Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Climate Change, Sea Water Dynamics, and Economic Sustainability: Revisiting Shrimp Aquaculture in the Tuticorin Coastline

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This study investigates the significant effects of global climate change on the marine ecosystem of the Tuticorin coast, a key area for shrimp farming, by analysing changes in water quality from 2009 to 2018, including temperature, pH, salinity, dissolved oxygen, and nutrients. Notable increases in temperature and salinity, along with fluctuations in pH and nutrient levels, were observed, indicating a shift from the coast's previously temperate conditions. By comparing water quality parameters from 2018 with established shrimp culture benchmarks using a paired sample t-test, the research highlights critical deviations that could impact shrimp health, growth, and productivity. Although statistical significance teeters on conventional thresholds, the practical implications for shrimp farming are undeniable. This study underscores the urgent need for adaptive strategies and policy reforms to mitigate the impacts of climatic alterations on shrimp culture, ensuring its resilience and sustainable future. In light of ongoing climate change, the study underscores the necessity of scientific, economic, and societal shifts to safeguard and sustain marine-based livelihoods in regions like Tuticorin.
Keywords: Climate Change, Tuticorin Coast, Shrimp Culture, Water Quality Parameters, Coastal Aquaculture.

1. Introduction

The natural process of climate change is a beneficial driving force behind Earth's evolution, making life as we know it possible—after all, without the end of the Ice Age, humanity might never have thrived. The real danger lies in human-induced climate change, which accelerates these shifts, disrupting ecosystems and endangering our future. Coastal regions, rich in biodiversity, are particularly vulnerable, with industries like aquaculture facing substantial risks. With wild fish stocks dwindling due to overfishing, aquaculture has emerged as a crucial and sustainable solution to meet the rising global demand for aquatic products (AskarySary et al., 2012; FAO, 2020). As hubs of human activity, coastal zones play a pivotal role in supporting food security and economic stability for communities worldwide. However, this critical interdependence is increasingly threatened by the complex challenges posed by climate change (Kandu, 2017; Krishnan & Birthal, 2008). Climate change looms as a significant challenge, endangering global food production systems and disrupting the quality and yield of seafood, including shrimp (Beach and Viator, 2008; Hamdan et al., 2015; Myers et al., 2017). The intricate relationship between coastal aquaculture and environmental health is increasingly important as we address the multifaceted challenges of climate change, which threaten global food security and human wellbeing (Kandu, 2017; Blanchard et al., 2017; Dabbadie et al., 2018; FAO, 2020; Nayagam et al., 2019).

The aquaculture industry, notably the fastest-growing food production sector globally, is expanding rapidly. Especially shrimp farming, which is vital for global food security, supplying high-quality protein and essential nutrients, combating malnutrition, and fostering economic stability in coastal areas (Raveendran and Sacratees, 2024; Dayal et al., 2013). Despite its growth, the sector's sustainability is threatened by both current and anticipated impacts of climate change (Maulu et al., 2021). Aquaculture faces direct threats from rising sea levels, ocean acidification, changing precipitation pattern, extreme weather events and fluctuating coastal water temperatures, endangering marine biodiversity and the livelihoods reliant on this sector (Raveendran and Naik, 2023; Fleming et al., 2014; Blanchard et al., 2017; Troell et al., 2017; Zolnikov, 2019). This highlights the vulnerability of the aquaculture value chain to the effects of climate change and underscores the urgent need for resilience and adaptive strategies to mitigate these challenges (Cochrane et al., 2009; Bueno and Soto, 2017; Dabbadie et al., 2018).

