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Climate Change–Induced Shifts in Fish Availability and Their Impacts on the Socio-economic Life of Small-scale Fishers in Kerala

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Abstract

Climate change is restructuring marine ecosystems globally, but its impacts are especially pronounced in tropical coastal regions where small-scale fishing communities rely directly on ocean resources for livelihood, food security, and cultural continuity. Kerala, situated along the south-western coast of India, is one of the world's most densely populated coastal belts where approximately one million people depend on marine fisheries, either directly or indirectly. Over the last three decades, the coastal waters of Kerala have undergone substantial physical and biogeochemical transformations: increasing sea surface temperatures, shifts in monsoon timing, altered upwelling phenology, increasing salinity variability, expansion of oxygen minimum zones, and more frequent extreme events such as marine heatwaves and cyclonic disturbances. These environmental perturbations have led to profound changes in fish behaviour, migration, survival, spawning success, and population dynamics, resulting in observable shifts in species composition, spatial distribution, and overall availability of fish — particularly small pelagic species such as the Indian oil sardine (Sardinella longiceps), which historically formed the backbone of Kerala's marine economy. This article synthesizes more than two decades of scientific, socioeconomic, and policy literature to evaluate how climate- induced changes in fish availability affect the socioeconomic life of Kerala's small-scale fishermen. Using an interdisciplinary framework, the article examines environmental drivers, ecological responses of key fish species, long-term landing patterns, income and livelihood disruptions, community-level vulnerabilities, adaptation strategies, and the emerging governance challenges. Special attention is given to the collapse of oil sardine stocks after 2015, which triggered a livelihood shock across multiple districts, highlighting the interconnectedness of climate, ecology, and society. The background finds that declines in fish availability have reduced catch per trip, increased the cost of fishing effort, deepened household debt, triggered occupational shifts, amplified food insecurity, and increased psychological stress within fisher communities. While adaptation strategies such as gear diversification, deeper-water fishing, aquaculture uptake, and cooperative models are emerging, structural and financial constraints limit their effectiveness. The paper concludes by identifying key research gaps and proposing pathways for climate-resilient fisheries governance in Kerala.

1. INTRODUCTION

Coastal regions across the world are experiencing unprecedented environmental upheavals due to anthropogenic climate change. Rising sea surface temperatures, changes in ocean circulation, intensification of extreme weather events, and disruptions in primary productivity are reshaping marine ecosystems at scales that challenge historical patterns of human- environment interaction. For societies deeply intertwined with coastal and marine environments, especially traditional fishing communities, these changes are not merely environmental phenomena but drivers of economic, cultural, and social transformation. Kerala, located on India's southwestern coast, presents a compelling case study of the vulnerabilities and challenges associated with climate change and marine fisheries. Stretching approximately 590 kilometers along the Arabian Sea, the state possesses one of India's most vibrant marine ecosystems, enriched by the annual southwest monsoon and seasonal coastal upwelling that drives high biological productivity. For centuries, these ecological dynamics have sustained the livelihoods of artisanal and small-scale fishers dwelling in the narrow coastal belt. Fishing is not only an occupation but a cultural identity, shaping community life, traditional knowledge systems, dietary habits, and social relations. As of recent estimates, Kerala hosts more than 2,20,000 active marine fishers, with nearly 10 lakh (1 million) people depending on the fisheries sector indirectly through processing, vending, auctioning, transportation, net-making, and other allied activities. Small-scale fishers are traditional, locally operating fish harvesters who rely on *Kattamaram,* small boats, simple technology, and low capital, mainly serving household consumption and local markets. Small-scale fishers form the backbone of Kerala's marine economy, particularly in districts like Thiruvananthapuram, Kollam, Alappuzha, Ernakulam, Thrissur, Malappuram, Kozhikode, and Kannur [1].

Climate Change as a Transformational Force

Over the last two to three decades, multiple lines of scientific evidence indicate that Kerala's coastal waters have undergone significant environmental change. Satellite-derived data show increasing sea surface temperatures (SST) across the Arabian Sea, with warming rates among the fastest in the Indian Ocean region. Simultaneously, the timing and intensity of the southwest monsoon — historically predictable and central to the region's fish productivity — have become increasingly erratic. Seasonal upwelling, which brings nutrient-rich waters to the surface, is also exhibiting altered intensity and timing, thereby affecting primary productivity and food availability for pelagic fish. These environmental shifts translate directly into ecological consequences: alterations in spawning cycles, mismatches between fish larvae and plankton blooms, geographical redistribution of species, changes in fish body condition, increased susceptibility to disease, and unpredictable migration patterns. Over time, these ecological transformations manifest in commercial fish landings, causing fluctuations — and in some cases collapses — in the populations of key fish species. Among such species, the Indian oil sardine holds exceptional importance. For nearly a century, oil sardine has been Kerala's "poor man's fish" due to its affordability, availability, and nutritional richness. Sudden and dramatic declines in sardine landings after 2015 sent shockwaves through Kerala's coastal economy, triggering widespread livelihood crises [2].

Socioeconomic Vulnerability of Small-Scale Fishers

Climate-induced fish stock fluctuations affect small-scale fishers more intensely than mechanized fleets for several reasons. Small-scale fishers rely on nearshore waters, which are more sensitive to temperature and salinity changes. Their fishing craft and gear have limited range and storage capacity, and their financial resources are insufficient to absorb repeated fishing failures. Unlike mechanized fleets, small-scale fishers depend heavily on daily income to meet household needs; thus, even short-term fluctuations in catch can translate into acute financial distress. With reduced fish availability, fishers experience lower catch per unit effort (CPUE), increased number of "zero-catch days," higher fuel costs, and greater time spent at sea. These economic pressures contribute to rising household debt. Sociocultural impacts are equally significant: community tensions rise, youth migrate away from fisheries, traditional institutions weaken, and women working in post-harvest activities experience falling incomes.

Fish scarcity also influences food security in Kerala because fish — particularly sardine — is a major source of animal protein for low-income households [3].

Need for an Interdisciplinary Review

Existing studies on Kerala's fisheries tend to focus either on ecological aspects (such as climate impacts on fish stocks) or socioeconomic dimensions (such as livelihood vulnerability). However, given the deep interconnectedness of climate, ecology, and society, a comprehensive interdisciplinary synthesis is needed to understand the broader implications of climate-induced fish availability shifts. This review aims to fill that gap by integrating scientific, ecological, economic, and social perspectives.

Structure of the Review

This review is organized into ten major sections. Following this introduction, Section 2 discusses key environmental changes in the Arabian Sea, while Section 3 examines ecological responses of fish species. Section 4 presents trends in fish landings and species composition. Section 5 explores socioeconomic impacts on small-scale fishers, followed by a detailed discussion of adaptation strategies in Section 6. Section 7 evaluates policy and governance responses, while Section 8 identifies interdisciplinary research gaps. Section 9 proposes future directions for climate-resilient fisheries, and Section 10 concludes with a synthesis of major findings.

2. CLIMATE CHANGE AND MARINE ENVIRONMENTAL SHIFTS IN THE ARABIAN

SEA

The Arabian Sea is one of the most dynamic and climatically sensitive marine regions within the northern Indian Ocean. Its biological productivity, hydrological structure, and seasonal dynamics have been historically shaped by the South Asian monsoon system — one of the strongest climatic engines on the planet. For centuries, the predictable alternation of the southwest and northeast monsoons generated seasonal upwelling patterns that enriched Kerala's coastal waters, supporting high fish biomass and robust fisheries. However, extensive oceanographic research over the past three decades indicates that the Arabian Sea — particularly its eastern boundary near the Indian coast — is undergoing accelerated and unprecedented changes associated with anthropogenic climate forcing. These changes have direct and cascading consequences for the availability, distribution, and reproductive success of marine fish species that sustain Kerala's small-scale fishermen. This section synthesizes scientific evidence regarding key physical and biogeochemical changes in the Arabian Sea, their observed trends, and their ecological implications. The goal is to establish a clear understanding of the environmental transformations that underpin the shifts in fish availability examined later in this article.

2.1 Rising Sea Surface Temperature (SST): A Fundamental Driver of Marine Change

One of the clearest signals of climate change in the Arabian Sea is the significant rise in sea surface temperature. Analyses from satellite records, ocean buoys, and model reanalysis data consistently show that the Arabian Sea has warmed rapidly since the 1980s, with certain pockets off the Kerala–Karnataka coast warming at rates exceeding the global average for tropical oceans.

Magnitude and Trends of Warming

The average increase in sea surface temperature along the Kerala coast is estimated to be approximately:

- **0.2°C to 0.4°C per decade** since the mid-1980s
- **~1°C total warming** over the last 30–40 years

Although this figure may appear modest, even a 0.5–1°C rise in SST is environmentally transformative in tropical marine ecosystems, where many species operate near their upper thermal tolerance limits. Small pelagic fish such as sardines and anchovies are especially sensitive to temperature changes, and warmer waters can affect their metabolic rates, migration behaviour, and spawning success.

Spatial and Seasonal Variability

SST rise is not uniform across seasons:

- **Pre-monsoon (March–May):** Sharp warming spikes; marine heatwaves increasingly reported.
- **Monsoon (June–September):** Traditionally cooler due to upwelling, but recent years show weakening cooling effects.
- **Post-monsoon (October–December):** Gradual warming persists longer into winter.

This shift has disrupted the historical thermal cycles that fish species relied upon for migration and breeding.

2.2 Changing Monsoon Dynamics and Their Ecological Significance

The southwest monsoon has historically been central to the marine productivity of Kerala's coastal waters. Its winds drive coastal upwelling — the process by which cold, nutrient-rich subsurface waters rise to the surface, triggering high phytoplankton growth that sustains fish populations. Emerging research shows that monsoon variability is increasing due to global warming.

