Russell,1998).

2.3 Biology of Asian Sea Bass

The euryhaline nature of *Lates calcarifer* enables it to tolerate a wide range of salinities, from freshwater rivers to marine coastal waters (FAO, 2016). It has a broad mouth with an oblique jaw and a silvery body that bears 7-9 dorsal spines (Rimmer & Russell, 1998). *Barramundi* can reach a length of 70–120 cm, while some individuals can grow up to 200 cm and weigh up to 60 kg (FishBase, 2025). Asian sea bass *(Lates calcarifer)* migrates between freshwater and saltwater environments; However, it primarily inhabits coastal lagoons, estuaries, mangrove creeks, and river mouths (Roberts, 2021). Sex-changing characteristics, referred to as a hermaphroditic pattern, are observed in the life cycle of *Lates calcarifer,* in which individuals initially mature as male and later change sex to become females (Roberts *et al.,* 2021). Despite the fact that spawning occurs in coastal waters near river mouths during the monsoon season, the nursery grounds are primarily found in mangrove creeks and estuaries (Leber *et al.,* 2004).

2.4 Global importance, Aquaculture & Fisheries Goal

Globally, the Asian sea bass is a highly regarded species for aquaculture because of its adaptability, fast growth and nutritional value(Macbeth & Palmer, 2011). Several reports have been published on the market size of Asian sea bass, among which Future Market Insights indicated the global market size of this fish. In this report, the global market size of Asian sea bass was valued at USD 1,012 million in 2024 and is projected to grow at a compound annual growth rate (CAGR) of 4.5%, reaching an estimated USD 1567 million by 2034, highlighting the global significance of this species (Future Market Insights, 2024). Additionally, a report by Future Market Insights 2024 indicates that the global production of Asian sea bass was 1,200 tons in 2024 and is projected to grow between 2024 and 2034 at annual rates of 6.6% in Japan, 3.4% in China, 4.2% in India, 7.6% in Germany and 9.3% in the United Kingdom. On the other hand, cage, pond and recirculating aquaculture (RAS) have been introduced in several countries, including Thailand, Malaysia, Indonesia, Australia, and Bangladesh, which renders *Lates calcarifer* an ideal species for aquaculture in these regions (Islam *et al.,* 2023).Thus, *L. calcarifer* has expanded aquaculture opportunities worldwide.

2.5 Size and Maturation

An uncommon hermaphroditic behavior is observed in the life cycle of Asian sea bass, where it reaches full maturity at the age of 3-4 years, typically at a size of 60-70 cm total length and weight 2-4 kg(Che-Zulkifli *et al.,*2023;Ravi *et al.,* 2014; Roberts *et al.,* 2021). After reaching 85-100 cm total length (TL) over 4-8 years, Barramundi is considered a fully mature fish (FAO, 2021; Animal Diversity Web, 2023). However, a different trend is observed in other South Asian countries. For instance, variations in total length and weight are observed in Bangladesh, where the record total length was 40.1 cm with a weight of approximately 3-4 kg (Haque *et al.,* 2020; Hossain *et al.,* 2023). Rapid sexual maturity is observed in South Asian countries such as Singapore, Thailand ,and Malaysia, where Asian sea bass typically matures at around 2.4 years of age, with an average total length of 59 cm and weight of 2.7 kg. Notably, when individuals reach 3 kg, over 70% of males undergo sex reversal to become females.

2.6 Intestinal Microbiota Dynamic & Food

Studying intestinal microbiota is one of the most effective ways to understand the food and feeding behavior of any species (Luan et al., 2023). A study involving 720 specimens

collected from the southwest coast of Bangladesh, with total length (TL) from 25.4 to 40.1 cm, provided a detailed overview of the diet of Lates calcarifer. Analysis of intestinal contents revealed that the diet consisted of 34%teleosts, 10%insects, 23%macro-crustaceans, 10%algae and 17% zooplankton (Hossain et al.,2013). Seasonal variations also influence the food and feeding behavior of this fish. Unlike the monsoon period, the stomach of Lates calcarifer is fuller during the pre-monsoon period (Haque et al., 2020; Krishna et al., 2016).
Moreover, spawning also affects the feeding behavior of Asian sea bass. That's because, during the pre-spawning phase, females undergo a fattening process to build up energy reserves for egg development and the energetically demanding spawning activities (Mushahida-Al-Noor et al., 2013). In India, prey diversity was assessed by a study by Panchakshari in 2026. This study showed that the diet of Lates calcarifer consists of approximately 34% crustaceans, 22% fish and their larvae, 13% mollusks, and 10% algae. Yet, a different feeding trend has been observed in Australia. Changes in the feeding habits of barramundi with increasing size and maturation have been well documented by Davis (1985). Firstly, small fish (4–80 mm) primarily consume copepods and amphipods. Secondly, medium sized fish (41-400 mm) fed on Sicydiidae, Penaeidae, unidentified Natantia, Chandidae (Ambassis spp., Denariusa bandata), Odonata nymphs, and melanotaeniids. Finally, the large fish consumed prey including Clupeidae, Mugilidae, Ariidae, Polynemidae, and Engraulidae (Davis, 1985; Kamruzzaman et al., n.d.). Controlled breeding of Asian sea bass in Australia began in 1984 (Copland & Grey, 1987). Barlow et al. (1993) also elaborated on the feeding behavior of this fish, describing how Lates calcarifer shifts its feeding strategy from roving to lurking. An experimental study was carried out by Williams et al. (2003) in Queensland demonstrates that increasing crude protein levels in artificial feed resulted in proportional improvements in the growth rate of Asian sea bass. Studies revealed striking information about the changes in feeding behavior of Lates calcarifer across three different regions of Bangladesh.
The concentration of zooplankton was highest in July (34.9%) and lowest in April (10.5%), whereas algae concentration peaked in March (56.9%) and was lowest in June (2.1%). Furthermore, consumption of different fish was highest in May (23.1%) and was lowest in September (16.4%). Similarly, crustacean consumption peaked in October (23.2%) and was lowest during the winter (7.7%) (Al-Noor et al., 2012; Karmaker and Das, 2001; Kamruzzaman et al., 2013).

2.7 Environmental Factors & Growth

2.7.1 Temperature and Growth:

The initial stages of a fish's life cycle primarily involve embryonic development and hatching. To investigate hatching success, fertilized eggs from Australian strain broodstock of *Lates calcarifer* were incubated under different temperature regimes, with 30°C identified as the optimal temperature for hatching (Thépot & Jerry, 2015). Furthermore, temperature can influence the growth of Asian sea bass. For example, a study involving 6,000 juveniles, collected from the natural environment with an initial weight of 86.82 ± 1.9 g, reported an average daily weight gain of 2.51 g at 24.8°C and 28.3°C (Mostofa et al., 2024). A similar study conducted by Katersky and Carter (2005) demonstrated that the growth rate was proportional to the temperature increase, with the optimal temperature for growth in the range of 27–36°C. Moreover, the growth performance of the fish can be influenced by both temperature and body size. A 26-day experimental study conducted under six temperature regimes for both smaller fish (≈21 g) and larger fish (≈147 g) revealed that the average growth of smaller fish was highest at 29.1 °C, whereas larger fish exhibited maximum growth at 32 °C (Bermudes *et al.,* 2010). Myogenesis (muscle formation) is also affected by temperature in *Lates calcarifer*. Although a study conducted at Northern Fisheries Center demonstrated a proportional relationship between temperature and hatching time, with the greatest total length gain at 31°C, muscle fiber development in Asian sea bass was more pronounced at lower temperatures (Carey et al., 2009).

Additionally, in a 12 - week trial at 26.5–29°C,Catacutan and Coloso (1997) evaluated the effects of varying carbohydrate and lipid levels on juvenile bass and observed a significant daily growth rate of 0.39–0.67 g/day. Fish should be cultured within their thermal tolerance range. Two different experiments were performed within the thermal tolerance range of *L.calcarifer* (21–39 °C). The results revealed a significant change in the growth rate of Asian sea bass, with growth increasing progressively from 27 to 36 °C, while lower growth was observed at 21 and 39 °C (Katersky & Carter, 2007). In the natural environment, temperature, size and seasonal changes influence the daily weight gain of fish. For instance, juvenile *L.calcarifer* (initial weight 2.5g) reared at 26.25–29.2°C exhibited a daily weight gain of 0.21–11.13 g/day, with the highest growth occurring in the pre-monsoon and the lowest growth in the post-monsoon season (Anil et al., 2010). To test the adaptability of two geographically distinct *L.calcarifer* populations (southern and northern) under three temperature regimes, results showed that 22°C favored southern species; however, 28°C was considered optimal for both populations(Newton et al., 2013). Similarly, for European sea bass *(Dicentrarchus labrax*), growth rate increased with rising temperature, and the highest growth was observed at 1.881–1.917 g/day at 24.9°C (Person-Le *Ruyet et al.,* 2004). Species such as *Cirrhinus mrigala* also exhibited this trend, with the highest weight gain observed at 30 °C.

2.7.2 Salinity & Growth

Salinity must be maintained at a constant level during experimental studies. For instance, in an experimental hatching study, salinity was maintained at 30‰, whereas in another study, salinity was maintained at 32‰, where the weight gain ranged from 0.39–0.67 g day^{-1} Carey et al., 2009; Catacutan & Coloso, 1997). Variations in salinity levels can significantly affect the growth rate of Asian sea bass. Asian sea bass (*Lates calcarifer*) exhibited growth rates ranging from 0.22 to 11.13 g day^{-1} at salinities of 33–35 ‰, while a more stable growth of 1.881–1.917 g day^{-1} was recorded at 34.9–35.1 ‰ (Anil et al., 2010; Le Ruyet et al., 2004). To investigate growth efficiency in hyper saline conditions, a study at three feeding frequencies found growth ranged between 1.31-1.48g/day, whereas another study at three salinities for fry and fingerlings found growth and survival remained constant at 10,20 and 30 ppt (Salama, 2008; Sen et al., 2019). Salinity can also effect the osmoregulation process of fish. *L.calcarifer* requires more energy for osmoregulation at 0 and 50 psu, whereas at 35 psu, it expends less energy (Saghafiankho et al., 2020). Daily weight gain can be affected by salinity; for example, at 45 ppt, *L.calcarifer* loses weight regardless of the higher growth observed at 15 ppt and 5 ppt (Partridge & Lymbery, 2008). Although impressive growth (4.75 g/day) was observed in a study conducted in Moheshkhali- Bakhali (Mostofa et al., 2023), fish reared in low to moderate salinity (3.2-12.2ppt) showed a much lower daily weight gain of 0.18 g/day(Insivitawati et al., 2022).

2.7.3 pH & Growth

pH also has a significant effect on the growth of *L,calcarifer.* During the experimental study on hatching, the pH was maintained within the range of 7.95 to 8.15 (Carey et al., 2009). A weight gain of 0.39–0.67 g/day was observed at a pH range of 7.7–8.0 (*Catacutan & Coloso, 1997*).

Variation in the growth of Asian sea bass has been observed across different pH levels, with the highest growth (11.2 g) recorded at pH 8.22, compared to lower growth (1.881–1.917 g) at pH 7.94–8.00 (Anil et al., 2010; Le Ruyet et al., 2004). Several studies maintained the pH level between 7.2 and 7.6 during experiments involving Asian sea bass (*Lates calcarifer*) (Partridge & Lymbery, 2008; Salama, 2008, Golam Mostofa et al., n.d.; Insivitawati, Hakimah, & Chudlori, 2022).

2.7.4 Alkalinity and Growth

At different salinity regimes, the highest daily weight gain (1.00 ± 0.12 g/day) was observed under moderate alkalinity conditions ranging from 126- 162 mg/L.

3.Materials and Methods

To identify suitable growth zones within the Moheshkhali-Bakkhali River estuary across two different seasons, we used an integrated approach to assess how environmental parameters influence the growth of *Lates calcarifer*. The methodology encompassed systematic data collection, model construction, validation, and spatial analysis, combining both in situ measurements and satellite-derived environmental variables.

Advanced statistical modeling techniques, including a Generalized Additive Model (GAM), were applied to examine the complex, nonlinear relationships between key environmental factors and fish weight gain. Geographic Information System (GIS) tools were further utilized to visualize spatial patterns, generate predictive surfaces, and delineate potential high-growth zones within the Moheshkhali–Bakkhali Estuary.

This integrated framework enables a comprehensive understanding of how variations in temperature, salinity, dissolved oxygen, pH, and other parameters influence the growth performance of Asian sea bass. By merging statistical rigor with spatial analytics, the study not only quantifies environmental effects but also pinpoints ecologically suitable zones that support enhanced growth during different temporal conditions in the estuarine environment.