This study concentrates on the Tuticorin coastal region within the Gulf of Mannar, a UNESCO Biosphere Reserve. This area is significant for its shrimp farming development, particularly species like Penaeus vannamei and Penaeus monodon, fuelled by strong international demand. The international demand for shrimp, driven by its nutritional value and market versatility, underscores the importance of this industry for economic and job creation in coastal regions like Tuticorin, where aquaculture operations have spurred socio-economic development (Dayal et al., 2013; Vousdoukas et al., 2020; Srinivas & Venkatrayulu, 2023; Ottinger, et al., 2016; Ngasotter, et al., 2020), which supports thousands of families and contributes to the regional economy, making the health of the marine ecosystem a paramount concern for the future of this industry (Muthuraman et al., 2019; Mukul, 1994; Mohamed, 2022; Meiaraj & Jeyapriya, 2019; McClanahan et al., 2015; Malarvannan & Balamurugan, 2018; Krishnan & Birthal, 2008; Kodzo & Addo, 2013; Khan, 2020; Katiha et al., 2017; Jayasankar, 2018; Jayanthi et al., 2018; Jana & Jana, 2003; Balakrishnan et al., 2017). However, the prosperity brought by shrimp farming in Tuticorin faces challenges from climate change, including disease outbreaks in shrimp populations due to rising sea temperatures and changes in water quality parameters such as salinity and oxygen levels, which can impact shrimp survival and growth. Additionally, extreme weather events and sea-level rise pose risks to aquaculture infrastructure (Johnson et al., 2016; Sekar et al., 2009).

In view of these concerns, this study aims to delve into the specific changes occurring within the Tuticorin coast, utilizing global and regional climate models to comprehend the impacts on marine parameters and, consequently, on aquaculture. The necessity for this empirical investigation is underscored by the extensive body of research examining the effects of climate change on aquaculture at various scales (De Silva and Soto, 2009; Yazdi and Shakouri, 2010; Clements and Chopin, 2016; Chung et al., 2017; Froehlich et al., 2017; Handisyde et al., 2017; Harvey et al., 2017; Klinger et al., 2017; Beveridge et al., 2018). This study highlights the socio-economic and cultural importance of shrimp aquaculture in Tuticorin, a critical livelihood for many families and a key indicator of broader environmental changes. It investigates the impacts of climate change on marine water quality and shrimp farming by analysing data from 2009, 2015, and 2018. The objectives include: (1) documenting changes in water quality parameters over the years to establish a timeline of environmental shifts, (2) evaluating deviations in 2018 water parameters from optimal benchmarks for shrimp culture, and (3) assessing the broader implications of climate change on aquaculture sustainability. By linking local environmental changes to global climate trends, the study provides actionable insights and strategies to mitigate adverse impacts, ensuring the resilience and sustainability of the shrimp farming industry in this region.

2. Materials and Methods

The study analysed key water quality parameters for 2009, 2015, and 2018, drawing data from reputable sources such as Rasayan Journal, IRJET, Springer's Applied Water Science, and reports from the Commissioner of Fisheries and Coastal Aquaculture Authority. A longitudinal analysis combined with paired sample t-tests compared 2018 parameters against shrimp culture benchmarks, identifying deviations and underlying trends. The insights were visually represented through a radar/spider chart generated using Matplotlib, a Python visualization library.

Hypothesis

H0: Climate change has not significantly altered the water quality parameters in the Tuticorin coast.

H1: Climate change has significantly altered the water quality parameters in the Tuticorin coast.

3. Results and Discussions

Table: - 1. Coastal length of Tamil Nadu

S. No.	Coastal Districts	Coastal Length (Km)
1	Chennai	19.0
2	Tiruvallur	27.9
3	Villupuram	40.7

4	Pudukottai	42.8
5	Thanjavur	45.1
6	Thiruvarur	47.2
7	Tirunelveli	48.9
8	Cuddalore	57.5
9	Kanyakumari	71.5
10	Kanchipuram	87.2
11	Tuticorin	163.5
12	Nagapattinam	187.9
13	Ramanathapuram	236.8
Total		1076.0

(Source: Commissioner of Fisheries, Govt of Tamil Nadu)