Key Observed Changes

1. **Delayed monsoon onset** in several recent decades
2. **Shortened monsoon duration** in some years
3. **Increased frequency of "breaks"** within the monsoon
4. **Intensified but uneven rainfall patterns**
5. **Greater cyclone interference during monsoon months**

These changes alter wind fields in the Arabian Sea, which in turn modify the strength and timing of upwelling.Impact on Upwelling-Driven Productivity

If upwelling is weakened or delayed:

The nutrient injection is reduced

- Phytoplankton blooms shift in timing or intensity
- Zooplankton (fish larvae food) biomass decreases
- Connection between food availability and spawning cycles breaks down

This mismatch is particularly damaging to oil sardine, which depends on synchrony between plankton peaks and larval stages.

2.3 Altered Upwelling Dynamics: The Engine of Kerala's Fishery

- **Incre**
- **ased variability** linked to global climate

oscillations The decline in upwelling strength has

profound ecological effecs.

- **Consequences for Marine Life**
- Lower primary productivity
- Reduced fish biomass
- Altered seasonal availability of pelagic fish
- Migration of fish to cooler, deeper waters

These changes make catch patterns increasingly unpredictable for artisanal fishers who depend on historical seasonal cycles.

2.4 Variations in Salinity and Mixed Layer Depth (MLD)

Sea surface salinity (SSS) and mixed layer depth (MLD) are key physical factors influencing fish behaviour.

Sea Surface Salinity

Kerala's salinity patterns depend on:

- Monsoon rainfall
- River runoff
- Primary productivity Observations in the

Arabian Sea indicate:

- A **shoaling (shallower) MLD** due to increased
- surface warming
- Reduced mixing depth, limiting nutrient flux

Coastal upwelling is the most critical phenomenon underpinning Kerala's marine fish production. Traditionally, upwelling peaks during June to September, with cold-water intrusions detectable even in coastal surface layers.

Recent studies show:

- **Weakened upwelling intensity** in several post-2010 years
- **Delayed initiation**, shifting from June to July in some years
- **Reduced cooling effect** (surface temperatures not dropping as much)
- **Shortened duration** of active upwelling

- Upwelling
- Intrusions from the Arabian Sea central gyre

Recent changes include:

- Higher surface salinity during pre-monsoon season due to warming and evaporation
- Dilution events during extreme rainfall years
- More irregular salinity cycles overall

Many fish larvae are highly sensitive to salinity changes, especially anchovies and sardines.

Mixed Layer Depth (MLD)

MLD determines:

- Nutrient mixing
- Heat distribution
- Light penetration

- Greater stratification and reduced vertical exchange

These physical processes weaken the biological pump that historically enriched Kerala waters with food for pelagic species.

2.5 Expansion of Oxygen Minimum Zones (OMZs)

The Arabian Sea hosts one of the largest naturally

- Altering circulation patterns

Recent findings indicate

- OMZ boundaries are expanding both horizontally and vertically
- Coastal hypoxia events are becoming more

frequent Low-oxygen conditions force fish to:

- Migrate to narrower mid-water depth bands
- Avoid certain areas entirely
- Experience physiological stress

This affects catch availability in shallow coastal waters used by small boats.

2.6 Marine Heatwaves: Emerging Threats to Coastal Fisheries

Marine heatwaves (MHWs) — periods of prolonged extreme warming — are an increasingly common occurrence in the Arabian Sea.

Characteristics of MHWs

- Lasting several days to weeks
- Caused by atmospheric blocking, low winds, and high solar radiation
- Enhanced in years with weak monsoon winds
- Often follow El Niño events

The frequency of MHWs off Kerala has increased especially after 2010.

- Flow patterns are becoming irregular Such

changes affect:

- Larval recruitment
- Movement of shoaling species
- Spatial distribution of fishable stocks

Fishers often report that fish “do not follow old routes anymore.”

2.8 Increased Frequency of Cyclones and Extreme

- yclones occurring during

unusual seasons

occurring oxygen minimum zones in the world. Climate warming intensifies these zones by:

- Reducing oxygen solubility
- Increasing stratification

Ecological Consequences

- Mass mortality of plankton
- Disruption of fish migration cues
- Alteration of spawning grounds
- Decline in sardine body condition
- Increased susceptibility to disease

These events have been linked to particularly poor fish landings in years like 2016 and 2019.

2.7 Changing Currents and Circulation Patterns

The West India Coastal Current (WICC) and East India Coastal Current (EICC) influence larval transport, nutrient flux, and fish dispersal along Kerala’s coast.

Climate change is modifying these patterns:

- WICC reversals are occurring earlier or later than usual
- Current intensities are weakening

Events

Although the Bay of Bengal has historically been more cyclone-prone, the Arabian Sea is experiencing:

- More cyclones
- Stronger cyclones
- C

- Longer storm life cycles

Examples include:

- Cyclone Ockhi (2017) — dramatically affected Kerala's fishing communities
- Cyclones Nilam, Mekunu, Kyarr,

Vayu, Tauktae — all altered fishing conditions Cyclones disrupt fishing in many ways:

- Destroy traditional boats and gear
- Reduce safe fishing windows
- Create rough sea conditions for weeks
- Damage fish breeding grounds

Small-scale fishers are most vulnerable because their artisanal craft are not built for high-risk conditions.

2.9 Combined Effects: Increasing Environmental Variability and Unpredictability

The multiple environmental changes described — warming, altered monsoon, weaker upwelling, salinity fluctuations, deeper OMZs, and extreme events — interact synergistically to produce:

- High interannual variability
- Unpredictable fishing seasons
- Shorter windows of productive fishing
- More frequent mismatches between fish availability and fishing effort

Artisanal fishers who traditionally rely on ecological knowledge inherited over generations find that the "old signs" no longer hold:

- Wind direction no longer predicts fish abundance
- Bird movements are less reliable signals
- Water colour anomalies have shifted
- Seasonal cues are less consistent [3].

3. ECOLOGICAL RESPONSES OF FISH TO CLIMATE-INDUCED ENVIRONMENTAL CHANGE

Climate-driven changes in the Arabian Sea do not affect fish populations through a single mechanism; rather, they exert a complex web of influences on physiology, reproduction, distribution, trophic interactions, and survival. Fish are highly sensitive to temperature, oxygen, salinity, and primary productivity — all of which have been altered in Kerala's coastal waters. This section synthesizes ecological evidence on how fish species, especially small pelagics such as Indian oil sardine, mackerel, anchovy, and whitebait, have responded to environmental shifts. These species are ecologically important not only because they dominate Kerala's landings but also because their population dynamics are tightly coupled to climatic oscillations.

3.1 Thermal Sensitivity and Metabolic Stress in Pelagic Fish

Temperature plays a defining role in the physiology of marine fish. Most tropical pelagic fish live near their upper thermal tolerance range. Even minor warming can increase metabolic rates, affecting growth, survival, and fecundity. Kerala's small pelagics are particularly sensitive to temperature changes because their preferred thermal window lies between 26.5°C and 28.5°C. When sea temperatures exceed these thresholds, several physiological effects occur. Warmer waters increase metabolic demand, forcing fish to consume more energy for basic bodily functions. If food availability does not rise correspondingly, fish experience nutritional stress. This has already been documented in sardines caught off the Kerala coast, which show reduced fat content and lower body condition during years of elevated sea surface temperature. Chronic exposure to warmer waters can also alter fish reproductive timing by affecting gonad maturation rates. Small pelagics often rely on narrow thermal windows for successful spawning. When these windows shift or shrink, reproductive cycles become erratic, leading to irregular spawning intensity and poor recruitment of juveniles into the population. Most importantly, high temperature events such as marine heatwaves lead to mass mortality of plankton, creating food scarcity for fish larvae. These thermally induced ecosystem imbalances amplify interannual variations in fish populations, making fish availability less predictable for artisanal fishers.

3.2 Shift in Geographic Distribution and Depth Migration

As coastal waters warm and oxygen minimum zones expand, fish species often relocate to areas that offer more favourable conditions. Several studies and fisher observations confirm that many species previously abundant in nearshore waters have begun shifting either poleward, further offshore, or deeper in the water column. Off Kerala's coast, sardines and mackerel traditionally migrate along predictable routes. However, warming waters have driven these fish northward and offshore, especially during certain seasons. Fishermen in Kerala frequently remark that sardine schools are increasingly found closer to Karnataka and Goa rather than along Kerala's southern coast. Some shoals are observed 20–40 kilometres offshore, far beyond the usual reach of non-mechanised boats. These distributional changes increase operational costs for mechanised boats and make traditional boats ineffective in accessing key species. Vertical migration patterns are also changing. In response to hypoxic intrusion from expanding oxygen minimum zones, pelagic fish may move to mid-depth refuges. This vertical relocation places them outside the optimal operating depth for traditional gears such as shore seines and small mesh gill nets, making artisanal fishing less productive.

The combination of horizontal and vertical distribution shifts is one of the most significant drivers of declining catches for small-scale fishers in Kerala.

3.3 Reproductive Failure and Recruitment Decline

Climate-induced environmental variations alter reproductive success in several ways. Many fish species exhibit strong synchrony between spawning and seasonal changes in water temperature, salinity, and plankton abundance. When these variables shift unpredictably, spawning success is compromised. Oil sardine, for example, exhibits peak spawning during periods of moderate temperatures and stable salinity. The alteration of these conditions has led to several years of poor spawning since 2010, with especially weak recruitment observed in 2015–2016 and 2019–2020. Historically strong sardine cohorts have become rarer. Scientists report a decoupling between phytoplankton blooms and sardine larval presence, meaning larvae often hatch when food is insufficient. Mackerel and anchovies have also exhibited erratic reproductive patterns, with spawning periods either compressed or advanced, causing mismatches between environmental conditions and larval needs. Such mismatches reduce survival rates of early life stages, leading to population instability. Long-term recruitment failure is one of the major causes of fish collapses, and unless environmental regimes stabilise or adaptive management is implemented, recovery becomes difficult.

3.4 Boom-and-Bust Cycles Intensified by Climate Variability

Pelagic fish are known for their natural population variability, often driven by environmental oscillations such as El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD). However, climate change amplifies these oscillations, causing more extreme "boom-and-bust" cycles. Periods of unusually high productivity, such as 2007–2008 when sardine catches surged unexpectedly; Sudden collapses, such as after 2015, when sardine abundance dropped sharply across Kerala's coast; Erratic recovery patterns, with some years experiencing partial rebounds and others complete crashes. These cycles create economic instability. During boom years, fish become abundant and cheap, lowering fisher income even when catch volume is high. During bust years, fish scarcity drives prices up, but low catch volume cancels out these gains. Increasing amplitude of these cycles is one of the clearest indicators of climate-driven stress.