3.1 Study Area

Bangladesh, a South Asian country endowed with a low-lying delta, vast coastline, and tropical monsoon climate, covers approximately 5.5% of the Bay of Bengal's marine area (Asia, 2022; Bangladesh Bureau of Statistics, 2020). Among the three diverse coastal zones of Bangladesh, this study primarily focuses on the eastern zone along the Bay of Bengal, due to its relative stability, dominant accretion dynamics, and lower susceptibility to storm surges (Saddam et al., 2025). Our study area primarily focuses on the Cox's Bazar region in southeastern Bangladesh as the study area, characterized by a low-lying, sediment-dominated coastal plain that is highly prone to erosion. The study area encompasses the southeastern coast of Bangladesh, specifically the Moheshkhali–Bakkhali River estuary, located at 21° 27′ 02″N, 91° 58′ 16″E. Due to its suitability as a breeding and nursery ground for fish, crustaceans, and other estuarine species, the Moheshkhali–Bakkhali River estuary is considered an ideal site for aquaculture. Figure 1 illustrates the areas within the estuary identified as favorable for fish growth.

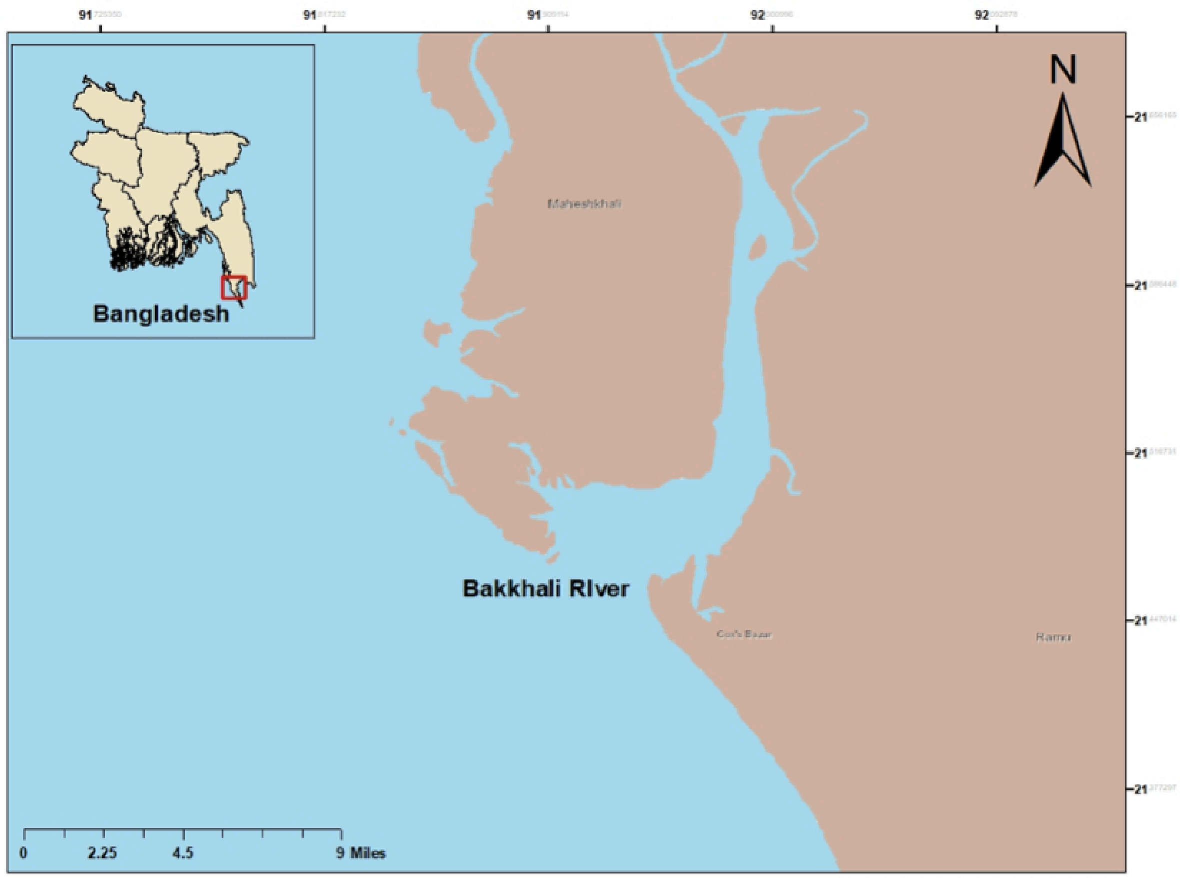

Figure 3.1:Map of the Moheshkhali–Bakkhali Estuary illustrating the complete sampling transect.

3.2 Research Design:

The research design for this study was structured to comprehensively evaluate how key environmental parameters influence the growth of *Lates calcarifer* and to identify the most suitable aquaculture zones for this species within the southeastern region of Bangladesh, specifically across the Bakkhali- Moheshkhali river estuary. The overarching goal of the research was strategically linked to the systematic execution of various methodologies and steps, effectively connecting the research questions to the actions taken. To initiate the research process, careful analysis of acquired material and brainstorming sessions led to the development of a well-defined research theme. The research problem focused on determining the optimal range of environmental parameters in the Bakkhali-Moheshkhali River estuary to identify the most suitable regions that support the better growth of the *Lates calcarife.* This problem was addressed by formulating clear and measurable research objectives.

The primary objective of this study was to identify the most suitable regions for optimal growth of Asian sea bass based on their environmental requirements. A secondary objective was to assess the operational conditions of the Cox,s Bazar's first breeding facility- the

Greenhouse Hatchery- to better understand its role in supporting sustainable seabass production.

Data collection played a pivotal role in this study, where both primary and secondary data sources were utilized. Primary data encompassed temperature and salinity, Do obtained through the use of Conductivity-Temperature-Depth (CTD) profiler. Furthermore, Interviews were done to identify the suitable fisheries area where the most *L.calcarifer was mainly* found.

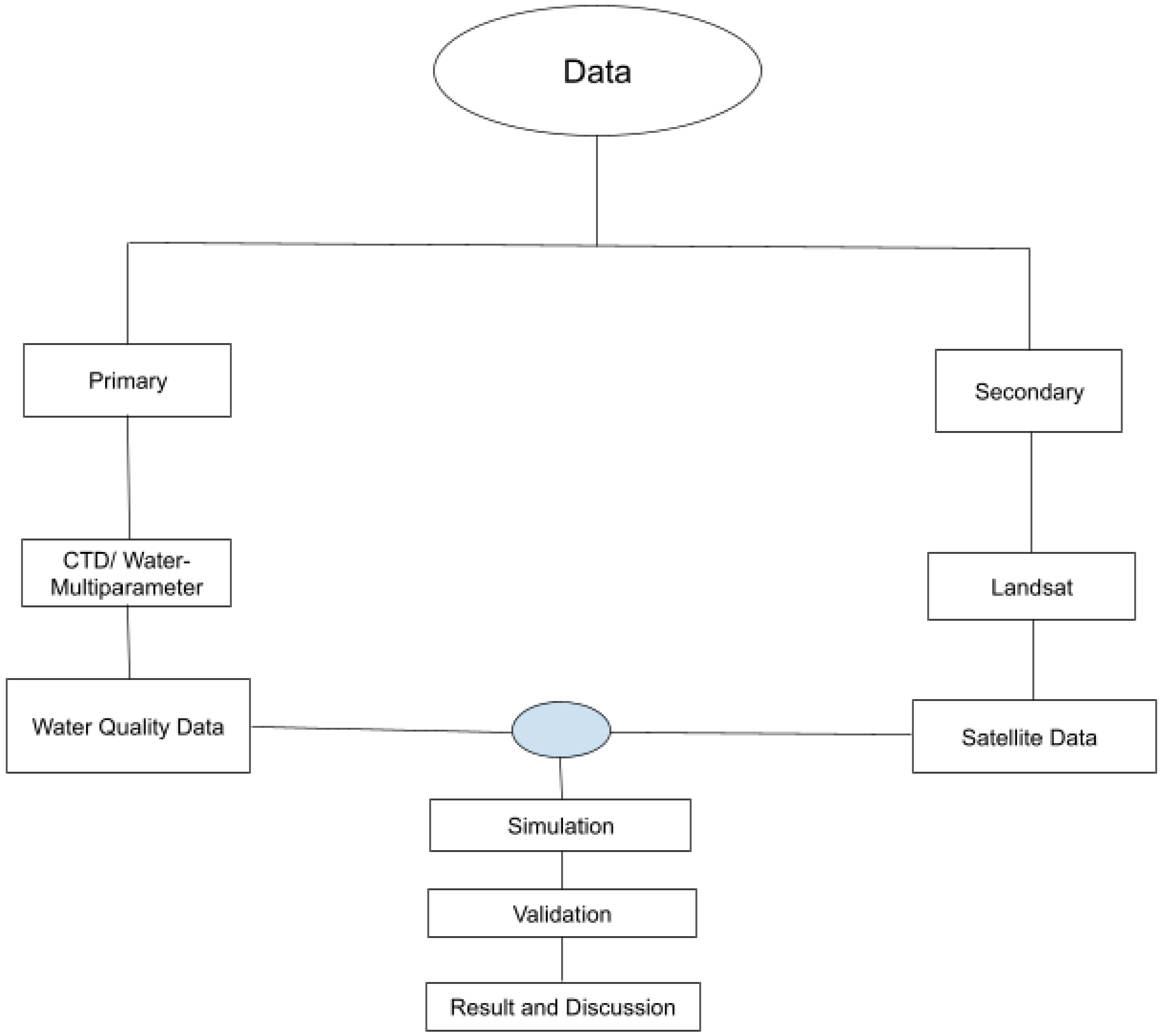

Figure 3.2: Research and Design and approach

3.3 Data collection & Data processing

This study examined the developmental patterns and ecological responses of Asian sea bass (*Lates calcarifer*) within the brackish water environments of southeastern Bangladesh. The investigation encompassed the full production cycle, from controlled hatchery propagation to subsequent growth and maturation under semi-intensive pond culture. Sampling and observations were conducted at two key sites: the Greenhouse Hatchery *(Figure 2),* the first artificial breeding facility for *L. calcarifer* in Bangladesh, and a commercial aquaculture pond in the Khurushkul region, where juveniles were cultured following standard pond management protocol. Location of the Greenhouse Hatchery, Cox's Bazar, Bangladesh.

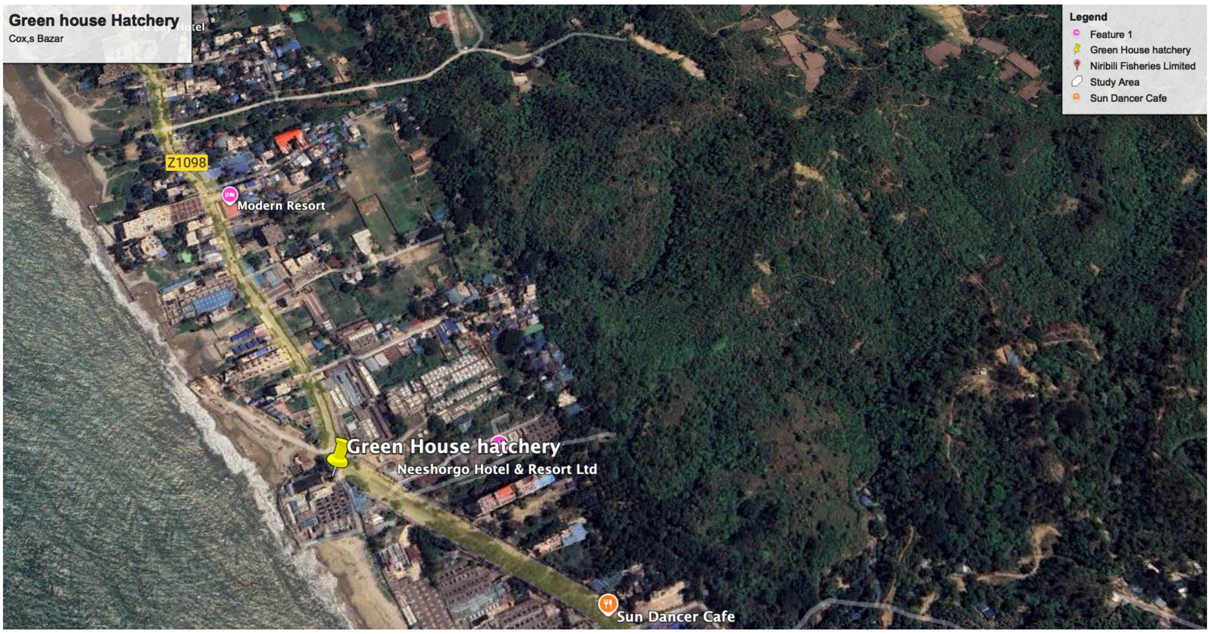

Figure 3.3: Location of the Greenhouse Hatchery, Cox's Bazar, Bangladesh.