Tamil Nadu's 1,076 km coastline represents 13% of India’s coastline, with an Exclusive Economic Zone (EEZ) of 0.19 million sq.km (9.4% of India’s EEZ) and a continental shelf of 41,412 sq.km. Among its 13 coastal districts, Tuticorin, Nagapattinam, and Ramanathapuram have the longest coastlines. Tuticorin, strategically located in the Gulf of Mannar Biosphere Reserve, is crucial for environmental conservation and supporting coastal livelihoods. Renowned for its major port handling minerals and industrial cargo, it plays a key role in trade and economic growth. Tuticorin’s thriving aquaculture sector leverages its brackish water ecosystems, enabling shrimp farming (vannamei, black tiger), which supports local livelihoods and contributes significantly to the state’s economy.

Impact of Climate Change on Sea Water Quality in Tuticorin Coast

Climate change significantly impacts seawater quality along the Tuticorin coast, disrupting marine ecosystems and aquaculture. Rising sea temperatures alter species distribution and reduce dissolved oxygen, while ocean acidification lowers pH, harming marine life like shellfish and coral reefs. Changes in precipitation and salinity, along with increased nitrates, nitrites, and ammonia from evaporation, runoff, and stratification, further degrade water quality. Intensified storms and saltwater intrusion exacerbate these challenges, fostering harmful algal blooms and threatening marine health and aquaculture sustainability in the region.

Table: -2. Water Quality Parameters of Sea Water in Tuticorin Coast

SI.No.	Parameter	Range		
		2009	2015	2018
1	Temperature (°C)	24.0	29.7	38-42
2	pH	7.10	8.5	9.8
3	Salinity(ppt)	10.20	26.1	39.41
4	DO (Dissolved Oxygen) (mg/L)	<1	4.963	6
5	Ammonia(ppm)	0.700	0.526	6.3

6	Nitrite(ppm)	0.009	0.215	1.25
7	Nitrate(ppm)	0.41	2.047	3.98

(Sources: https://doi.org/10.1007/s13201-015-0363-2 , https://www.irjet.net/archives/V5/i4/IRJET-V5I4604.pdf, C. Puthiya Sekar et al. ISSN: 0974-1496 CODEN: RJCABP)

Data analysis reveals significant changes in marine parameters along the Tuticorin coast, driven largely by climate change. Sea temperatures rose sharply from 24.0°C in 2009 to 38-42°C by 2018, reflecting global warming trends. pH levels increased from 7.10 to 9.8, indicating greater alkalinity. Salinity nearly quadrupled, rising from 10.20ppt to 39.41ppt, likely due to altered rainfall and evaporation patterns. Nutrient levels (ammonia, nitrite, nitrate) surged to 6.3ppm, 1.25ppm, and 3.98ppm respectively, signalling increased runoff linked to intensified weather events. These changes highlight the region's vulnerability to climate impacts.

Table: - 3. Desirable Water Quality parameters of Brackish Water Shrimp Farms

SI.No.	Parameters	Range
1	Temperature (ºC)	28-33
2	pH	7.5-8.5
3	Salinity (ppt)	15-25
4	DO (Dissolved Oxygen) (mg/L)	5-7
5	Alkalinity (mg/L)	100-120
6	Ammonia (ppm)	<0.01-0.1
7	Nitrite (ppm)	<0.01-0.1
8	Nitrate (ppm)	<0.03-0.1

(Source: Coastal Aquaculture Authority)