3.5 Case Study: The Collapse of the Indian Oil Sardine

The oil sardine collapse after 2015 is one of the defining ecological events in Kerala's recent fisheries history. Sardines accounted for nearly one-third of Kerala's total marine fish landings for decades, supporting thousands of families involved in fishing, processing, and marketing.

Between 2010 and 2014, landings were exceptionally high, creating a perception of ecological stability. However, from 2015 onwards, landings crashed by nearly 50–70 percent in many districts.

Climate Factors Behind the Collapse

Several interlinked drivers contributed to this collapse:

Persistent rise in surface temperature weakened sardine spawning success; Delayed and weakened upwelling resulted in low plankton density; Marine heatwaves during 2015 and 2016 created inhospitable conditions; Increased salinity in some seasons disrupted egg and larval survival; Expansion of hypoxic zones forced sardines into deeper waters. These ecological disruptions converged to produce one of the most severe fisheries collapses in Kerala's history.

Consequences for the Ecosystem

The collapse triggered trophic shifts:

Predators such as tuna and seer fish migrated elsewhere; Lesser-preferred species filled ecological gaps; Phytoplankton blooms remained underutilised during some seasons; Nutrient cycles were altered due to changed grazing patterns.

Consequences for the Fishery

Sardine scarcity caused economic distress across Kerala, especially in southern districts. Prices rose dramatically, making sardine unaffordable for low-income families. Fishers increasingly targeted alternate species, which were often lower in price or required different gear systems.

The sardine collapse remains the strongest example of how climate change can restructure both marine ecosystems and human societies.

3.6 Changes in Species Composition and the Rise of Non-Preferred Species

As climate change reorganises ecological niches, Kerala's coastal waters have seen a decline in traditionally dominant species and an increase in non-traditional species.

Several species such as threadfin breams, ribbonfish, and small scads have become more abundant, partly because they are more tolerant of warmer and low-oxygen waters. Meanwhile, valuable species such as sardine, mackerel, anchovy, and penaeid prawns have declined.

This shift in species composition affects fishers economically. The new species may be less preferred by consumers, fetch lower market prices, or require different gears to harvest effectively. In some years, the proportion of low-value species or bycatch has surged significantly, leading to reduced profitability despite more fishing effort.

3.7 Trophic Mismatches and Disrupted Food Webs

Climate change disrupts the synchrony between different levels of the marine food chain. Phytoplankton bloom timing is affected by temperature, light, and nutrient availability. If fish larvae hatch when phytoplankton is scarce, larval mortality increases dramatically. In Kerala, such timing mismatches have contributed to Weak juvenile recruitment; Lower survival rates; Poor year-class formation in sardines and anchovies. These mismatches reflect broader disruptions in the biological clock of the marine ecosystem.

3.8 Increased Disease Susceptibility and Parasite Loads

Warmer waters are more conducive to pathogens. Fish immune systems become weakened when exposed to thermal stress, making them susceptible to bacterial infections, fungal diseases, and parasitic infestations.

There have been reports of higher parasite loads in sardines during certain post-2015 years. While disease may not be the primary driver of collapse, it can exacerbate mortality during periods of ecological stress.

3.9 Behavioural Changes and School Fragmentation

Traditional knowledge among Kerala's fishers includes reading the behaviour of fish schools based on sea conditions, bird patterns, water colour, and surface disturbances. In recent years, fishers consistently report:

Fragmented fish schools; Erratic movement patterns; Short-lived surface shoals; Increased unpredictability of fish emergence. These behavioural shifts are consistent with ecological stress and altered predator–prey dynamics in warming waters

[4]. LONG-TERM TRENDS IN FISH LANDINGS AND CHANGING SPECIES COMPOSITION IN KERALA

Long-term fisheries data offer one of the clearest windows into how climate-induced environmental changes translate into real shifts in fish availability. Kerala has some of the most detailed fisheries records in India, owing to the long-standing work of research institutions such as CMFRI and the Fisheries Department. These datasets reveal unmistakable patterns: declining abundance of historically dominant species, fluctuating annual production, increasing incidence of low-value catch, and more frequent years of poor landings. Yet, these trends cannot be interpreted in isolation. They must be contextualized within a broader ecological and socioeconomic framework in which climate variability, mechanization, overcapacity, and environmental degradation interact in complex ways. This section examines the evolution of Kerala's marine fish landings over the last two decades, focusing on the ecological and economic implications of shifting species dominance. The long-term changes in species composition reflect both climate stress and the adaptive behaviour of fishing fleets. The combined effect of these changes is a transformed fisheries landscape in which predictability has diminished, economic risks have increased, and traditional knowledge systems have been challenged.

3.10 Overview of Kerala's Marine Landings: Two Decades of Change

Kerala's marine fish production reached historical highs in the early 2010s, with annual landings occasionally exceeding 600,000 tonnes. This period created a perception of surplus abundance. However, the high landings were followed by a steep decline, and recent years show substantial variability.

Several long-term patterns emerge from historical landings data:

Production cycles have become more erratic after 2010; Dominance of small pelagic fish has weakened; Contribution of non-mechanized craft has diminished; Deep-sea species occasionally spike but remain unpredictable; Low-value species form an increasing share of total landings. The rise and fall of sardine and mackerel populations strongly influence total marine production levels because these species historically accounted for a major share of the catch. When their availability declines, overall landings drop even if other species increase. Mechanized fleets sometimes compensate for reductions in nearshore species by fishing deeper or farther offshore, but small-scale fishers cannot do so. Thus, the trends described here disproportionately affect artisanal communities.

3.11 The Decline of Oil Sardine: A Defining Trend

Few fisheries phenomena in India have drawn as much attention as the collapse of oil sardine stocks after 2015. Sardine landings were the economic and nutritional backbone of coastal communities, especially in southern Kerala. The collapse was not only a biological event but a socioeconomic shock of unprecedented scale. Throughout the 2000s and early 2010s, sardine landings oscillated but remained largely robust. Some years, such as 2012 and 2013, witnessed historically high catches exceeding 300,000 tonnes. These booms masked underlying ecological vulnerability that was already developing due to rising temperatures and weakening upwelling. The sudden collapse after 2015 stunned both scientists and fishers. Landings in many districts fell to less than one-third of normal levels. Reports from landing centres describe days when only a few baskets of sardines arrived, compared to hundreds just a few years earlier. The socioeconomic consequences included loss of income, reduced fish availability for low- income consumers, collapse of drying yards, and shifts in labour patterns among women fish vendors. Sardine prices doubled or tripled in some years, pushing a formerly inexpensive staple beyond the reach of poorer households. While the collapse had multiple drivers, the central role of environmental change is unmistakable. Extreme marine heatwaves and weak monsoon winds made reproduction difficult and forced schools away from Kerala's nearshore waters. Although there have been intermittent signs of recovery, sardine stocks remain highly unstable, underlining their sensitivity to climate variability.

3.12 Fluctuations in Mackerel and Anchovy: Support Species Under Stress

Mackerel and anchovy have traditionally supplemented sardine landings and filled ecological and economic niches when sardines declined. However, these species too have shown fluctuating trends in recent years, creating instability in the availability of small pelagic fish as a whole. Mackerel abundance historically peaks during the post-monsoon season when coastal waters cool and plankton production increases. Yet warming seas and disrupted current systems have altered these seasonal patterns. Mackerel are increasingly caught during atypical months or farther offshore. Fishers report that mackerel schools appear suddenly and disappear just as quickly, unlike in the past when seasonal patterns were more predictable. Anchovy species have also declined in several districts. Their larvae are extremely sensitive to salinity and temperature fluctuations, making them vulnerable to the combined effects of marine heatwaves and erratic rainfall. Anchovy landings once stabilized income for many fishers during lean sardine years, but their instability now compounds livelihood stress. The synchronous stress on sardines, mackerel, and anchovies represents a broader crisis: climate change is undermining the resilience of Kerala's entire small pelagic ecosystem.

3.13 Increase in Low-Value and Non-Preferred Species

As preferred species decline, Kerala's coastal waters are witnessing a marked rise in low-value or non-traditional species. Among these are threadfin breams, ribbonfish, juvenile scads, ponyfish, and certain deep-water demersal species encountered by trawl fleets.

Several of these species are more tolerant of higher temperatures and low-oxygen conditions. They also benefit from reduced competition when dominant pelagics decline. Threadfin breams, for example, have shown increasing catches in recent years, partly because trawl vessels target them more actively, but also because environmental conditions increasingly favour them.

Ribbonfish, once considered a supplementary catch, now frequently dominate landings in certain seasons. While they fetch reasonable export prices, they do not compensate economically for the loss of sardines and mackerel, particularly in domestic markets.

Low-value bycatch — including non-edible or low-demand species — has also increased in some seasons, indicating ecological imbalance. Although trawl fleets simply discard much of this catch, its rise reflects deeper changes in the food web and habitat conditions.

3.14 Seasonal Unpredictability and Breakdown of Traditional Fishing Calendars

Kerala's fishery has long been synchronized with monsoon cycles and seasonal upwelling. Traditional fishers relied on deep ecological knowledge transmitted across generations to anticipate fish abundance based on weather patterns, currents, and biological rhythms. Climate change has eroded this predictability. Fishers consistently report that fish no longer appear during traditional seasons. Sardines, once abundant during specific monsoon periods, may now be available in unexpected months or absent entirely during the usual peak season. Mackerel schools migrate irregularly, and anchovies show unpredictable presence in the nearshore zone. These changes undermine the value of traditional knowledge — one of the most significant intangible assets of artisanal fishers. Younger fishers increasingly express uncertainty regarding whether the knowledge of their elders is still relevant in a changing climate.

3.15 Impact on Processing and Value Chain Industries

Kerala's fishery is supported by processing industries that rely on consistent supply. The decline of key species has reshaped these value chains.