3.3.1 Hatchery Environment: Greenhouse Hatchery

Although there were no well-established breeding hatcheries in Bangladesh, we obtained our brood stock from the first successful facility, the Greenhouse Hatchery located in the Cox's Bazar region. We selected this hatchery due to its well-regulated operations, proper maintenance, and effective management practices. Breeding, juvenile, and adult tanks are maintained in separate designated areas within the hatchery. Furthermore, rearing the three developmental stages of this species involves maintaining optimal water quality and implementing proper feeding management. The study was conducted over a ten-month period, from January 2025 to October 2025. Water quality parameters, including temperature, salinity, dissolved oxygen (DO), and pH, were measured using a water multi-parameter analyzer (Model: YSI ProDSS, USA) and a handheld refractometer (Model: ATAGO S-28E, Japan) for precise tank observations. Among all the tanks in the hatchery, the breeding tank was recognized as the most precisely managed and closely regulated unit due to its vital role in facilitating spawning and fry development. To ensure optimal breeding conditions, hatchery staff routinely monitored environmental parameters and recorded feed inputs on a daily basis. For breeding purposes, a total of 30 brood fish were sourced from diverse natural habitats along the coastal region, specifically from the Bakkhali River, Moheshkhali River, Chakaria-Chafaldandi, Sonadia Island, and the Naf River estuary.

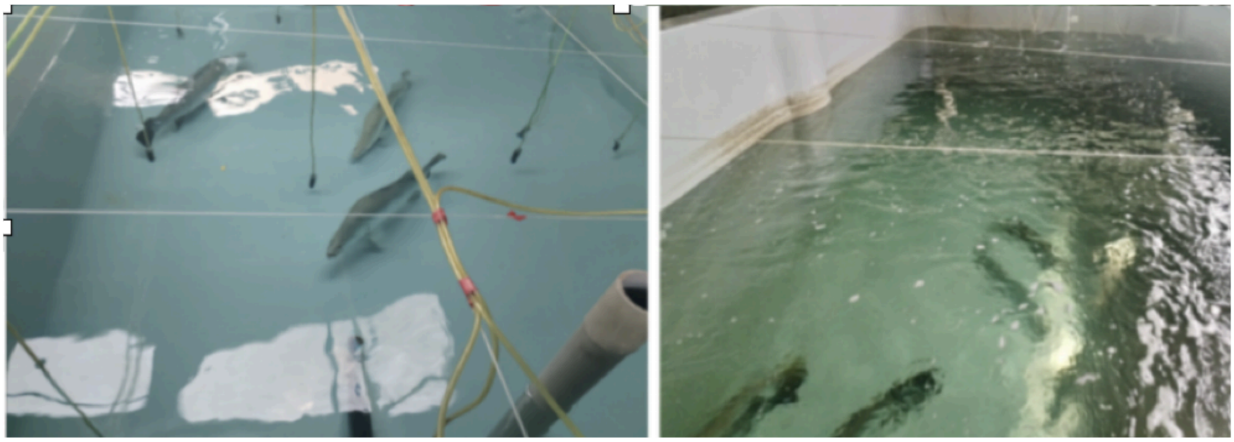

Figure 3.4: The breeding tank used for breeding purposes in the hatchery environment.

Additionally, to ensure optimal health conditions for *L. calcarifer,* proper maintenance of water quality is essential. To enhance water circulation and maintain adequate oxygen levels, a mechanical water purification system was employed to treat seawater directly from the sea (Figure 3.5).

Figure 3.5: Advanced water circulation tank with purification system.

After breeding, the fish fry were transferred to a rearing tank and cultured until they reached the juvenile stage. At this stage, the fry were primarily fed *Artemia,* while the brood fish were provided with shrimp; however, pellet feed was also provided during this time for adjustment.

Figure 3.6:Live shrimp and formulated pellet feed provided for Asian sea bass (*Lates calcarifer*) during the feeding trials.

The juveniles initially did not accept pellet feed, so they were gradually acclimated through a stepwise adaptation process. The pellet feed, formulated following *Catacutan and Coloso (1995)*, contained 35–40% fishmeal, 10–15% soybean meal, 10–15% shrimp meal, 10–15% carbohydrates (wheat, rice bran, corn), and 1–2% binders/others.

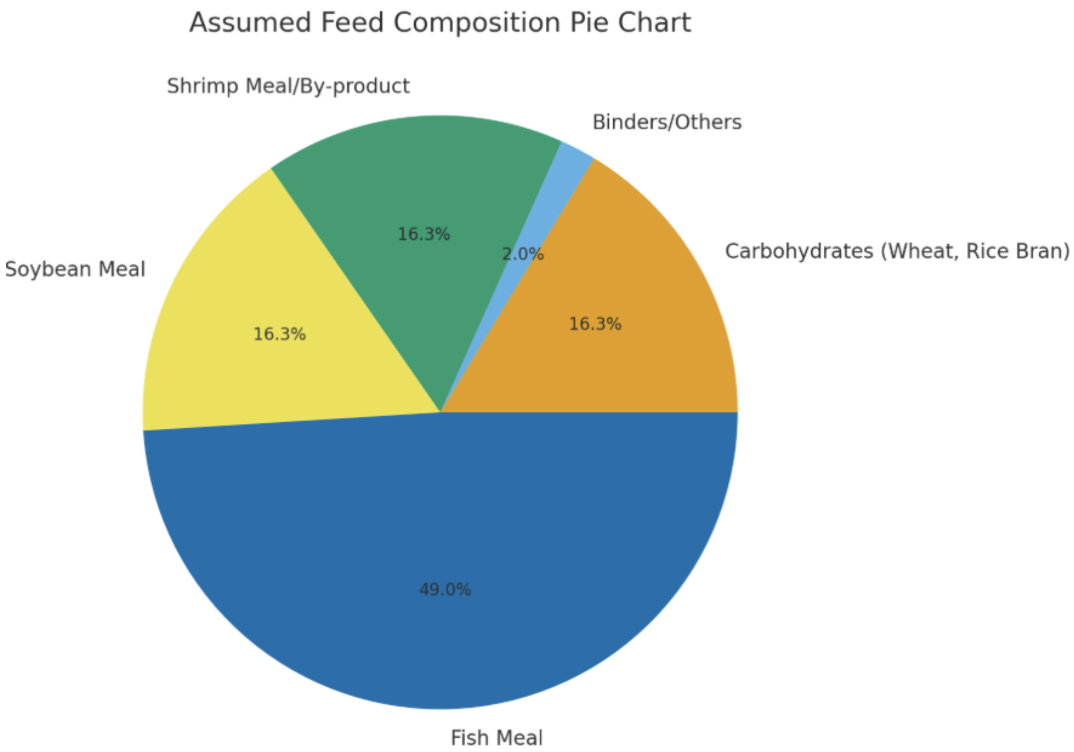

Figure 3.7: Ingredients commonly utilized in formulated pellet feed for Asian sea bass (*Lates calcarifer*) by the hatchery authorities.

Water quality parameters were monitored weekly throughout the study period. Key parameters- including salinity, temperature and pH were measured using a multiparameter water quality probe and refractometer to ensure accurate and consistent environmental assessment.

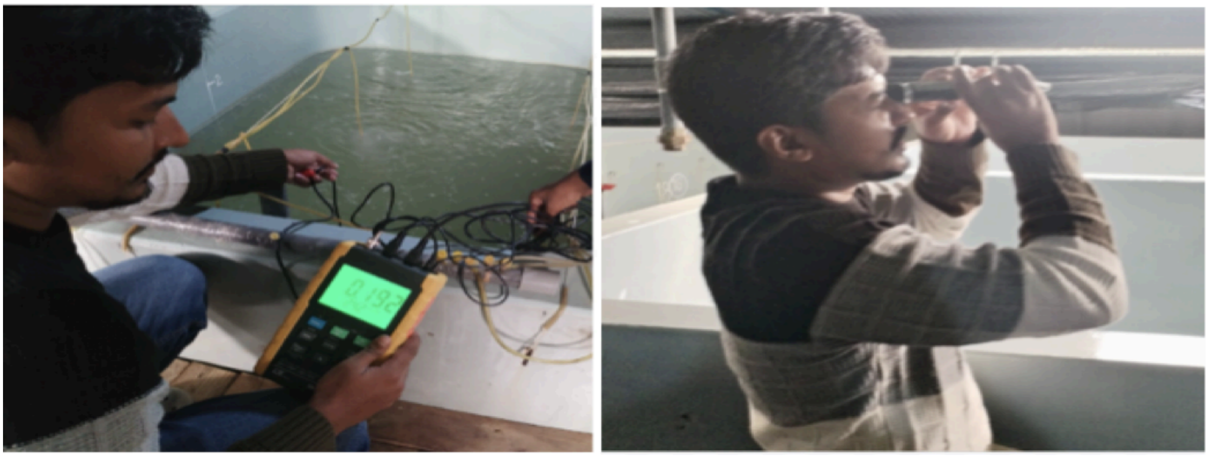

Figure 3.8: Measurement of water quality parameters on a daily basis.

3.3.2 Pond Environment: Khuruskul, Cox's Bazar

After transportation from the hatchery to the pond, the juvenile seabass were initially held in a net cage to allow them to gradually adjust to the new pond conditions. The fish remained in the cage for seven days, during which they were closely monitored to ensure proper acclimatization. Once they showed stable behavior and adapted successfully to the pond environment, they were released into the main pond. Throughout this acclimation period, the survival rate and weight of the juveniles were recorded to assess their condition and overall health.

Figure 3.9:Cages installed within the pond system to facilitate environmental acclimation of Asian sea bass (*Lates calcarifer*).

The study was carried out at a pond located in the Khurushkul area of Cox's Bazar Sadar Upazila. Figure 3.9 presents the geographical position of the aquaculture site. Field observations were conducted from January to December 2025, during which a total of 20 fish species were recorded. The investigation focused on monitoring key water quality parameters—temperature, salinity, pH, and alkalinity—along with the growth rate of the cultured fish within the pond system.

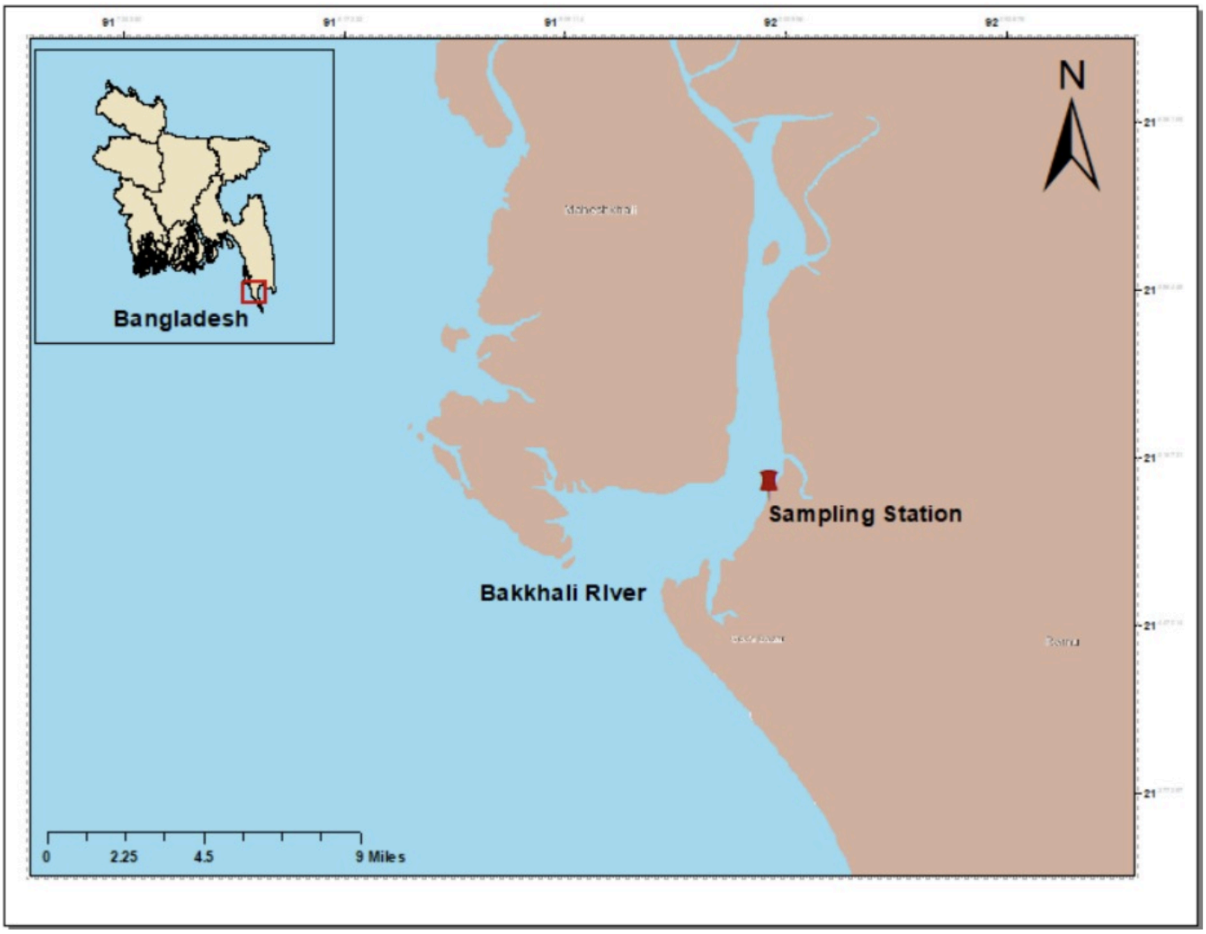

Figure 3.10: Map of the Khurushkul fish farm showing the specific sites where species observations and environmental monitoring were conducted during the study.