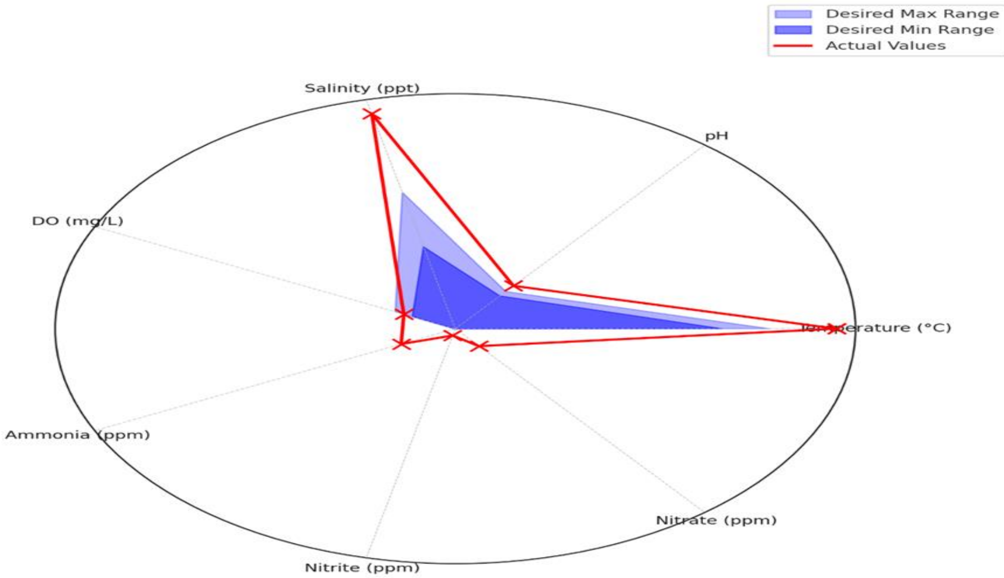
Optimal brackish water shrimp farming requires specific water quality parameters. Ideal conditions include a temperature of 28-32°C, pH of 7.5-8.5, salinity of 10-25 ppt, and dissolved oxygen (DO) of 4.0-6.0 mg/L. Alkalinity should range from 100-120 mg/L, with low ammonia (<0.5 ppm), nitrite (<0.1 ppm), and nitrate (<0.1 ppm) levels to prevent stress and toxicity. Maintaining these parameters ensures shrimp health and successful farming.

Table: - 4. Comparison between the desired and the actual water quality parameters

SI.No.	Parameters	Range	
		Desired	Actual
1	Temperature(ºC)	28-33	38-42
2	pH	7.5-8.5	9.8
3	Salinity(ppt)	15-25	39.41
4	DO (Dissolved Oxygen) (ppm)	5-7	6
5	Ammonia(ppm)	<0.01-0.1	6.3
6	Nitrite(ppm)	<0.01-0.1	1.25

7	Nitrate(ppm)	<0.03-0.1	3.98

Fig 1: Comparison between the desired and the actual water quality parameters



Given are the actual and desired level of water quality parameters, now let's compare it using paired sample t-test.

Paired Sample t-test Analysis

Difference between Actual and Midpoint of Desired Values:

1. Temperature: d_1=8
2. pH: $d2 = 1.8$
3. Salinity: $d3 = 19.41$
4. DO: $d4 = 0$
5. Ammonia: $d5 = 6.245$
6. Nitrite: $d6 = 1.195$
7. Nitrate: $d7 = 3.915$

Now let's calculate the mean of the differences;

$$\bar{d} = \frac{8 + 1.8 + 19.41 + 0 + 6.245 + 1.195 + 3.915}{7}$$

= 5.65

Calculating the standard Deviation of Differences;

$$s_d = \sqrt{\frac{\Sigma(d_i - \bar{d})^2}{n-1}}$$

Here d_i are the individual differences and n is the number of pairs, computing the values to the given equation;

$$s_d = \sqrt{\frac{(8-5.65)^2 + (1.8-5.65)^2 + (19.41-5.65)^2 + (6.245-5.65)^2 + (1.195-5.65)^2 + (3.915-5.65)^2}{6}}$$

Computing that;

$$s_d \approx 6.40$$

Calculating t-test;

$$t = \frac{\bar{d}}{s_d/\sqrt{n}}$$

$$t = \frac{5.65}{6.40/\sqrt{7}}$$

$$t \approx \frac{5.65}{2.42}$$

$$t \approx 2.33$$

At a 0.05 significance level (2-tailed) with 6 degrees of freedom, the critical t-value is 2.447. Since the computed t-value (2.33) is below this, we fail to reject the null hypothesis, indicating no statistically significant difference between desired and actual water parameters. However, the t-value is close to the critical value, suggesting the practical differences may still be important for shrimp farming.