Drying yards, once busy with sardines and anchovies, now operate intermittently. Women who depend on drying and vending face reduced workdays, lower earnings, and greater financial instability. Dried sardine, a staple in many rural households, has become scarce in low-catch years. The fishmeal industry, which uses sardines and other small pelagics as raw material, has also been affected. Reduced availability forces factories to source fish from distant states or shift to low-quality substitutes. Frozen seafood processors occasionally benefit from increases in threadfin breams or ribbonfish, but the irregularity of supply limits stable operations. Export patterns have also shifted, with some species becoming more available while others decline. Overall, climate-driven changes ripple across the entire fisheries value chain, from fishers to processors to consumers.

3.16 District-Level Differences: Uneven Impacts Across Kerala

Climate effects are not uniform across Kerala. Southern districts such as Thiruvananthapuram and Kollam experienced the earliest and most severe sardine declines, partly due to stronger warming and salinity fluctuations in this region. Northern districts such as Kozhikode, Kannur, and Kasaragod occasionally reported better landings in certain years, though these gains are inconsistent. Mechanized trawl fleets in central Kerala are often able to offset declines in pelagics by targeting deep-water species, but small-scale fishers in both northern and southern districts lack this flexibility. Therefore, geographic differences reinforce socioeconomic inequalities.

3.17 Mechanization and Overcapacity: Stress Multipliers

While climate change is the primary ecological driver of declining fish availability, the role of human-induced fishing pressure cannot be ignored. The expansion of mechanized trawling and ring seines in the last few decades has increased competition for diminishing fish stocks. Ring seines, in particular, are extremely efficient at harvesting pelagic shoals. Their widespread use contributed to rapid depletion of sardine and mackerel during periods of low recruitment. Mechanization interacts with climate change in two critical ways: It accelerates depletion during ecological downturns; It leaves fewer fish to rebuild populations when environmental conditions eventually improve. Thus, the decline in preferred species is shaped by both environmental and anthropogenic pressures.

3.18 Combined Consequences: A Fisheries System in Transition

The cumulative effect of changing landings, shifting species composition, and seasonal unpredictability is a fisheries system undergoing profound transformation. Instead of a sardine-dominated pelagic ecosystem with predictable seasonal rhythms, Kerala now faces a more fractured and uncertain marine environment. Small-scale fishers feel this transformation most intensely because their livelihoods depend on daily catches, and their gear and vessels are least equipped to adapt to environmental shifts. Mechanized fleets, although more flexible, also face rising operational costs and ecological uncertainties. Kerala's fisheries are moving toward a future characterized by greater risk, reduced resilience, and heightened socioeconomic vulnerability unless climate-resilient management approaches are implemented [5] (Figure 1).

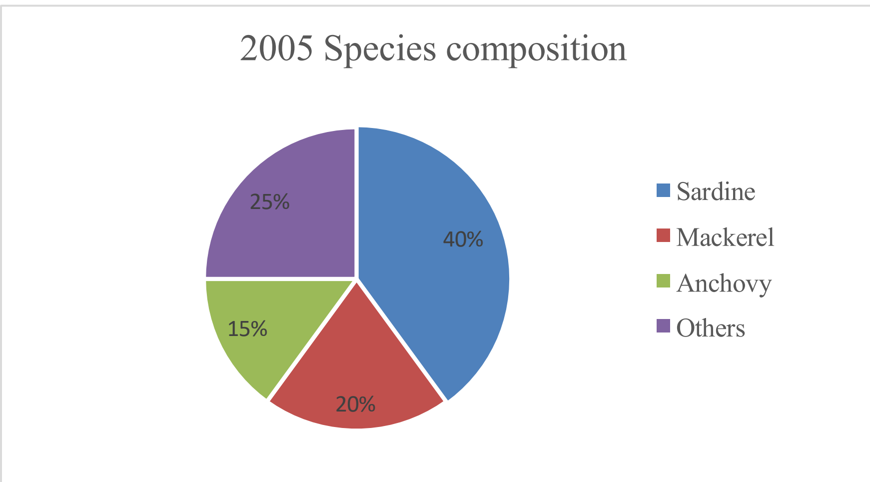
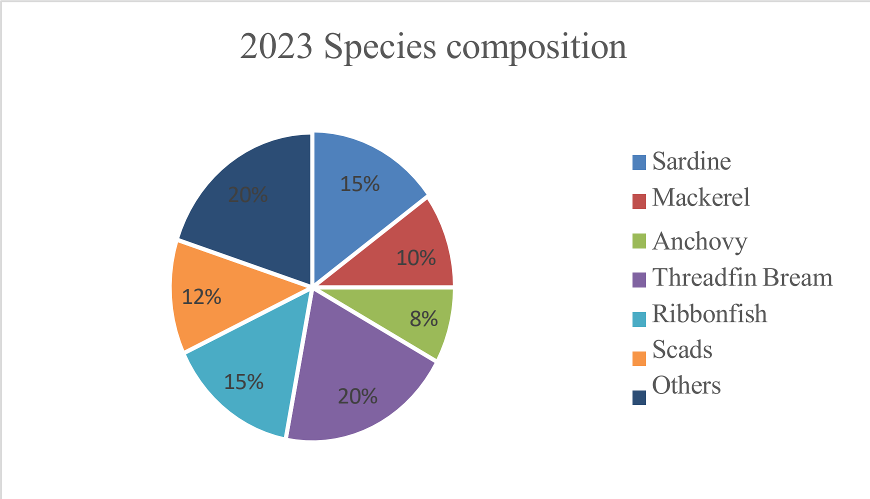


Fig. 1: Species compositions in aquatic ecosystem in Kerala [6]



4. SOCIOECONOMIC IMPACTS OF CLIMATE-INDUCED SHIFTS IN FISH AVAILABILITY ON KERALA'S SMALL-SCALE FISHERMEN

The ecological disruptions described in earlier sections have profound consequences for Kerala's small-scale fishermen, whose livelihoods depend on predictable access to nearshore fish stocks. Unlike mechanized fleets that can travel farther into the sea or modify nets to target different species, artisanal fishers rely primarily on the stability of nearshore resources. Climate change has destabilized this foundation, creating economic hardship, restructuring labour patterns, altering community dynamics, and intensifying inequality. This section explores how the decline and unpredictability of fish availability affect income, employment, gender roles, debt cycles, food security, and social resilience among artisanal fishing communities. These communities possess deep ecological knowledge shaped over generations; yet, the accelerating pace of climatic change is eroding the ecological rhythms that once sustained them. The resulting socioeconomic challenges are not merely economic adjustments—they represent a transformation of cultural identity and community structure.

3.19 The Centrality of Fishing to Kerala's Coastal Society

Fishing is not only an economic activity in Kerala; it is a way of life. Coastal communities hold intricate knowledge of tides, currents, winds, fish behaviour, and seasonal cycles. Historically, this knowledge allowed fishers to adapt to variability and sustain livelihoods even during lean years. The integration of fishing with local markets, women-led vending networks, auction systems, and community-based credit structures created a tightly interlinked socioeconomic ecosystem. Climate change disrupts not just fish availability but the entire social fabric woven around fisheries. When species disappear or become unpredictable, fishers face not just loss of income but cultural displacement. Many express a sense of being "disconnected from the sea," highlighting the intangible dimensions of climate vulnerability.

3.20 Income Volatility and Declining Earnings

The most direct impact of changing fish availability is income loss. Small-scale fishermen typically rely on daily earnings, with no salaries, social security, or guaranteed prices. Their income depends on what the sea provides each day. When sardines, mackerel, or anchovies fail to appear, earnings collapse. Before the sardine crash of 2015, a typical small-scale fisherman in districts like Kollam or Alappuzha could expect reasonably consistent daily income during peak seasons. After the collapse, many reported 30–60 percent reductions in annual earnings. Seasonal windfalls that once stabilized household finances have become rare. Income volatility has increased more than income decline. Fishers might have one unexpectedly good day followed by several days of near-zero catch. Such volatility complicates household budgeting, makes loan repayment unpredictable, and fuels chronic stress. The cost of fishing has also risen. Fuel prices fluctuate, nets require frequent replacement due to harsher sea conditions, and boats damaged during extreme weather events need repairs. Even when catches remain stable, rising costs can erode profit margins.

3.21 Increased Debt and Financial Insecurity

Debt is pervasive in Kerala's coastal communities, but climate-driven instability has intensified dependence on informal lenders. Many fishers borrow for boat repairs, fuel, nets, and household expenses. When catches fail, they are unable to repay, pushing them deeper into debt cycles. Informal lenders often impose high interest rates. Community credit groups exist but are insufficient to meet rising needs. Government welfare schemes provide periodic relief, but these do not address structural vulnerability. A new trend is the rise of "multi-source indebtedness," in which fishers take small loans simultaneously from cooperatives, moneylenders, pawn brokers, and friends. This diversification of lenders reflects growing desperation and declining ability to repay. Women from fishing households, who manage household finances, face significant stress in balancing daily needs with irregular income. Many pawn jewelry repeatedly to manage shortfalls, leading to long-term asset erosion.

3.22 Reduced Access to Fish for Household Nutrition

Ironically, fishing communities now struggle to access fish for their own consumption. Species such as sardine, once abundantly available and affordable, have become expensive during scarcity years. Many fishing households report consuming less fish than before, substituting cheaper alternatives or reducing protein intake. The decline in local fish consumption affects nutritional security, especially among children and elderly individuals. Fish contributes crucial micronutrients such as omega-3 fatty acids, vitamin D, calcium, and iodine. Reduced intake has long-term health implications. Women fish vendors, who historically brought home small portions from the day's sales, now find less leftover fish available as catches decline. When sardine prices rise sharply, even fishers cannot afford to buy adequate quantities. Climate change thus affects not only livelihoods but also the nutritional foundation of coastal communities.