We recorded the initial weight of the *L.calcarifer* at the beginning of the culture period and the final weight at harvest. Throughout the culture period, a tracking system was used to monitor individual fish and measure their weight gain over time. After harvesting, all fish were weighed using a digital balance to accurately determine their final weight and assess overall growth performance.

Figure 3.11: Illustration of the cultivated fish species observed in the study.

3.2.3 Collection of Environmental Parameters: Bakkhali River Estuary

For precise assessment of coastal environments, continuous monitoring is crucial. While satellite observations offer important information on coastal water dynamics, obtaining reliable data for narrow water bodies—such as the Bakkhali River—was challenging. The spatial resolution of available satellite products was often insufficient for detailed analysis, and data coverage for this specific region remained limited. To address these constraints, in-situ measurements were conducted within the narrow channel throughout the study period.

However, extensive field-based environmental monitoring is both costly and logistically demanding. Therefore, this study also incorporated a socio-economic and citizen-science approach. More than 100 local fishermen and community members were interviewed to identify areas where *Lates calcarifer* (Asian sea bass) are frequently encountered. Their collective knowledge allowed us to map 12 key fishing hotspots (Figure 10). These identified locations were then selected for systematic monthly environmental data collection.

Based on detailed input from local fishermen, we identified several key locations—Nuniarchara, Nazirar Tek, the Bakkhali estuary mouth, Khurushkul, and the Moheshkhali estuary mouth—as productive areas for Asian seabass. These sites were therefore selected as the primary zones for environmental monitoring. Throughout 2025, we conducted monthly measurements across multiple points within the Bakkhali River estuary, covering both the monsoon and post-monsoon seasons.

Figure 3.12: Identification of Suitable Fishing locations using Stakeholders interviews.

To obtain precise in-situ data, we used a WiMo multiparameter CTD (NKE Instrumentation) along with an Algal Torch (BBE Moldaenke), enabling accurate detection of key water-quality variables at each sampling point.

All field measurements were integrated spatially using ArcGIS 10.8. Environmental datasets from the CTD and Algal Torch were georeferenced using WGS84 GPS coordinates and incorporated into a geodatabase for further analysis. Kriging interpolation was then applied to generate continuous spatial layers representing environmental gradients across the study area.

Figure 3.13: In-situ environmental data collection using a CTD profiler and an Algal Torch instrument.

3.3.4 Satellite Data Collection

Over the course of one year, sea surface temperature (SST) data were obtained from the Copernicus Sentinel-3 satellite data stream. The dataset was derived from the Sentinel-3 SLSTR (Sea and Land Surface Temperature Radiometer), which operates across 11 spectral bands. Specifically, Bands S7, S8, and S9 of the SLSTR sensor were utilized to monitor SST variations. These thermal infrared bands are optimized to detect radiation emitted from the ocean surface, enabling accurate and detailed assessment of spatial and temporal changes in sea surface temperature.

The sea surface temperature (SST) data were processed to Level-2 standards by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). The dataset was processed using SNAP (Sentinel Application Platform) version 8.00 and ArcGIS 10.4.1. SNAP, developed by the European Space Agency (ESA), provided the tools necessary to manipulate and enhance these datasets for image processing purposes. Initially, daily swath data were mosaicked, and the study region was extracted using SNAP software. These mosaicked files were then aggregated into monthly datasets through Level-3 binning, achieving a spatial resolution of 4 km per pixel. Subsequently, the processed SST data were prepared for further analysis in ArcGIS, ensuring they were ready for spatial visualization and integration with other geospatial data layers.

3.3 Fish Growth Rate Modeling Approach

Hastie and Tibshirani developed the Generalized Additive Model (GAM) to examine the relationship between a single response variable and one or more predictor variables (Hastie & Tibshirani, 1990). This method is flexible and effective for performing non-linear regression analysis (Dominici, 2002). By utilizing smooth functions as regressors, GAM achieves greater flexibility compared to linear regression models (Simpson, 2018). At the initial stage of habit modeling, multicollinearity among explanatory variables was assessed using Variance Inflation Factor (VIF) analysis and Spearman's rank correlation. When fitting a GAM, it is important to consider multicollinearity among predictor variables, particularly when including multiple environmental factors such as temperature, salinity, pH and alkalinity. Multicollinearity occurs when predictor variables in a regression model are highly correlated with each other (Graham, 2003). Testing for multicollinearity before running a GAM is crucial to ensure that predictor variables are not highly correlated, as this can distort coefficient estimates and impair model interpretation and performance.

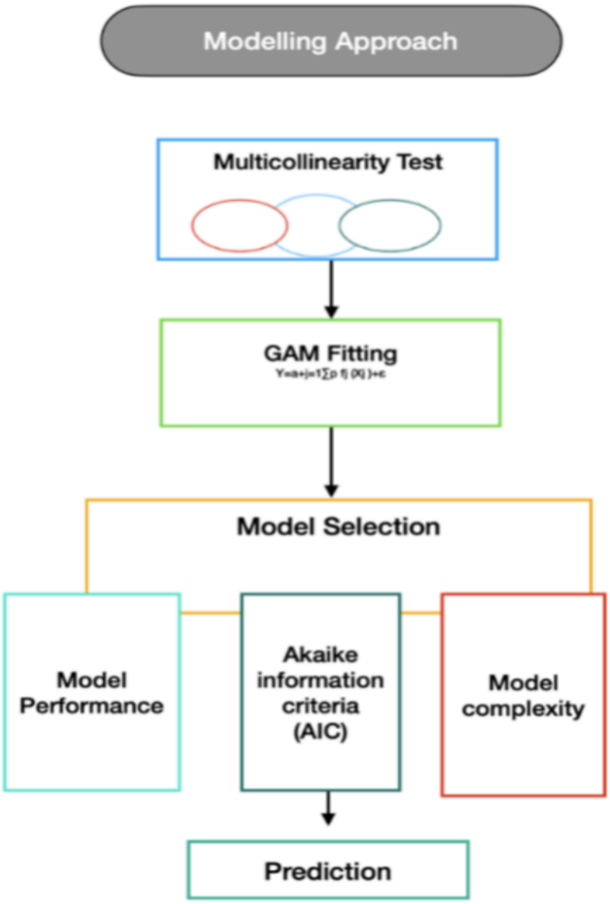

Figure 3.14: Diagrammatic representation of the analytical workflow used to model the growth rates of *Lates calcarifer*.

The model is expressed as:

$$Nit = \alpha + f1(Tit) + f2(Sit) + f3(pHit) + f4(DOit) + \beta Seit + \varepsilon it$$

Where, N= The response variables describe the fish growth rate at location i and Time t.

a = The intercept term.

X: Predictor variables (temperature, salinity, pH, alkalinity) at location i, for the j-th variable, at time t.

fj: Smooth functions applied to the predictor variables Xij, allowing for modeling of non-linear relationships. The Generalized Additive Model (GAM) allows flexible, non-linear relationships between each predictor and the response variable.

β: Coefficient for the season factor.

c: Error term capturing the residuals or noise in the model. This represents the random variability in the response variable that is not explained by the predictor variables and their smooth functions.

4.Results

4.1 Hatchery environment

We analyzed the hatchery environmental data to identify the optimal ranges of water quality parameters, feeding rates and other management factors maintained throughout the rearing period.

4.1.1 Breeding Tank

For breeding purposes, the hatchery maintains a highly regulated and well managed tank, which functions as the designated breeding tank.Improving breeding performance and achieving higher survivability were the main objectives of the hatchery; therefore, the carefully adjusted the thank condition to mimic the natural environment.Like assessing dataset quality, univariate analysis forms the basis for advanced analytical procedures. Therefore, we performed box-plot analysis on the hatchery's environmental dataset to understand the distribution patterns.

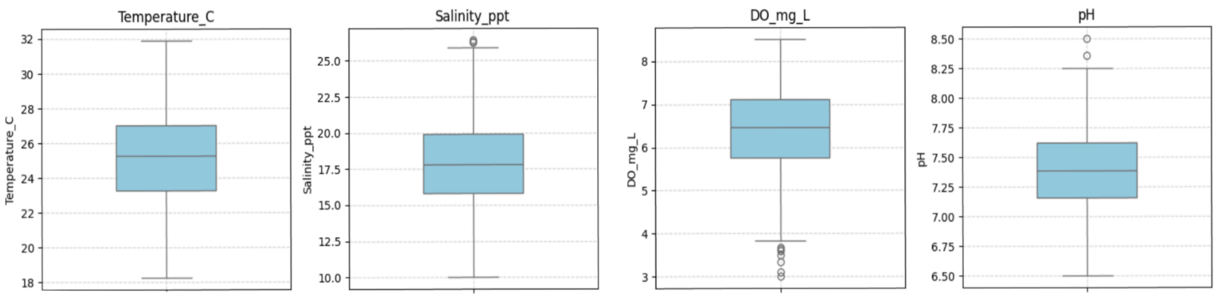

Figure 4.1:Box-plots showing the distribution of environmental parameters (Temperature, Salinity, pH, Dissolved Oxygen) in the hatchery dataset.

The box-plots illustrate that the optimal ranges of the hatchery environmental parameters over the 8-month period were: temperature 23.28–27.03°C, salinity 15.83–19.91 ppt, pH 7.16–7.63, dissolved oxygen (DO) 5.75–7.11 mg/L.
Monitoring seasonal trends helps to understand the critical role of maintaining stable environmental parameters for hatchery performance. We observed variations in environmental parameters across different seasons.Temperature was lower during the winter months and increased during the summer months, while salinity decreased in the summer before rising again in subsequent months. Minimal changes in dissolved oxygen (DO) were observed, likely due to continuous monitoring and management by the hatchery authorities.

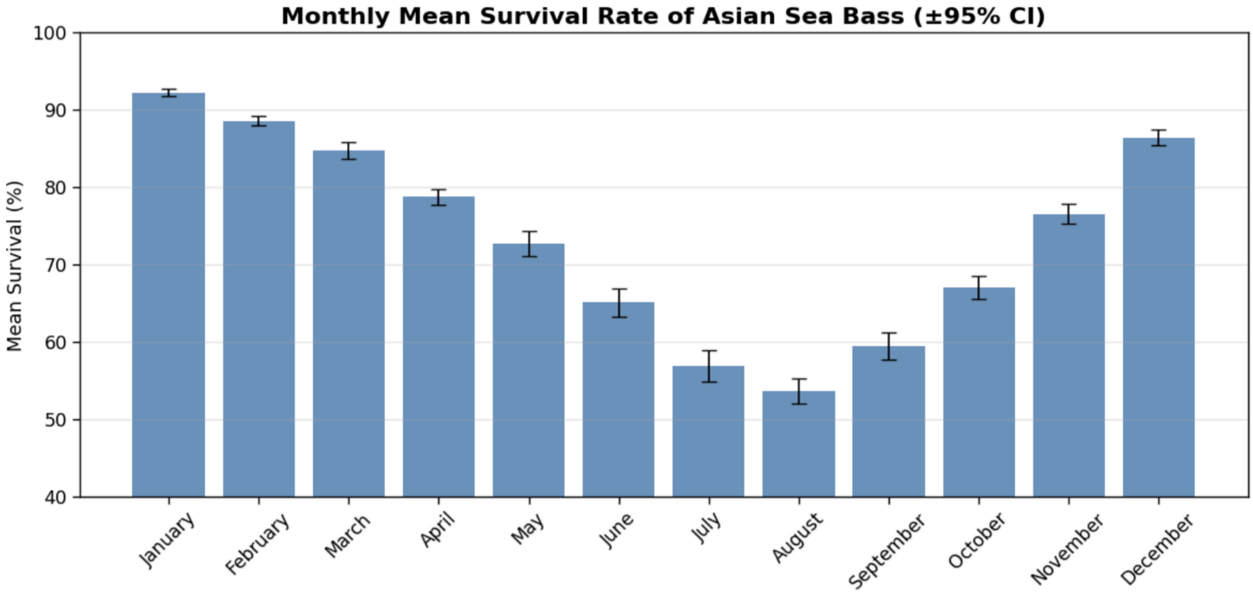

Figure 4.2: Monthly survival patterns of Asian sea bass *(Lates calcarifer)* reared in a controlled greenhouse hatchery.