The data highlights an evolving marine ecosystem impacted by climate change, affecting biodiversity and economic activities like shrimp farming. While a paired t-test shows no statistically significant differences at the 0.05 level, practical implications remain, as deviations in temperature and salinity could still affect shrimp health and yield.

This study evaluates changes in marine water quality along the Tuticorin coast, critical for shrimp farming, between 2009, 2015, and 2018 due to climate change. Findings reveal rising sea temperatures (24°C to 38-42°C), increased pH (7.10 to 9.8), quadrupled salinity, and elevated nutrient levels (ammonia, nitrite, nitrate), driven by reduced rainfall, higher evaporation, and runoff. These shifts stress shrimp, affecting growth, survival, and disease resistance, nearing critical thresholds for aquaculture sustainability. The study underscores the urgent need for adaptive shrimp farming practices to address climate-induced marine changes.

Economic Sustainability Concerns Amidst Climate Change Threats

Aquaculture in India, as a sector that significantly bolsters the economy, faces a crucial juncture where the potential threat of climate change could unravel the gains achieved over the years. In 2021-22, the impressive aquaculture production of 12.12 million tonnes highlighted India's capacity as a global aquaculture leader. The industry has not only contributed to the country's food basket but has also been instrumental in providing employment to approximately 37.88 million people as of 2020, with 20.67 million engaged directly in aquaculture practices. These figures underscore the critical importance of the sector in sustaining livelihoods and driving economic growth. The robust growth of the global aquaculture market, which saw an increase from $37.66 billion in 2022 to $41.45 billion in 2023 at a CAGR of 10.0%, with India maintaining the second rank globally, reflects the country's pivotal role in this expanding industry. This growth trajectory, projected by the IMARC Group to surge to 19.9 million tonnes by 2028 at a CAGR of 8.1%, signifies not only the sector's remarkable potential but also its vulnerability to climate-induced risks.

The Nexus of Economic Growth and Climate Risks

India's aquaculture has contributed around 1% to the GDP and over 5% to the agricultural GDP, delineating its essential role in the nation's economic landscape. The sector's export performance has been formidable, with earnings of ₹57586.48 crores in 2020-21, and a significant escalation in total exports to 7,28,123 million tonnes in 2021-22. Such economic indicators highlight the substantial impact that any disruption caused by climate change could have, not just on the sector, but on the nation's economy at large.

4. Conclusion

The changing water quality along the Tuticorin coast due to climate change highlights the urgent need for strategic action to sustain shrimp farming, vital to the region's economy and livelihoods. Key measures include adopting climate-resilient shrimp breeds, precision aquaculture, robust infrastructure, sustainable insurance models, and adaptive practices. Policies, international collaboration, economic diversification, and community engagement are crucial, alongside improved monitoring and integrated coastal zone management. A holistic approach, combining proactive measures and collective efforts, can help Tuticorin's marine ecosystem adapt and thrive, ensuring the resilience of its shrimp farming sector and broader maritime environment.

Acknowledgment

I would like to express my sincere gratitude to all those who have contributed to the completion of this research. Special thanks to my supervisor, Dr. Sacratees J., for his invaluable guidance and support throughout this study. I also extend my appreciation to the participants and organizations that provided data and insights crucial to this research. Finally, I'm a recipient of Indian Council of Social Science Research Doctoral Fellowship and this article is largely an outcome of the doctoral work sponsored by ICSSR, so I am indebted to ICSSR for sponsoring this article through my research work. However, the responsibility for the facts stated, opinions expressed and the conclusion drawn is entirely that of the author.

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