3.23 Changing Roles and Livelihood Adaptation Among Women

Women play a central role in Kerala's fisheries economy as vendors, processors, auctioneers, carriers, and owners of small businesses. They are among the first to feel the impact of declining landings. When fish availability drops, women vendors receive smaller baskets from auction yards. Their income decreases, while the cost of transport and ice rises. Competition among vendors grows more intense, often leading to reduced margins and increased working hours. Dry fish processors—mostly women—are particularly vulnerable. When sardines and anchovies disappear from landing centres, drying yards fall silent. Women lose a critical source of income that traditionally helped stabilize household budgets. Some women attempt to diversify into other informal sector jobs such as cleaning work, tailoring, or small-scale retail. However, these jobs often pay less and are irregular. The transition is emotionally difficult because many women consider fish vending part of their identity. The increased need to contribute financially sometimes creates tension within families, especially when male fishers experience reduced earning capacity. These social strains reflect deeper anxieties about the future of fishing as a viable livelihood.

3.24 Youth Disengagement and Occupational Shifts

Younger generations in fishing communities increasingly view fishing as an unstable and unattractive livelihood. Many youths seek employment in tourism, construction, hospitality, or overseas, particularly in Gulf countries. The shift is driven by: The unpredictability of fish availability; Rising operational costs; Exposure to extreme weather events; Perceived lack of dignity and stability in fisheries work. This migration affects community cohesion. Traditional knowledge transfer from older to younger generations weakens. Fewer young people learn skills such as net mending, navigation, and species identification. Over time, the erosion of knowledge may further undermine the community's ability to cope with environmental change.

3.25Labour Patterns and Work Dynamics in Fisheries

Fluctuating catches affect not only fishers but also the broader labour ecosystem. Auctioneers, ice factory workers, transporters, boat crew, and harbour labourers all depend on consistent landings. When catches fall:

Harbours operate below capacity; Auction rooms run shorter hours; Transport trucks remain idle; Ice factories lose revenue; Seasonal migrant labour faces unemployment. Conversely, occasional high-catching days create labour surges requiring additional hands, but these are temporary and unpredictable. This unstable labour rhythm creates uncertainty throughout the coastal economy, extending the impact of climate change well beyond fishing households.

3.26Safety Risks and Hazard Exposure

Climate change increases the frequency and severity of storms, cyclones, and rough sea conditions. Small-scale fishers often operate without sophisticated safety equipment, making them vulnerable to accidents. Fishers report more unpredictable weather, with sudden squalls, strong currents, and shifting wind patterns that amplify risk. Expanding hypoxic zones and changing water colour make it difficult to read the sea using traditional techniques. Many households cope with these risks by reducing fishing trips or avoiding certain seasons. While this enhances safety, it reduces income and deepens financial strain. The psychological impact is considerable: fishers describe heightened anxiety, fear of accidents, and stress during long hours at sea.

3.27Social and Cultural Impacts

Fishing communities possess rich cultural traditions tied to the sea. Rituals, festivals, boat blessings, and community gatherings reinforce social solidarity. However, declining fish availability undermines these traditions. Boat-owner cooperatives sometimes fragment under financial stress; communities experience tension over access to fishing grounds; conflicts arise between traditional and mechanized craft; and uncertainty fuels pessimism about the future. Cultural narratives shift from pride in fishing heritage to fear of livelihood collapse. Elders express concern that younger generations will not sustain fishing traditions. The erosion of cultural identity is one of the most intangible yet profound consequences of climate change [6].

4 CLIMATE CHANGE, FISHING EFFORT, AND LIVELIHOOD ADAPTATION STRATEGIES IN KERALA

The challenges posed by climate change and ecological disruptions have compelled Kerala's small-scale fishing communities to adopt various adaptation strategies, both formal and informal. These strategies encompass changes in fishing effort, gear modification, seasonal and spatial shifts in fishing activity, diversification of livelihoods, cooperative structures, and engagement with governmental and non-governmental support mechanisms. Understanding these adaptations is critical for designing sustainable fisheries management policies that can simultaneously conserve marine resources and enhance socioeconomic resilience.

4.2 Intensification and Shifts in Fishing Effort

A common adaptive response to declining fish availability is increased fishing effort. Fishers often embark on longer trips, operate more frequently, or fish during previously avoided times. This effort intensification is evident in several districts along Kerala's coast. For instance, fishermen who once relied solely on daylight trips now engage in extended night fishing to target migratory shoals. However, intensified effort is a double-edged sword. While it temporarily offsets income loss, it often results in diminishing returns due to lower fish density, ecosystem stress, and higher operational costs. Fuel expenditures, wear and tear on nets, and risk exposure rise sharply. Over time, this strategy can accelerate depletion of fish stocks, particularly for vulnerable pelagic species such as sardines and mackerel.

4.3 Gear Modification and Technological Adaptation

Small-scale fishers have attempted to adjust their gear to cope with changing fish behavior and distribution. Modifications include altering net mesh sizes, adjusting net depth, experimenting with different net shapes, and using small motorized craft to access distant shoals. For example, the adoption of drift gill nets with adjustable depth mechanisms allows fishers to reach mid- water layers where small pelagics have migrated due to thermal stress. Similarly, some communities have started using ring seines with limited mechanization to expand the area of operation without fully transitioning to mechanized fleets. These adaptations require technical knowledge, financial investment, and maintenance. Fishers with limited capital or access to credit are often excluded, reinforcing socioeconomic disparities within communities.

4.4 Seasonal and Spatial Shifts in Fishing Patterns

Climate-induced changes in species distribution have necessitated temporal and spatial shifts in fishing. Traditional fishing calendars, once synchronized with monsoon winds and upwelling, are now unreliable. Artisanal fishers increasingly rely on observational cues such as water temperature, plankton blooms, and seabird activity to locate schools. Spatial shifts include fishing farther offshore or along less exploited sections of the coast. This is particularly evident in northern Kerala, where fishers from Kasaragod and Kannur travel several kilometers northward or into deeper waters to access sardine and mackerel shoals. While these shifts improve catch success, they increase fuel costs, trip duration, and exposure to rough seas. The effectiveness of spatial and temporal adaptation is constrained by vessel type, local regulations, and safety considerations. Small boats, lacking onboard navigation and safety equipment, face higher risks when attempting offshore excursions.

4.5 Diversification of Livelihoods

Given the volatility of fish availability, many fishing households have pursued livelihood diversification. Common strategies include: Part-time employment in tourism, construction, and hospitality; Engagement in small-scale agriculture, livestock rearing, or aquaculture; Women entering cottage industries, retail, or fish processing outside peak fishing seasons; Migration of male youth to urban centers or Gulf countries. Diversification improves income stability but introduces trade-offs. Fishers spending less time at sea may accumulate less ecological knowledge, potentially reducing their long-term adaptive capacity. Moreover, non-fishing income is often lower and less predictable, creating social and economic stress.

4.6 Community-Based and Cooperative Strategies

Kerala has a long tradition of fisher cooperatives, which provide collective marketing, credit access, and equipment sharing. These structures have proved invaluable in mitigating climate-related risks. For instance: Cooperative-run ice plants and cold storage facilities help preserve catches when fish availability is sporadic; Collective bargaining stabilizes prices in fluctuating markets; Shared credit and pooled resources allow communities to maintain boat and gear operations despite income volatility. Some cooperatives have initiated community monitoring of fish stocks, sharing knowledge about shifting species patterns. These local knowledge systems complement scientific monitoring and enhance adaptive capacity.

Despite these advantages, cooperatives face challenges: reduced membership due to youth migration, conflicts over access rights, and insufficient support during extreme environmental events.

4.7 Engagement with Governmental and Non-Governmental Support

Government agencies provide a range of support mechanisms, including: Subsidized boat repairs and gear replacement programs; Insurance schemes for fishermen; Weather forecasting and early warning systems for cyclones; Training programs for alternative livelihoods; Subsidies for ice, fuel, and cold storage infrastructure. Non-governmental organizations (NGOs) supplement these efforts by offering: Community awareness programs on climate resilience; Microcredit schemes for women and marginalized fishers; Skill development workshops; Advocacy for sustainable fishing practices. While helpful, the effectiveness of these interventions is uneven. Coverage gaps, bureaucratic delays, and insufficient customization for local ecological conditions often limit impact. Effective adaptation requires coordinated strategies that integrate ecological monitoring, socioeconomic planning, and community engagement.

4.8 Risk Management Through Knowledge and Innovation

Traditional ecological knowledge continues to inform adaptive strategies. Fishers observe changes in water colour, bird activity, and sea surface temperature to locate fish. Seasonal indicators, such as flowering of coastal mangroves or changes in plankton density, guide timing of fishing trips. Innovations complement traditional knowledge. Mobile apps providing real- time weather updates, GPS-based navigation, and market price alerts allow fishers to make informed decisions. Some communities have started using fish aggregating devices (FADs) to attract small pelagics nearshore, reducing the need for long offshore trips. Integration of traditional and modern knowledge represents a promising avenue for resilience, though equitable access to technology remains a challenge.

4.9 Social Networks and Informal Safety Nets

Fishermen rely heavily on social networks for risk sharing and survival. These networks provide: Mutual aid during extreme weather; Sharing of equipment and vessels; Information on distant fish schools; Temporary labour support during high-intensity fishing periods. During years of poor landings, these networks serve as informal safety nets. However, as climate change intensifies uncertainty, the strain on social networks grows. Out-migration, rising debt, and declining fish availability reduce the capacity for mutual support, weakening community resilience.

4.10 Adaptive Coping vs Maladaptive Responses

Not all adaptation strategies are beneficial in the long term. Some responses, while mitigating immediate economic stress, exacerbate ecological or social vulnerability. Examples include: Overfishing small pelagic stocks by extending trip durations or intensifying net effort; Shifting to destructive fishing methods to capture remaining stocks; Excessive reliance on debt to sustain livelihoods during lean years; Ignoring safety precautions during offshore trips. These maladaptive responses highlight the need for integrated policies that balance immediate livelihood needs with long-term ecological sustainability.