Sixty-four broodstock individuals sourced from the natural environment were maintained under controlled hatchery conditions.Survival exhibited strong seasonal variability, peaking during December-January and March, and declining markedly during June-August.

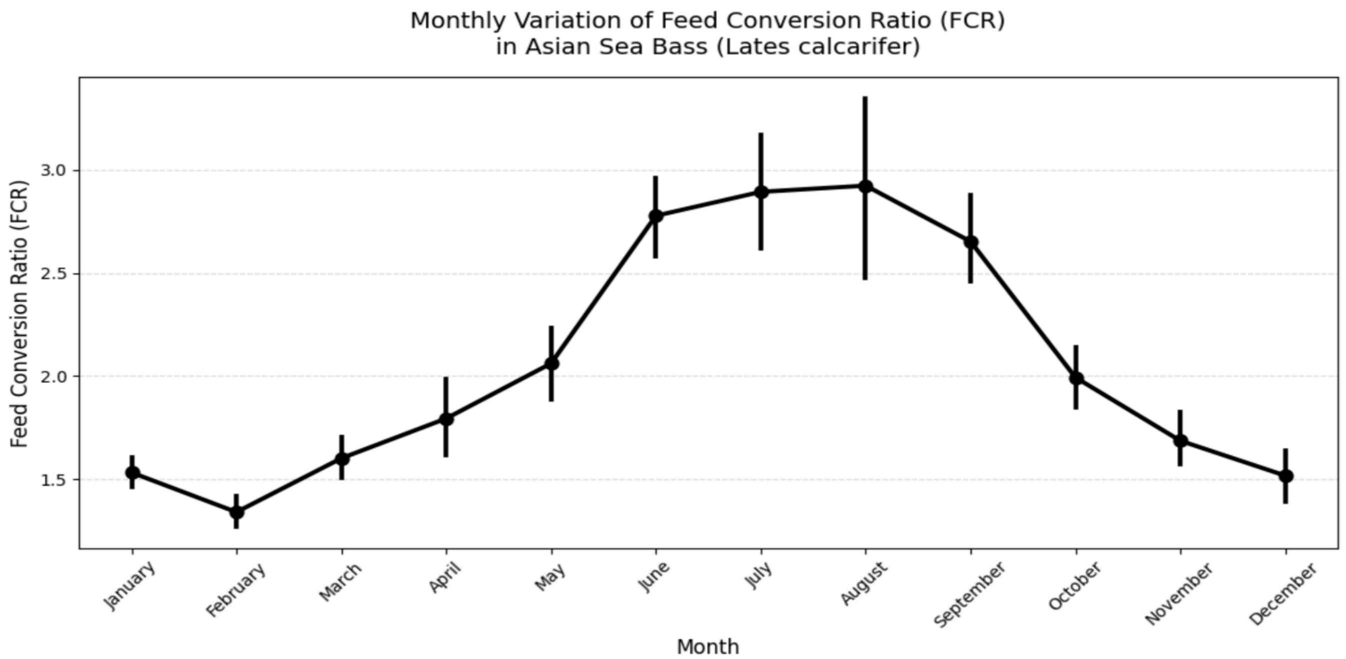

Figure 4.3: Monthly fluctuation of the feed conversion ratio (FCR) in the breeding tank of Asian sea bass (*Lates calcarifer*) throughout the year.

Month	Mean FCR	Standard Deviation (SD)	Minimum FCR	Maximum FCR
January	1.53	0.13	1.37	1.73
February	1.34	0.13	1.20	1.54
March	1.60	0.18	1.34	1.97
April	1.79	0.32	1.33	2.40
May	2.06	0.32	1.53	2.52
June	2.78	0.34	2.28	3.17
July	2.89	0.48	2.24	3.65
August	2.92	0.79	1.43	3.86
September	2.65	0.37	2.20	3.34
October	1.99	0.25	1.49	2.42
November	1.69	0.22	1.35	2.17
December	1.52	0.22	1.20	1.97

Table: 4.1: Monthly feed conservation ratio of the *(Lates calcarifer)* in the breeding tank of the Asian sea bass hatchery.

To understand fish growth and survival performance, the feed conversion ratio (FCR) is an important indicator that measures how efficiently fish convert feed into body biomass. A lower FCR indicates higher feed conversion efficiency, whereas a higher FCR reflects poor feed utilization.

$$FCR = Total\ Feed\ Consumed\ /\ Total\ Weight\ Gain$$

Different feed conversion ratios (FCR) were observed during the breeding period of Asian sea bass, with values ranging from 1.34 to 2.92. The lowest mean FCR was recorded in February (1.34 ± 0.13), followed by December (1.52 ± 0.22) and January (1.53 ± 0.13). Similarly, relatively low FCR values were observed in March (1.60 ± 0.18) and November (1.69 ± 0.22).

In contrast, higher mean FCR values were recorded during the mid-year period, with the highest mean FCR in August (2.92 ± 0.79), followed by July (2.89 ± 0.48) and June (2.78 ± 0.34). Moderate FCR values were observed during April, September, and October.

For ensuring the effects of environmental variables (Temperature, salinity, pH, Do) on weight gain and for predicting accurate fish growth, ViF is important because it detects multicollinearity among these variables. If predictors are highly correlated, the model can not correctly identify their individual effects, making prediction unreliable.We observed that the VIF values for these variables were less than 2, indicating very low multicollinearity. Moreover, we also performed a multicollinearity test on our dataset.

We conducted a correlation analysis to examine the presence of multicollinearity among the four explanatory variables used in this study: temperature, salinity, pH, and dissolved oxygen (DO). The results (Figure 1) indicate no significant correlations among these variables. Additionally, the Variance Inflation Factor (VIF) values for all variables were found to be below 2, confirming the absence of multicollinearity. Therefore, all variables were considered suitable for use in advanced statistical modeling.
Among the 15 model combinations tested for the four variables, the GAM model incorporating all explanatory variables (temperature, salinity, pH and Do) yielded the lowest AIC value, indicating the best model fit with minimal information loss.

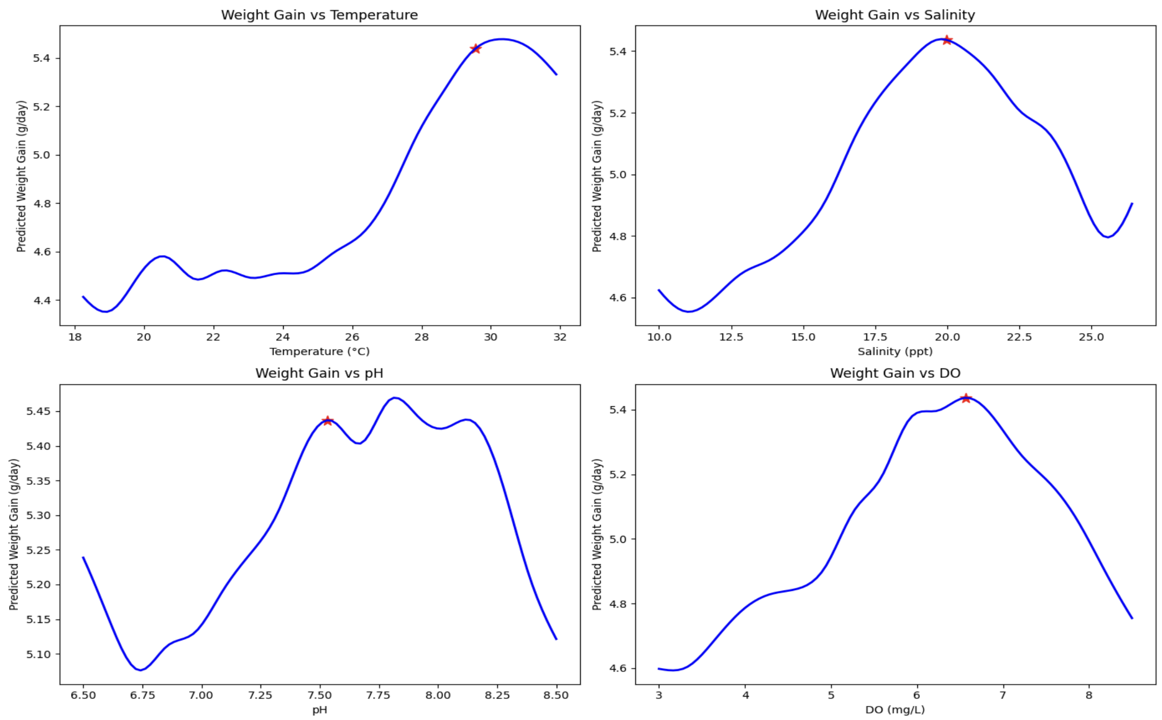

Figure 4.4: Predicted likelihood of optimal growth rate for Asian seabass across varying environmental conditions—salinity, temperature, pH, and dissolved oxygen—modeled using a Generalized Additive Model (GAM).

The modeled relationships between fish growth rate and key environmental variables are shown in the figure. The Generalized Additive Model (GAM) results indicate that higher growth rates are associated with a specific temperature range of 26–30 °C and salinity between 15–22 ppt, with peak growth occurring at approximately 20 ppt. Likewise, optimal growth is observed at dissolved oxygen levels between 5–7 mg L^{-1} and pH values of 7.00–7.75.

Drivers and Model validation:

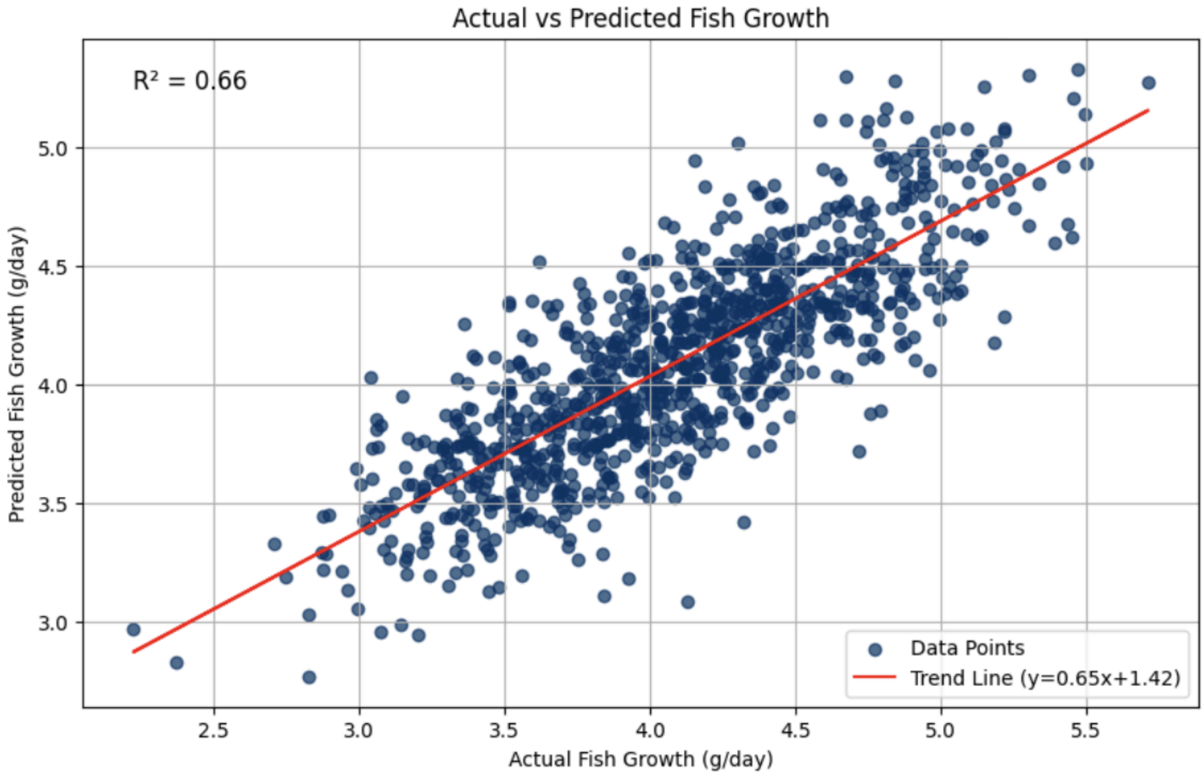

Figure 4.5:Comparison between observed daily weight gain and predicted daily weight gain for model validation in hatchery environment using Generalized additive model (GAM).

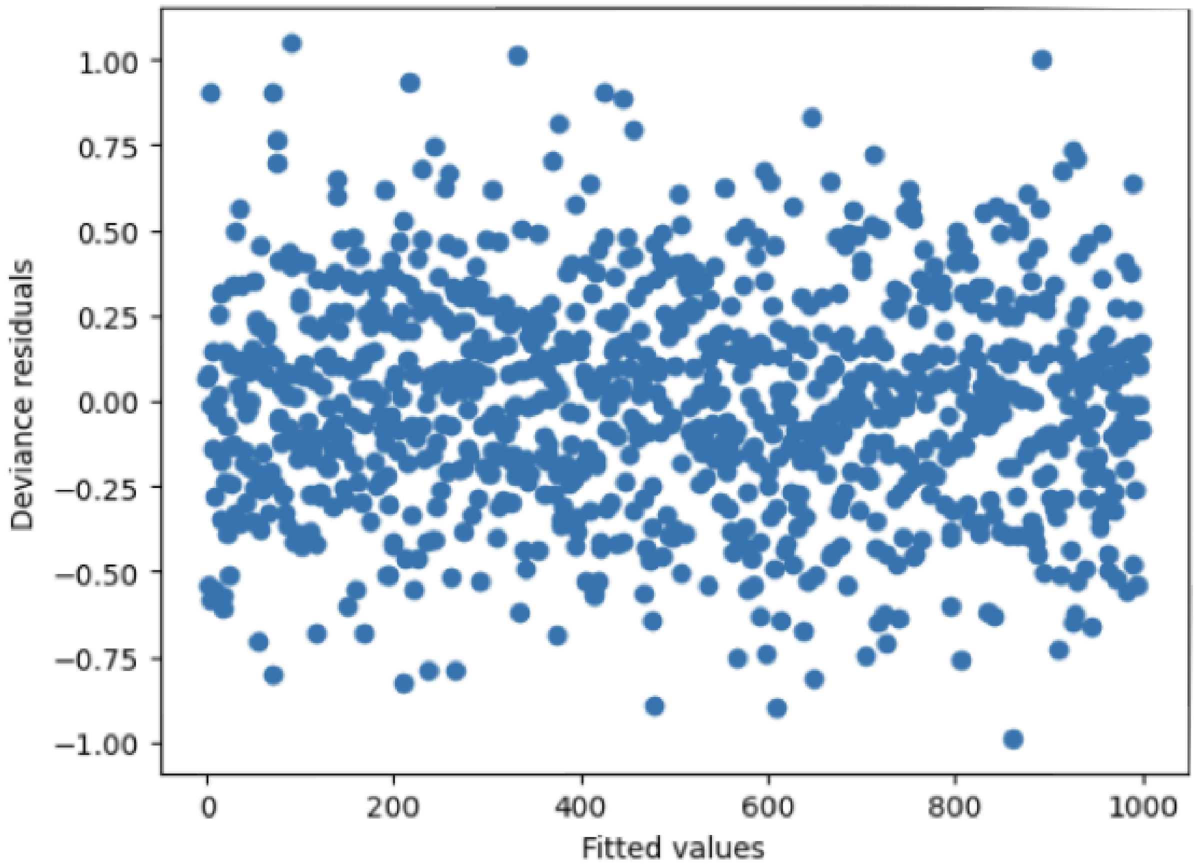

Figure 4.6:Scatter plot illustrating deviance residuals plotted against predicted values for generalized additive model (GAM).

The figures show that the trend line demonstrates a strong positive correlation between the actual and predicted weight gain of fish. This indicates that as the actual growth increases, the predicted weight gain also increases, following a linear relationship. The plot shows an R-squre value of 0.66 which indicates that the model explains 66% of the variability in the actual growth rates.

Residuals plot is another way to evaluate the model's prediction. For this reason, we conducted a residual plot to identify the model's performance. The residuals being roughly centered around zero is a positive indicates that the model fits the data well.

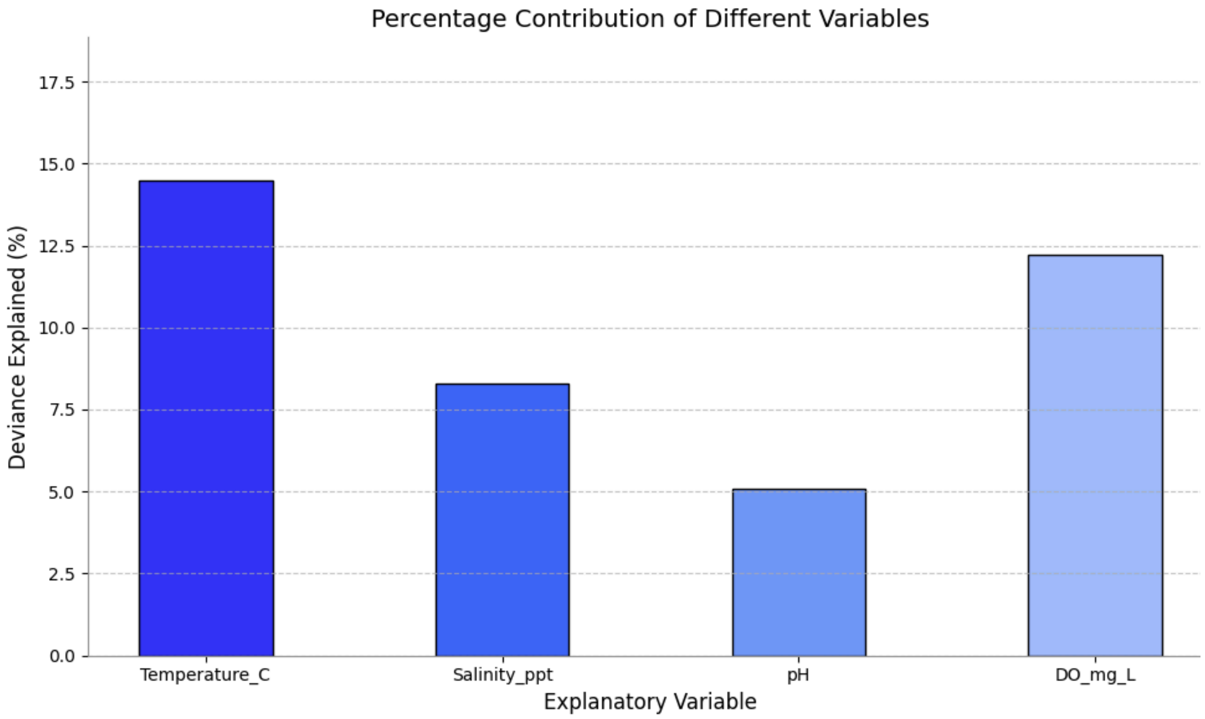

Figure 4.7: Individual variable explanatory power in the Generalized Additive model (GAM) for predicting weight Gain of *Lates calcarifer.*

In our final GAM model, we observed that temperature had the highest impact (14.9%, $p < 0.01$) on fish growth rate variability among the four explanatory variables, followed by salinity (11.21%, $p < 0.01$), dissolved oxygen (9.82%, $p < 0.01$), and water pH (7.8%, $p < 0.01$). The model overall explains about 44% of the variability in fish growth rate for the hatchery environment.

4.2 Environmental Parameters and Growth Zones in the Bakkhali and Moheshkhali River Estuaries

4.2.1: Multicollinearity Assessment and Model Selection

To ensure robust model selection and effectively handle the large-scale open-water environmental dataset, we first conducted a multicollinearity assessment using the five key parameters: temperature, salinity, pH, alkalinity, and dissolved oxygen (DO). The correlation matrix (Figure 4.8) indicates that none of the variables exhibit strong pairwise correlations, and all calculated Variance Inflation Factor (VIF) values were below 2. This confirms that collinearity is not present among the predictors and validates their suitability for inclusion in the Generalized Additive Model (GAM).

Furthermore, To identify the most appropriate model for explaining variations in growth rate in the open- water system, we developed 15 candidate GAMs using different combinations of the environmental variables. The Akaike Information Criterion (AIC) values computed for each model to evaluate their relative performance. Among these models, the GAM incorporating all four explanatory variables- temperature salinity, pH, alkalinity and Do- produced the lowest AIC score, indicating the best balance between model complexity and explanatory power.

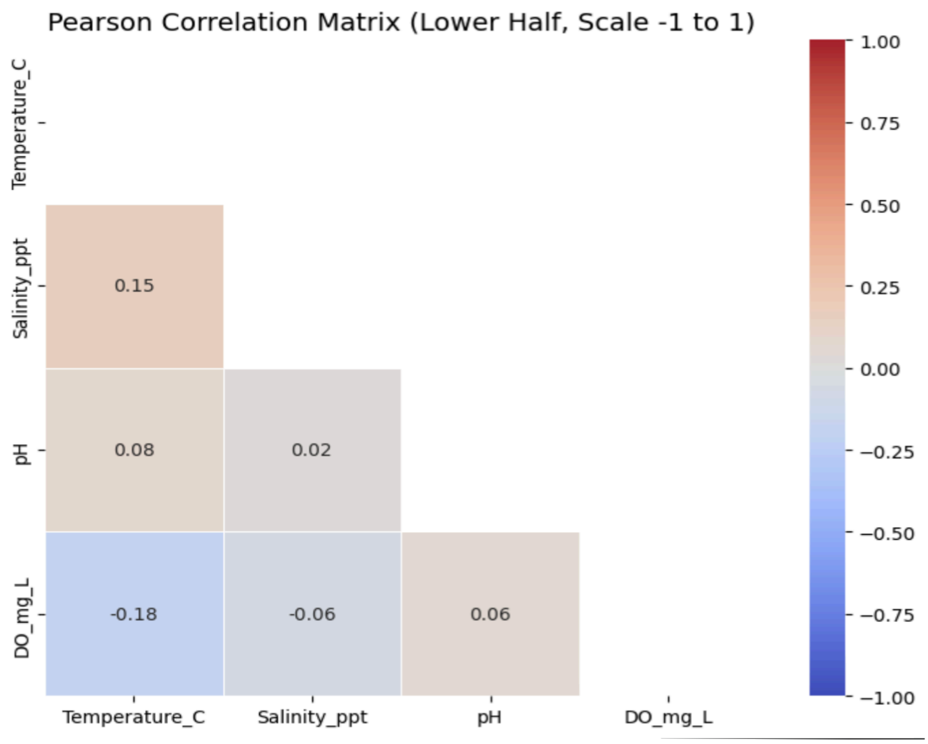

Figure 4.8:Pearson correlation matrix of environmental variables, where **+1** represents the highest positive correlation and **–1** represents the lowest (negative) correlation.

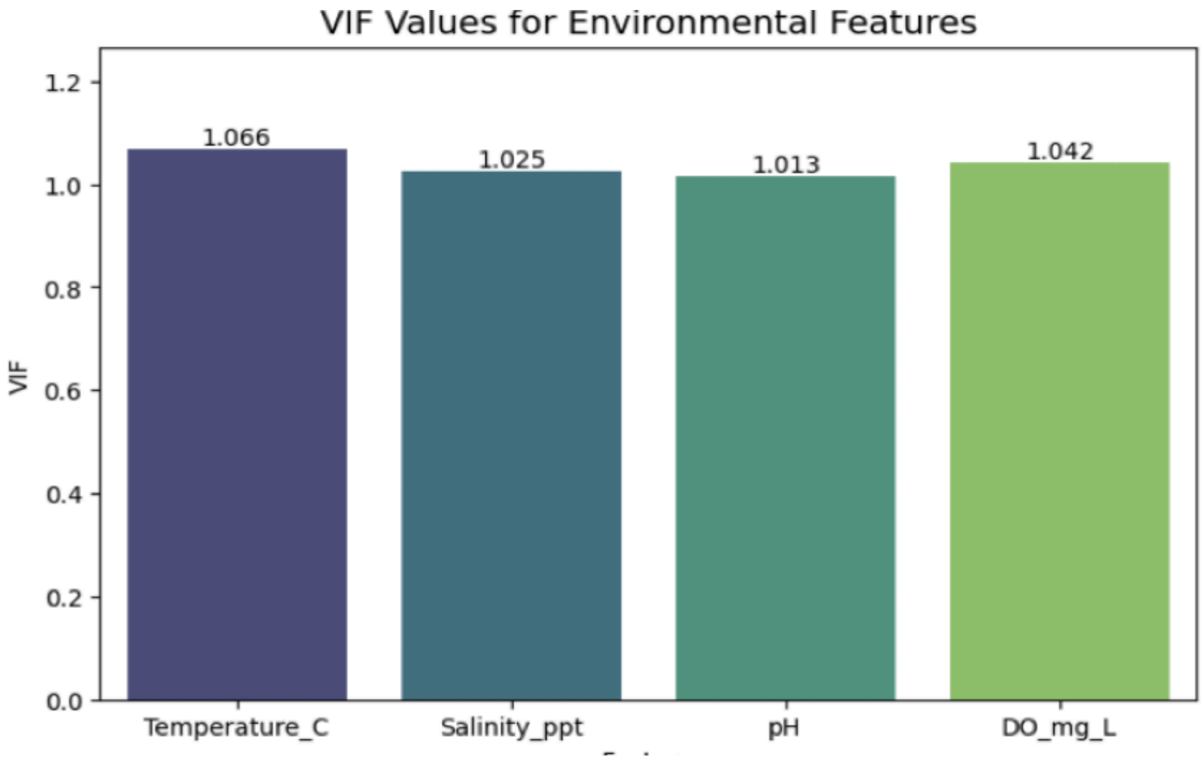

Figure 4.9: Variance Inflation Factor (VIF) values for four environmental parameters (Temperature, Salinity, pH, and DO).