4.11 Policy Implications for Climate-Resilient Fisheries

The observed adaptations suggest several policy priorities:

Promote sustainable fishing practices: Encourage gear modifications and seasonal closures that align with ecological realities. Enhance access to credit and insurance: Tailored financial products reduce dependence on high-interest informal loans. Support livelihood diversification: Provide training, microenterprise support, and skill development for non-fishing income sources. Strengthen community cooperatives: Expand cooperative-run infrastructure and improve governance to facilitate collective risk management. Integrate technology with traditional knowledge: Encourage use of mobile applications, FADs, and monitoring tools while preserving local ecological knowledge. Monitor species and environmental trends: Continuous scientific monitoring allows timely policy interventions and early warning for fishers. Address gender and youth inclusion: Ensure women and youth have equal access to adaptation resources, training, and decision-making platforms. Integrated approaches combining ecological monitoring, socioeconomic support, and community engagement are essential to enhance the resilience of small-scale fishing communities under climate stress [8].

5 ECONOMIC MODELLING AND RISK ASSESSMENT FOR SMALL-SCALE FISHERIES UNDER CLIMATE CHANGE

Quantifying the socioeconomic impacts of climate-induced shifts in fish availability requires systematic economic modelling and risk assessment. Small-scale fishers in Kerala face fluctuating income, high operational costs, and variable access to resources. Climate change intensifies these dynamics by altering species abundance, distribution, and seasonality, which directly affect both revenues and expenditures. This section integrates ecological trends with economic models to assess the vulnerability, resilience, and risk exposure of artisanal fisheries, providing insights for policy intervention.

Scenario	Quantity (kg/day)	Price (INR/kg)	Cost (INR/day)	Net Income (INR/day)
Pre-2015 (stable fish)	50	200	3,000	7,000
Post-2015 (declining fish)	25	300	3,500	3,250
Extreme scarcity year	10	400	4,000	0

The model demonstrates how climate-induced scarcity can reduce net income dramatically, even when market prices rise. Operational costs increase due to longer trips, more fuel consumption, and gear repair, which further erode profits.

7.2 Income Volatility and Risk Exposure

Income volatility is a key dimension of economic vulnerability. Standard deviation of daily or seasonal income ((\sigma_I)) can quantify the risk associated with unpredictable fish availability. Pre-2015, (\sigma_I) was relatively low because sardine and mackerel stocks were predictable. After 2015, (\sigma_I) has increased significantly, reflecting higher variability in catches.

Volatility directly affects household decision-making:

- **Credit and debt**: High volatility increases reliance on short-term loans, often at high interest rates.
- **Consumption smoothing**: Families must adjust food and health expenditures based on unpredictable income.
- **Investment**: Risk-averse fishers delay investment in gear or diversification due to uncertain returns.

This reinforces the need for targeted risk management interventions, such as microinsurance, flexible credit, and cooperative pooling.

7.3 Cost Structures and Operational Efficiency

Operational costs (C) are affected by vessel type, trip distance, fuel efficiency, and maintenance needs. Climate-induced fish migration increases the distance small-scale fishers must travel, increasing fuel expenditure and labour costs. Additional costs arise from gear modifications necessary to capture shifting species. For small-scale fishers, these costs often account for 40–60% of gross income, leaving little buffer for savings or debt repayment.

Cost Component	Pre-2015 (INR/day)	Post-2015 (INR/day)	Notes
Fuel	1,000	1,500	Longer trips due to species shifts
Net maintenance	500	700	Gear adaptation for pelagic species
Labour	800	1,000	Increased crew for extended trips

Ice and storage	300	300	Constant across periods
Boat maintenance	400	400	Routine repairs
Total Cost	**3,000**	**3,900**	

The table shows how costs escalate under climate-induced ecological variability, squeezing net income.

7.4 Price Dynamics and Market Responses

Fish prices ((P)) often rise when supply declines, but this does not fully compensate for reduced quantity ((Q)). During scarcity years, prices of sardines, mackerel, and anchovies may double or triple. However, several factors limit income gains:

- Smaller catches reduce total revenue despite higher unit prices.
- Market access can be constrained if landing centers operate irregularly.
- Low-value species that dominate post-collapse landings fetch poor market prices, reducing net income.

While price rises partially offset income loss, the high volatility of fish landings limits the stabilizing effect of markets.

Species	Pre-2015 Avg Price (INR/kg)	Post-2015 Avg Price (INR/kg)	Demand Effect
Sardine	200	400	High demand, low supply
Mackerel	250	500	Seasonal fluctuation
Anchovy	150	300	Moderate demand

Species	Pre-2015 Avg Price (INR/kg)	Post-2015 Avg Price (INR/kg)	Demand Effect
Threadfin bream	100	120	Low-value substitution
Ribbonfish	80	100	Low-value alternative

7.5 Scenario Analysis: Future Climate Impacts

Scenario modelling allows projection of potential future risks. Consider three climate scenarios:

1. **Moderate Warming (1–1.5°C increase, stable monsoons)**: Sardine and mackerel recover partially; small pelagic landings fluctuate ±20%. Net income reduces by 20– 30% compared to historical norms.
2. **High Warming (2–2.5°C increase, erratic monsoons)**: Small pelagics decline sharply; low-value species dominate. Income drops 50–70%; debt reliance increases; household food security deteriorates.
3. **Extreme Events (Marine heatwaves, cyclones, hypoxia zones)**: Catastrophic scarcity of nearshore species; net income may approach zero in certain months; adaptive capacity overwhelmed; migration out of fisheries increases.

These scenarios highlight the urgent need for adaptation and risk mitigation policies.

7.6 Risk Mitigation Strategies

Economic modelling suggests several key strategies to reduce vulnerability:

- **Diversified income portfolios**: Income from fisheries plus alternative livelihoods reduces dependency on variable catches.
- **Community pooling and cooperatives**: Collective storage, shared ice, and joint marketing stabilize income.
- **Insurance mechanisms**: Weather and catch insurance reduce financial shocks from extreme events.
- **Fuel and gear subsidies**: Targeted subsidies reduce operational costs, increasing net returns.
- **Market interventions**: Price stabilization mechanisms during scarcity prevent extreme revenue loss.

7.7 Integrating Ecological and Economic Indicators

A holistic risk assessment combines ecological and economic indicators:

[Vulnerability = f(Fish Availability, Income Volatility, Debt Levels, Safety Risk, Community Resilience)

For example:

- **Fish Availability (Q)**: Declining trend increases vulnerability.
- **Income Volatility ((\sigma_I))**: High standard deviation indicates greater economic risk.
- **Debt Levels (D)**: High reliance on informal loans magnifies financial vulnerability.
- **Safety Risk (S)**: Exposure to storms or offshore hazards increases non-financial risk.
- **Community Resilience (R)**: Strong cooperatives and social networks mitigate overall vulnerability.

By weighting these indicators, policymakers can prioritize districts and communities for intervention.

7.8 District-Level Risk Assessment

District-level analyses reveal heterogeneity in vulnerability. Southern districts (Thiruvananthapuram, Kollam) face high exposure due to early sardine collapse, weaker upwelling, and intensive trawling. Northern districts (Kannur, Kasaragod) exhibit slightly lower vulnerability due to more stable mackerel availability and active cooperatives.

District	Fish Availability	Income Volatility	Debt Levels	Safety Risk	Resilience	Overall Vulnerability
Thiruvananthapuram	Low	High	High	High	Moderate	Very High
Kollam	Low	High	High	High	Moderate	Very High
Alappuzha	Moderate	High	Moderate	Moderate	High	High
Kannur	Moderate	Moderate	Moderate	Moderate	High	Moderate
Kasaragod	Moderate	Moderate	Low	Moderate	High	Moderate

7.10 Summary: Economic Risk and Climate Change

Economic modelling demonstrates that:

1. Declining fish availability directly reduces net income for small-scale fishers.
2. Operational costs increase as climate-driven changes force longer trips and gear adaptations.
3. Income volatility and debt cycles amplify socioeconomic risk.
4. Market prices partially buffer income loss but cannot fully compensate for scarcity. District-level heterogeneity necessitates targeted, context-specific interventions.
5. Adaptive strategies—including diversification, cooperatives, and insurance—can enhance resilience if effectively implemented.

The integration of ecological, economic, and social indicators provides a comprehensive framework for understanding risk exposure and guiding policy interventions for small-scale fisheries in Kerala under climate change [9].

6 POLICY FRAMEWORKS, GOVERNANCE, AND CLIMATE-RESILIENT FISHERIES MANAGEMENT IN KERALA

The impacts of climate change on small-scale fisheries in Kerala underscore the critical need for robust governance, adaptive policy frameworks, and integrated management approaches. Climate-induced shifts in fish availability not only threaten livelihoods but also disrupt social cohesion, traditional knowledge systems, and regional economies. Effective policy must therefore address ecological sustainability, socioeconomic resilience, and institutional capacity simultaneously. This section examines the existing policy landscape, governance mechanisms, and potential pathways for fostering climate-resilient fisheries in Kerala.

6.2 Overview of Fisheries Governance in Kerala

Kerala's fisheries sector is governed through a combination of national legislation, state-specific policies, and local institutional frameworks. Key governing bodies include:

- **The Department of Fisheries, Kerala**: Responsible for regulation, licensing, infrastructure development, and welfare schemes.
- **Marine Fisheries Regulation Acts (MFRA)**: Implemented under state and central frameworks to manage resource access, gear restrictions, and fishing seasons.
- **Fisheries Cooperatives and Societies**: Local-level organizations managing shared resources, credit facilities, ice plants, and marketing.
- **Non-Governmental Organizations (NGOs)**: Engage in capacity building, awareness campaigns, and community-level risk mitigation.

These institutions operate within a decentralized governance model, where local panchayats and cooperatives play critical roles in implementation.

6.3 Existing Policy Measures for Climate Adaptation

Kerala has initiated several programs to support small-scale fishers in coping with environmental variability:

1. **Subsidies for Mechanization and Gear Modification**: Financial assistance for small motorized boats, fuel-efficient engines, and improved fishing nets.
2. **Insurance Schemes**: Weather-based crop and fish catch insurance schemes intended to mitigate loss from cyclones, floods, and extreme weather.
3. **Skill Development and Livelihood Diversification Programs**: Training in aquaculture, fish processing, and alternative income generation.
4. **Infrastructure Development**: Construction of harbors, cold storage facilities, ice plants, and auction halls to stabilize post-harvest losses.
5. **Early Warning and Forecasting Systems**: Provision of real-time weather updates and cyclone alerts through mobile apps, SMS, and local radio channels.