4.2.2 Driver of Fish growth in River

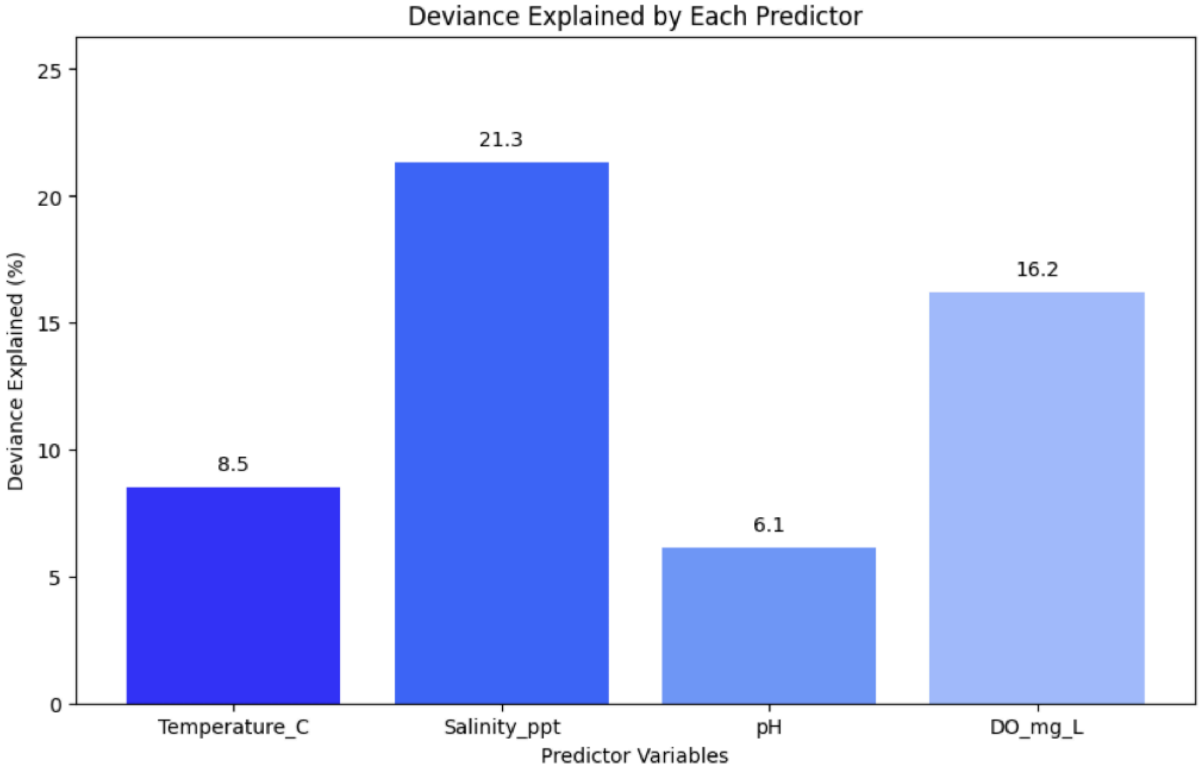

Figure 4.10: Individual Variable Explanatory Power in the Generalized Additive Model (GAM) for Predicting Weight Gain.

In the final GAM developed for the Moheshkhali–Bakkhali River estuary, salinity emerged as the most influential predictor of weight-gain variability, accounting for 21.3% of the explained variation (p < 0.01; Figure 4.9). This was followed by dissolved oxygen (DO), which contributed 16% (p < 0.01). Temperature also showed a notable effect, explaining 8.5% of the variability, while pH contributed 6.1%, both with statistically significant (p < 0.01) relationships.Collectively, these environmental variables explained 51.9% of the total variation in weight gain, highlighting their combined importance in regulating growth dynamics within the estuarine system.

4.2.3 Spatial Maps of Optimal Growth Zones and Environmental Parameter Influence

Figure 4.10 illustrates how fish growth varies between seasons, showing higher growth during the summer—characterized by elevated temperatures, increased rainfall, and fluctuating environmental conditions—compared to the winter season, which is marked by reduced precipitation and more stabilized environmental factors.

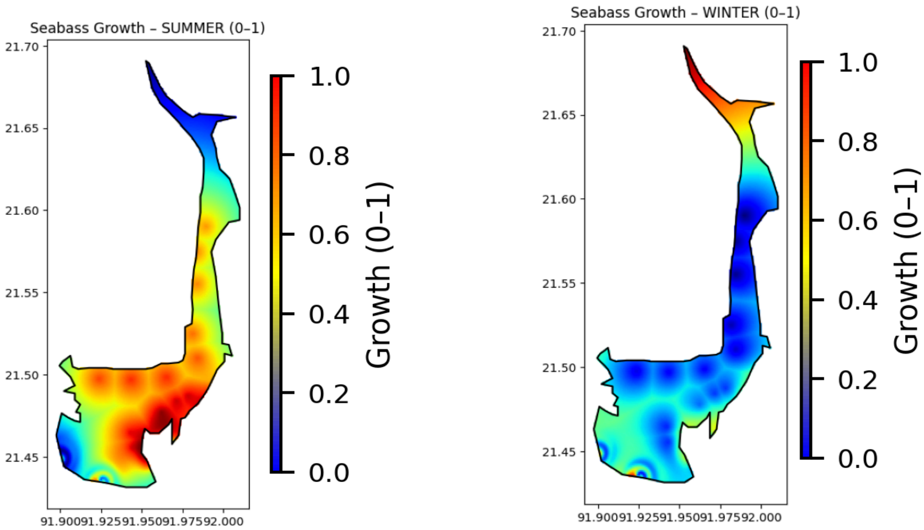

Figure 4.11:- Favorable area for *Lates calcarifer* growth predicted by Generalized Additive Model (GAM) in the Moheshkhali- Bakkhali Estuary a) for the summer season, b) winter season.

The growth rate difference observed between the summer and winter seasons serves explanatory variables such as Temperature, salinity,DO, Ph which is calculated to to fish growth using the GAM model. It is clear that the seasonal fluctuation is affected by environmental factors such as rainfall, river runoff and water temperature and salinity etc.

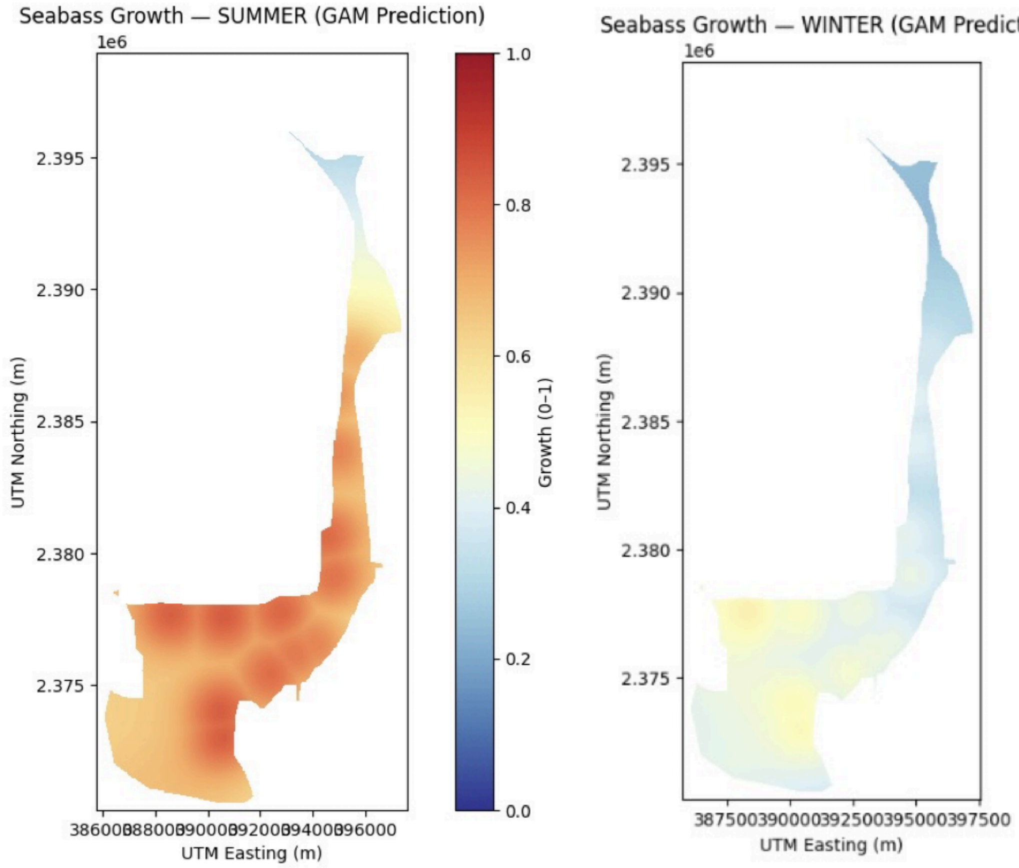

Figure 4.12- Favorable area for *Lates calcarifer* growth predicted by Generalized Additive Model (GAM) in the Moheshkhali- Bakkhali Estuary with prediction scale where +1 indicates the higher growth area and -1 indicates the lowest growth area.

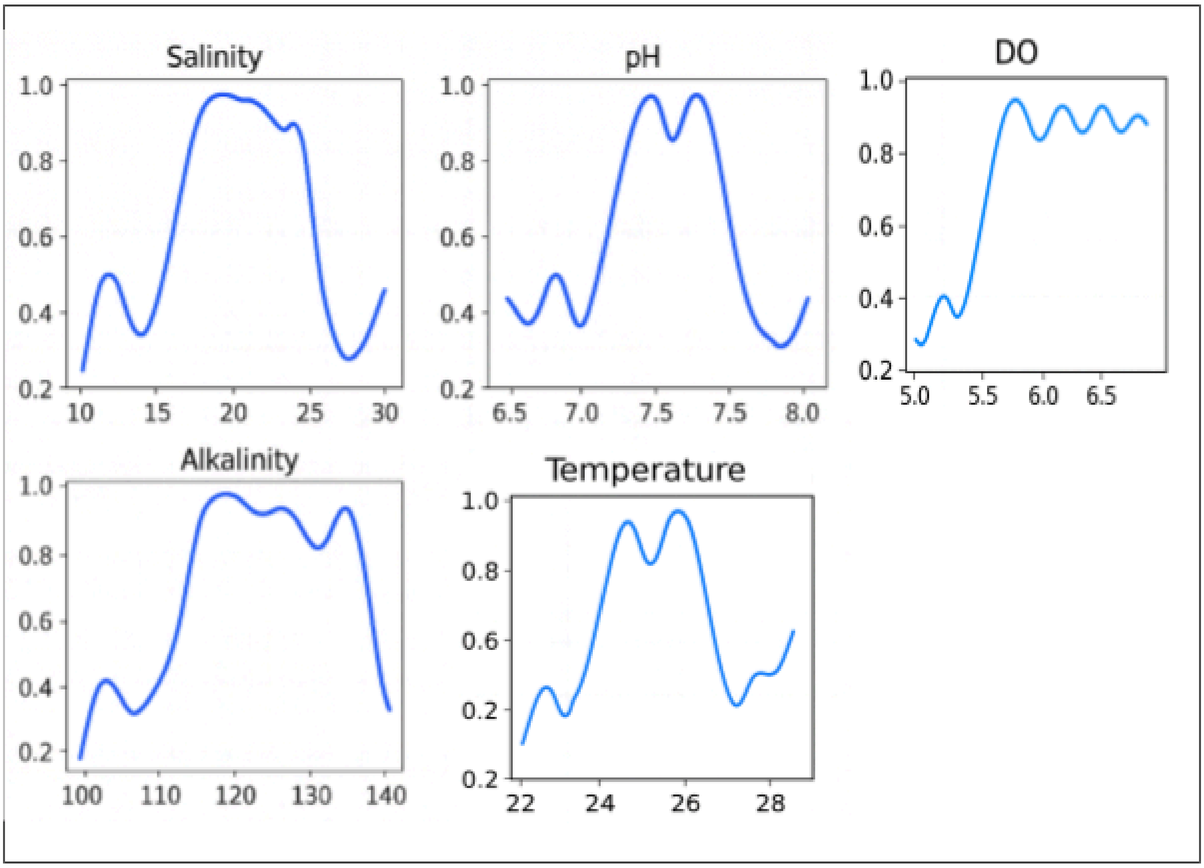

Figure 4.13: Prediction of optimal growth rate likelihood across different environmental conditions (Salinity, Temperature, pH, Do and alkalinity using Generalized additive model.