Despite these measures, gaps remain in terms of reach, inclusivity, and integration with climate science.

6.4 Challenges in Policy Implementation

Several factors constrain the effectiveness of existing policies:

- **Fragmented Governance**: Overlapping responsibilities among state departments, cooperatives, and panchayats create coordination challenges.
- **Limited Access for Marginalized Fishers**: Small-scale and women fishers often face difficulties in accessing subsidies, loans, and insurance due to bureaucratic hurdles.
- **Insufficient Data Integration**: Policy decisions frequently lack integration of real-time ecological data, leading to delayed or misaligned interventions.
- **Reactive vs. Proactive Measures**: Many programs focus on post-disaster relief rather than proactive resilience-building.
- **Inadequate Gender and Youth Focus**: Women and youth, despite being crucial stakeholders, are often underrepresented in governance and decision-making structures.

These gaps highlight the need for systemic reform and adaptive governance to address climate- driven vulnerabilities.

6.5 Towards Climate-Resilient Fisheries Management

Climate-resilient fisheries management involves integrating ecological, social, and economic dimensions into coherent strategies. Key principles include:

1. **Ecosystem-Based Management**: Policies should consider interdependencies among species, habitats, and human communities, rather than targeting individual species in isolation.
2. **Adaptive Management**: Management plans must be flexible, incorporating real-time monitoring, feedback loops, and iterative policy adjustment.
3. **Participatory Governance**: Fishers, cooperatives, local authorities, and NGOs should be actively involved in decision-making processes.
4. **Equity and Inclusion**: Ensuring women, youth, and marginalized groups have equal access to resources, training, and policy benefits.
5. **Science-Policy Integration**: Use of climate models, ecological monitoring, and socioeconomic data to inform proactive policy measures.

By embedding these principles, governance can shift from reactive crisis management to proactive resilience-building.

7.6 Institutional Mechanisms for Adaptive Governance

Kerala can strengthen governance through institutional mechanisms that enhance coordination, accountability, and responsiveness:

- **District-Level Fisheries Risk Units**: Multi-stakeholder teams monitoring climate impacts, species distribution, and market dynamics.
- **Cooperative Networks for Shared Resources**: Linking harbors, ice plants, and auction centers to reduce inefficiencies and enhance collective bargaining.
- **Community-Based Monitoring**: Fishers trained to document seasonal shifts, species availability, and ecological anomalies, feeding data into decision-making platforms.
- **Digital Platforms**: Mobile applications that combine weather alerts, market prices, species tracking, and policy updates for fishers and cooperatives.

Such mechanisms allow timely interventions and strengthen local capacity for climate adaptation.

7.7 Economic Instruments for Climate-Resilient Fisheries

Economic tools can complement governance reforms:

1. **Subsidies for Climate-Adaptive Gear**: Supporting fuel-efficient engines, FADs (fish aggregating devices), and mesh-adjustable nets reduces operational risk.

2. **Targeted Insurance**: Index-based insurance covering extreme weather, fish scarcity, and infrastructure damage.
3. **Market Stabilization Mechanisms**: Price guarantees or minimum support prices during low-catch periods to prevent income collapse.
4. **Microcredit for Diversification**: Loans for alternative livelihoods, women-led fish processing enterprises, and community-based aquaculture.

These measures help buffer fishers from economic shocks while incentivizing sustainable practices.

7.8 Social Protection and Livelihood Security

Social protection programs are crucial in reducing vulnerability:

- **Fisher Welfare Schemes**: Pension schemes, housing support, and healthcare benefits improve household resilience.
- **Skill Development Programs**: Training in alternative livelihoods, entrepreneurship, and aquaculture enhances adaptive capacity.
- **Women's Empowerment Initiatives**: Credit access, training in fish processing, and market support strengthen household income and decision-making capacity.

By linking social protection with climate adaptation, policies can mitigate both ecological and socioeconomic risks.

7.9 Community-Based Adaptation Practices

Kerala's small-scale fishing communities have historically employed local adaptation strategies, which can be integrated into formal governance:

- **Rotational Fishing Areas**: Community agreements to prevent overfishing and allow stock recovery.
- **Shared Ice and Cold Storage**: Cooperatives manage resources collectively, reducing post-harvest loss.
- **Seasonal Fishing Calendars**: Combining traditional knowledge with ecological data to optimize timing of fishing trips.
- **Peer Networks for Safety and Support**: Informal systems for crew sharing, emergency response, and mutual aid during extreme weather.

Recognizing and formalizing these practices can enhance local ownership of climate resilience measures.

7.10 Policy Recommendations for Kerala

Based on the integration of ecological, economic, and social evidence, the following policy actions are recommended:

1. **Strengthen Multi-Level Governance**: Create district and panchayat-level fisheries risk management units coordinating with state agencies.
2. **Enhance Access to Financial Instruments**: Expand insurance coverage, credit access, and subsidies for small-scale and marginalized fishers.
3. **Integrate Traditional and Scientific Knowledge**: Develop participatory monitoring systems combining fisher observations with scientific data.
4. **Promote Gender-Inclusive Policies**: Ensure women's participation in cooperatives, decision-making bodies, and training programs.
5. **Facilitate Diversification and Skill Development**: Support part-time employment, aquaculture, and small enterprise development.
6. **Implement Ecosystem-Based Management**: Include protected zones, seasonal closures, and sustainable catch limits aligned with climate projections.
7. **Strengthen Early Warning Systems**: Combine mobile alerts, radio broadcasting, and community communication to reduce disaster risk. These strategies aim to create a robust, climate-resilient, and socially inclusive fisheries sector [10].

8 CASE STUDIES AND EMPIRICAL EVIDENCE FROM KERALA'S COASTAL

COMMUNITIES

Kerala's coastline, extending approximately 590 kilometers along the Arabian Sea, is home to a diverse network of small-scale fishing communities. These communities are highly sensitive to climate-induced shifts in fish availability, which affect both ecological and socioeconomic outcomes. Empirical studies and field surveys offer rich insights into the lived experiences of fishers, illustrating adaptive strategies, challenges, and the efficacy of governance interventions. This section presents selected case studies from northern, central, and southern districts of Kerala, highlighting regional variation, adaptive responses, and policy implications.

8.7 Northern Kerala: Kannur and Kasaragod Districts

8.7.1 Ecological Observations

Kannur and Kasaragod districts are characterized by a mix of nearshore and offshore fishing activities, with small-scale mechanized and traditional craft operating along estuaries and the continental shelf. Recent studies indicate:

8.7.1.1 **Shifts in Pelagic Fish Stocks**: Sardine and mackerel shoals have migrated northward, likely influenced by rising sea surface temperatures and altered upwelling patterns.

8.7.1.2 **Decline in Traditional Species**: Anchovies and threadfin bream, historically abundant nearshore, are observed less frequently during pre-monsoon months.

8.7.1.3 **Emergence of Alternative Species**: Ribbonfish and small pelagic substitutes have become more prevalent, altering catch composition and market dynamics.

8.7.2 Socioeconomic Impacts

Fishers in Kannur report the following impacts:

8.7.2.1 **Income Volatility**: Daily earnings fluctuate by 50–70% between high- and low-catch periods, forcing households to rely on informal loans.

8.7.2.2 **Operational Stress**: Increased trip distances, higher fuel consumption, and extended fishing hours have raised costs.

8.7.2.3 **Youth Migration**: Many male youth have migrated to Gulf countries for employment due to declining fish availability, altering family structures and labor dynamics.

8.7.3 Adaptive Practices

Fishers have employed several adaptation strategies:

8.7.3.1 **Gear Modification**: Use of adjustable-depth gill nets and light attractors for nocturnal fishing.

8.7.3.2 **Cooperative Networking**: Ice plants and cold storage shared among cooperative members mitigate post-harvest loss.

8.7.3.3 **Diversification**: Households supplement income through agriculture, aquaculture, and small businesses.

8.7.3.4 **Knowledge Integration**: Local ecological knowledge guides fishing calendars and spatial targeting.

8.7.4 Observed Outcomes

8.7.4.1 **Economic Resilience**: Households with diversified income and cooperative membership exhibit higher stability.

8.7.4.2 **Social Adaptation**: Youth migration has reduced labor availability, challenging traditional knowledge transfer.

8.7.4.3 **Ecological Pressure**: Intensified fishing effort in offshore areas raises concerns about overexploitation [11].

8.8 Central Kerala: Alappuzha and Kollam Districts

8.8.1 Ecological Observations

Central Kerala's backwaters and estuarine systems historically supported small-scale fishers reliant on sardines, mackerel, and shellfish. Key changes include:

8.8.1.1 **Erratic Fish Arrival**: Climate variability has disrupted monsoon-linked upwelling, leading to delayed or absent shoals.

8.8.1.2 **Species Composition Shifts**: Low-value species dominate catches, reducing market revenue.

8.8.1.3 **Increased Cyclone Exposure**: Coastal infrastructure and fishing activity are increasingly threatened by cyclonic events in the Arabian Sea.

8.8.2 Socioeconomic Impacts

8.8.2.1 **Income Reduction**: Average daily earnings dropped by 30–50% during post-monsoon scarcity periods.

8.8.2.2 **Debt Accumulation**: Fishers increasingly rely on informal credit networks, with high- interest repayments.

8.8.2.3 **Gendered Impacts**: Women's role in fish processing and marketing is constrained due to reduced supply and limited storage capacity.

8.8.3 Adaptive Practices

8.8.3.1 **Rotational Fishing Zones**: Communities implement informal spatial rotation to prevent localized overfishing.

8.8.3.2 **Ice and Cold Storage Sharing**: Cooperative management of ice plants mitigates spoilage during lean periods.

8.8.3.3 **Alternative Livelihoods**: Training programs in aquaculture, handicrafts, and tourism- related employment are utilized.

8.8.3.4 **Safety Protocols**: Adoption of early warning alerts for storms reduces disaster-related losses.