The modeled relationship between fish growth rate and the key environmental variables is presented in Figure 4.13. The GAM results clearly indicate that higher growth rates of Asian sea bass occur within specific optimal environmental windows. Temperature showed the strongest influence, with maximum growth predicted between 25–28.5 °C. Salinity also had a major effect, with the most favorable range identified between 15–25 ppt. Growth probability increased within a narrow pH range of 6.75–7.50, reflecting the species' sensitivity to acid–base balance in the culture environment. Similarly, dissolved oxygen levels between 5.5–6.5 mg L^{-1} and alkalinity between 111–129 mg L^{-1} were associated with significantly higher growth responses. Together, these results highlight that Asian sea bass growth is highly dependent on maintaining a combination of these optimal environmental thresholds.

4.2.4 Model validation:

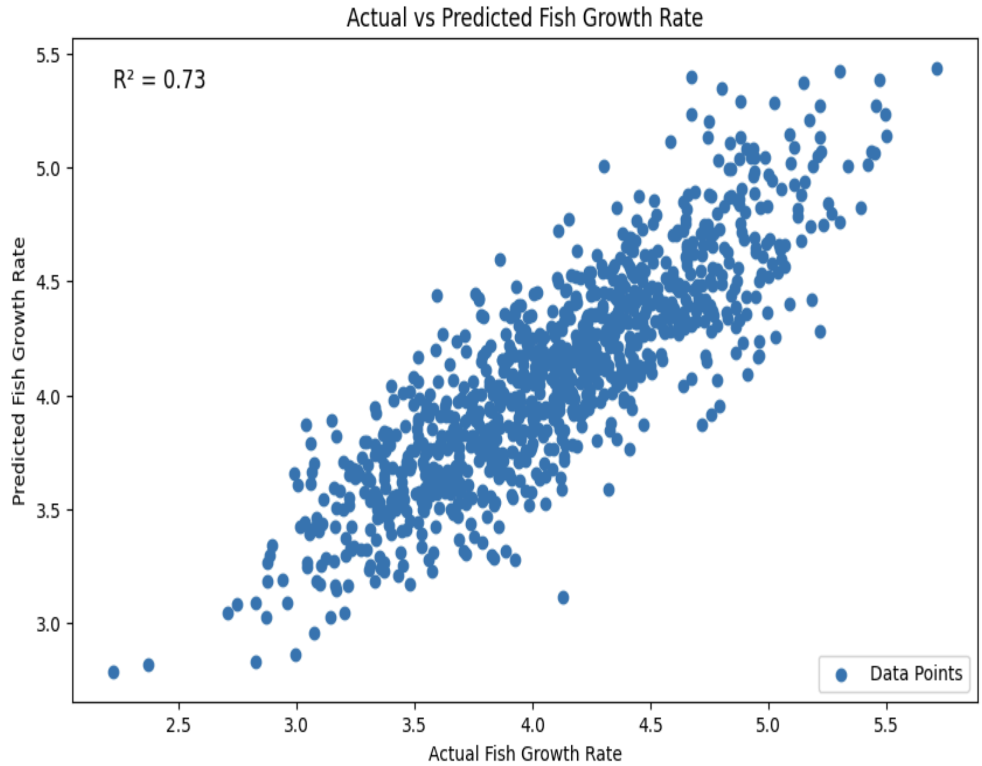

Figure 14: Comparison between observed daily weight gain and predicted daily weight gain for model validation in the Bakkhali and Moheshkhali environments using a Generalized Additive model (GAM).

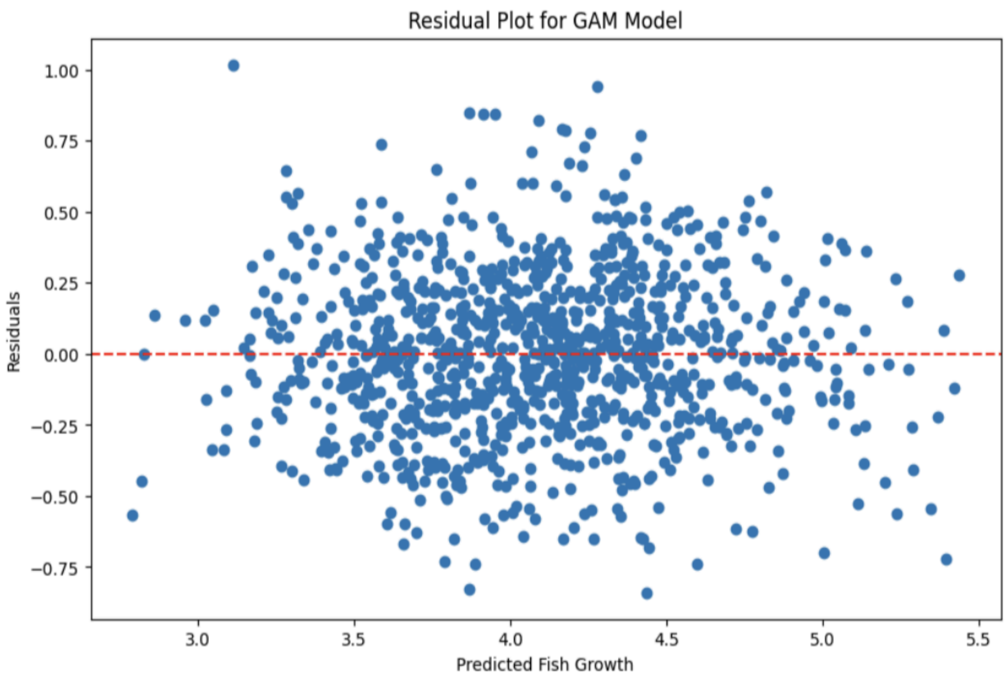

Figure 4.15: Scatter plot illustrating deviance residuals plotted against predicted values for generalized additive model (GAM).

For proper validation of the model, we conducted a regression analysis using an 80-20% data split. The actual and predicted growth values were calculated, and the results showed a strong positive correlation between them. The actual growth exhibited a proportional relationship with the predicted growth, and the R^2 value of 0.73 indicates that the model explains 73% of the variability of the observed growth rates.

Our model shows a relative residual plot, which was used to assess model performance by confirming that the residuals are evenly centered around zero.

5.Discussion

The present study evaluates the influence of key environmental factors on the growth of *L.calcarifer* , using five explanatory variables to assess growth performance and identify regions with optimal conditions for enhanced development.

5.1 Environmental driving factor for the fish growth

According to our model, salinity was the key driving factor for predicting weight gain.
(Effendi et al., 2023) determined that the optimal salinity for the growth of the Asian sea bass is 25 to 30 ppt. According to (Haque et al., 2023) and (Mostofa et al., 2023), *Lates calcarifer* thrive and grow within salinity range from 22.6- 35 ppt. Studies on the optimal salinity range for the growth of *Lates calcarifer* (Asian sea bass) have yielded varied results, including 15 ppt (Yusof et al., 2024), 10–25 ppt (Nhan et al., 2022), 10–20 ppt (Akram et al., 2024), 22 ppt (Hassan et al., 2021), and 10–25 ppt (Partridge & Lymbery, 2008). Our model predicted a suitable environment with salinity ranging from 15 to 25 ppt which aligns closely with previous studies that have shown this range to affect growth significantly.
Salinity is a critical factor in Asian sea bass culture, as fluctuations in this variable directly affect growth rate and overall production. Therefore, salinity variability remains a key concern for successful Asian sea bass farming, and our study aligns with previous findings demonstrating its significant influence on growth. While (Mostofa et al., 2023) reported a higher daily growth rate of 4.75g at 28-32 ppt compared to 0.79 at 20 ppt (Sen et al., 2019), our study's findings contradict with this low salinity trend. Other studies- including MAB Journal (2023), Wijayanto et al. (2021), Aquaculture (1994), and Aquaculture (2004) also reported an optimal salinity range of 15–28 ppt for *Lates calcarifer,* which closely aligns with the salinity range predicted by our model for suitable growth.
The second highest explanatory variable in our model is dissolved oxygen which affects the growth of *L.calcarifer* and our model predicted the Do value 5.5 -- 6.5 mg/L which was prior research quite similar. Mostofa et al., Anil et al. (2010), Salama and Al-Harbi (2007), and Wijayanto et al. (2021) reported that the optimal DO range for *Lates calcarifer* lies between 5 and 8 ppm, which closely aligns with our findings, indicating that DO is a key factor influencing the growth of Asian sea bass.Furthermore, in our model, dissolved oxygen accounted for 16.2% of the explained variance, indicating that this variable significantly

influences the growth of *L. calcarifer*. Several countries—including Australia, Saudi Arabia, the Philippines, Malaysia, Singapore, and Thailand—maintain dissolved oxygen (DO) levels strictly during Asian seabass culture, generally recommending a range of 5–9 mg/L. This recommended range aligns well with the DO conditions observed in our study (Carton et al., 2013), (Akram et al., 2024),(Ghosh et al., 2016),(Yasmin et al., 2023).

Temperature plays a critical role in the survival and growth of Asian sea bass *(Lates calcarifer).*

Previous studies have demonstrated that temperature significantly influence their growth.For instance, a temperature of 29.1 °C was associated with a maximum daily weight gain of 1.42 g/day, while growth declined dramatically at higher temperatures of 36–39 °C. Moderate temperature ranges, such as 26.5–29 °C, resulted in a daily weight gain of 0.90 g/day, and a narrower range of 27.1–28.6 °C supported optimal growth with daily weight gains between 1.31 and 1.48 g/day (Anil et al., 2010; Panchakshari, 2016; Barlow et al., 1993; Mostofa et al., 2023; Insivitawati et al., 2022). This study shows similar results using this gam model to predict higher growth rates between 25.5 to 28.5 degree celsius temperature. Temperature was also identified as a driving factor with our model explaining growth rate variation of the Asian sea bass.

Asian sea bass *(Lates calcarifer)* experience less physiological stress at neutral to slightly alkene pH levels because their erythrocytes (red blood cells) actively regulate intracellular pH to maintain oxygen transport capacity during periods of acidosis Paterson et al. (2003). Studies have shown that the optimal pH range for the growth of *Lates calcarifer* is between 7.2 and 8 (Carton et al., 2013; Akram et al., 2024; Ghosh et al., 2016; Yasmin et al., 2023), which aligns with our findings where the GAM model predicted higher growth probability within a pH range of 7.2–7.8.

5.2 Fish favorable growth condition region

Employing a Generalized Additive Model (GAM), we identified specific zones within the Moheshkhali- Bakkhali estuary where growth conditions for Asian sea bass *(Lates calcarifer)* are optimal. By integrating four key explanatory variables—temperature, salinity, dissolved oxygen (DO), and pH—our model demonstrated a strong capacity to predict habitat suitability. The analysis revealed distinct seasonal variations; specifically, the model predicted a significantly larger area of favorable growth conditions during the summer compared to the winter.This seasonal expansion can be attributed to environmental shifts driven by the monsoon. Heavy rainfall during summer increases river runoff, resulting in a substantial freshwater influx that dynamically alters salinity, temperature, pH, and DO levels within the estuary. These environmental patterns align closely with the species' reproductive biology. According to Haque et al. (2023), the peak breeding season for *L. calcarifer* in Bangladesh occurs from April to June, which coincides with the summer monsoon transition observed in our study.This synchronization suggests that these environmental parameters play a critical role in determining both optimal breeding and growth conditions.

Consequently, the Moheshkhali-Bakkhali estuary emerges as a prime candidate for sustainable aquaculture initiatives. The region's biodiversity and favorable physicochemical profile make it an ideal location for promoting environmentally friendly farming practices. Developing this area for sea bass culture aligns with sustainable development goals by ensuring a harmonious balance between ecological conservation and economic viability.

6.Conclusion

The impact of environmental parameters on the growth of Asian sea bass in the Moheshkhali–Bakkhali estuary on the southeast coast was assessed using a Generalized Additive Model (GAM). Through this approach, we successfully identified specific regions within the estuary that provide optimal conditions for *Lates calcarifer* growth. Seasonal variations were evident in our analysis, revealing distinct differences between summer and winter growth patterns. During the summer, characterized by higher temperatures and fluctuating environmental conditions, the areas supporting optimal growth expanded noticeably. These findings are valuable for informing coastal biodiversity conservation and supporting sustainable resource management in the estuarine environment. Future studies could further improve growth prediction accuracy by integrating additional ecological variables such as fish feed availability, nutrient levels, zooplankton and phytoplankton abundance, sediment composition, and habitat complexity, offering a more comprehensive understanding of the ecological dynamics influencing sea bass growth.

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