8.8.4 Observed Outcomes

8.8.4.1 **Economic Buffering**: Cooperatives and alternative income sources partially stabilize earnings.

8.8.4.2 **Knowledge Gaps**: Traditional ecological indicators are becoming less reliable under changing climatic conditions.

8.8.4.3 **Vulnerability of Marginalized Fishers**: Landless and small-boat fishers face higher risk due to limited access to adaptive resources [12].

8.8.5 Southern Kerala: Thiruvananthapuram District

8.8.6 Ecological Observations

Southern Kerala's coastal communities are highly exposed to environmental stress:

8.8.6.1 **Decline in Sardine and Mackerel Stocks**: Sustained decline observed over the last decade, linked to marine heatwaves.

8.8.6.2 **Shallow Water Depletion**: Nearshore ecosystems, including seagrass beds and estuaries, show reduced biodiversity due to trawling and sedimentation.

8.8.6.3 **Increased Frequency of Extreme Events**: Cyclones, storm surges, and flooding events are increasingly common.

8.8.7 Socioeconomic Impacts

8.8.7.1 **Severe Income Decline**: Many households report near-zero daily earnings during peak scarcity periods.

8.8.7.2 **High Debt Levels**: Reliance on informal loans is widespread, with repayment pressures exacerbating vulnerability.

8.8.7.3 **Outmigration and Labor Shortages**: Male youth migration has disrupted traditional fishing knowledge transfer.

8.8.7.4 **Social Stress**: Household tensions and community disputes over limited resources are reported.

8.8.8 Adaptive Practices

8.8.8.1 **Extended Trip Effort**: Fishers travel further offshore, despite safety risks, to access remaining pelagic stocks.

8.8.8.2 **Microenterprise Initiatives**: Some households engage in fish processing, retail, and small-scale aquaculture.

8.8.8.3 **Cooperative Engagement**: Ice and storage facilities, when functional, stabilize supply and revenue.

8.8.8.4 **Technology Use**: Limited adoption of mobile apps for weather alerts and market prices, though constrained by digital literacy.

8.8.9 Observed Outcomes

8.8.9.1 **High Vulnerability**: Households without cooperative membership or alternative income exhibit extreme socioeconomic stress.

8.8.9.2 **Safety Risks**: Offshore trips increase exposure to storms and accidents.

8.8.9.3 **Policy Gaps**: Limited access to subsidies, insurance, and credit exacerbates vulnerability.

8.9 Comparative Analysis Across Regions

District	Fish Availability	Income Volatility	Adaptive Capacity	Migration	Cooperative Engagement	Overall Vulnerability
Kannur	Moderate	High	High	Moderate	Strong	Moderate
Kasaragod	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Alappuzha	Low	High	Moderate	Low	Strong	High
Kollam	Low	High	Moderate	Low	Moderate	High
Thiruvananthapuram	Very Low	Very High	Low	High	Moderate	Very High

8.10Lessons Learned from Case Studies

1. **Diversity of Adaptive Strategies**: Communities employ a combination of technical, social, and economic adaptations, highlighting the importance of multifaceted resilience strategies.
2. **Cooperative Membership as a Buffer**: Fishers involved in cooperatives experience better income stability, access to resources, and collective risk management.
3. **Gender and Social Equity Matters**: Women and marginalized fishers face higher barriers to adaptation, emphasizing the need for inclusive policy design.
4. **Traditional Knowledge Under Stress**: Changing environmental patterns reduce the reliability of historical ecological indicators, necessitating integration with scientific monitoring.
5. **Regional Policy Tailoring**: Northern districts show moderate vulnerability with strong cooperatives, while southern districts face extreme vulnerability, requiring targeted intervention.

9.7 Policy Implications from Empirical Evidence

- **Targeted Support**: Southern districts require immediate interventions in credit, insurance, and alternative livelihoods.
- **Strengthening Cooperatives**: Expansion and Modernization of cooperative infrastructure can enhance resilience across all districts.
- **Technology Integration**: Mobile applications for weather alerts, species tracking, and market prices can enhance adaptive capacity.
- **Gender-Sensitive Programs**: Women's empowerment through training, credit, and leadership roles in cooperatives strengthens household and community resilience.
- **Adaptive Monitoring**: Integration of traditional knowledge with scientific data enables better forecasting and planning.

- **9.8 Summary of Empirical Insights**

The case studies reveal that climate change-induced shifts in fish availability have tangible effects on:

- **Income Volatility**: Reduced catches and operational cost escalation create financial stress.
- **Migration Patterns**: Youth outmigration alters labor dynamics and knowledge transfer.
- **Adaptive Strategies**: Gear modification, trip extension, diversification, and cooperative participation are common responses.
- **Social Vulnerability**: Households lacking resources, cooperatives, or alternative income exhibit higher vulnerability.
- **Governance Gaps**: Inefficient policy implementation and limited access to support amplify socioeconomic stress.

These insights provide a strong empirical foundation for designing evidence-based, climate- resilient fisheries policies in Kerala [13].

10. CONCLUSIONS

AND RECOMMENDATIONS

As climate change continues to reshape marine ecosystems, its effects are increasingly felt in the livelihoods of Kerala's small-scale fishermen. The preceding sections have explored these impacts from multiple angles, examining shifts in fish availability, assessing economic consequences through modelling, evaluating policy frameworks, and analyzing lessons from local case studies. Part 10 brings these insights together, weaving them into a coherent narrative that highlights the socioeconomic challenges faced by fishermen, evaluates the effectiveness of existing policies, and outlines strategic, actionable recommendations. The synthesis reveals that ecological shifts are altering both the quantity and timing of fish stocks, affecting key species that underpin local fisheries. Seasonal variations have become less predictable, while the distribution of commercially important species has shifted, creating new uncertainties for fishing communities. These ecological changes translate directly into economic and social consequences, as small-scale fishermen experience fluctuations in income, rising operational costs, and heightened livelihood insecurity. The combination of environmental unpredictability and limited adaptive capacity underscores the vulnerability of these communities, particularly among households with fewer resources and women who often play critical roles in post- harvest activities. Policy and institutional analysis indicates that while government initiatives and local adaptive strategies have mitigated some impacts, gaps remain. Existing regulations, subsidies, and support mechanisms are often insufficient to address the pace and scale of change. Case studies demonstrate that communities employing cooperative approaches, knowledge sharing, and early-warning systems exhibit greater resilience, suggesting that participatory and locally tailored strategies are essential for long-term adaptation. Drawing together ecological, economic, and policy perspectives, the study identifies key conclusions about the nature of vulnerability and resilience in Kerala's small-scale fisheries. Climate-driven changes in fish availability have tangible effects on livelihoods and community well-being, highlighting the urgent need for integrated interventions that combine scientific monitoring, economic planning, and community engagement. Recommendations emerging from this synthesis emphasize regulatory reforms, enhanced adaptive fisheries management, livelihood diversification, skill development, cooperative initiatives, and strengthened research and monitoring systems. Implementation strategies must consider feasibility, potential barriers, and active collaboration among government agencies, NGOs, cooperatives, and local communities to ensure effectiveness. Ultimately, the study underscores that securing the future of Kerala's small-scale fisheries requires approaches that are ecologically informed, economically viable, and socially inclusive. By aligning adaptation strategies with sustainability goals and resilience-building measures, policymakers and stakeholders can help safeguard livelihoods while preserving the ecological integrity of the region's coastal waters. This integrated approach provides a roadmap for navigating the intertwined challenges of climate change, fisheries management, and socioeconomic well-being, ensuring that the voices and needs of small-scale fishermen remain central in shaping a sustainable and resilient future.

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References

[1] Gills R, Padua S, Ramachandran C, Varghese E, Vivekanandan E, Ratheesh KR, George G. Impacts, adaptation and mitigation efforts in Kerala's coastal food system: a socio-ecosystem evaluation of fishing community responses to climate change. International Journal of Advances in Engineering Sciences and Applied Mathematics. 2025 Mar 8:1-9.

[2] Mohan S, Mishra SK, Sahany S, Behera S. Long-term variability of Sea Surface Temperature in the Tropical Indian Ocean in relation to climate change and variability. Global and Planetary Change. 2021 Apr 1;199:103436.

[3] Islam MM, Islam N, Habib A, Mozumder MM. Climate change impacts on a tropical fishery ecosystem: Implications and societal responses. Sustainability. 2020 Sep 25;12(19):7970.

[4] Nagelkerken I, Allan BJ, Booth DJ, Donelson JM, Edgar GJ, Ravasi T, Rummer JL, Vergés A, Mellin C. The effects of climate change on the ecology of fishes. PLOS climate. 2023 Aug 7;2(8):e0000258.

[5] Jha S, Sudhakar SD, Majumder S, Joseph S, Nair TB. A multidecadal study of the Malabar upwelling system influencing Indian Mackerel landings along the coasts of Karnataka and Kerala, south-east Arabian Sea. Journal of Marine Systems. 2024 Nov 1;246:104012.

[6] Cleetus RI, Asha CV, Suson PS, Nandan SB. Species Diversity and community assemblage of planktonic rotifers from Vembanad Estuary-Kerala, India. International journal of oceanography and marine ecological system. 2015 Jan 1;4(1):1.

[7] MENON N. Vulnerability of the fishery dependent communities to climate change in Kerala. Indian Journal of Economics & Business. 2015;14(3):423-35.

[8] Jeevamani JJ, Priya P, Infantina JA, Abhilash KR, Behera DP, Samuel VD, Soundararajan R, Purvaja R, Ramesh R. An integrated approach to assess coastal vulnerability versus fisheries livelihood sustainability: Strategies for climate change adaptation in Sindhudurg, west coast of India. Environment, Development and Sustainability. 2021 Mar;23(3):4011-42.

[9] Hanich Q, Wabnitz CC, Ota Y, Amos M, Donato-Hunt C, Hunt A. Small-scale fisheries under climate change in the Pacific Islands region. Marine Policy. 2018 Feb 1;88:279-84.

[10] Kumaran TV, Joseph R. Understanding Climate Change Impacts and Navigating Pathways to A Resilient Future. Center for Development Economic. 2024 Jan;11(19):01-25.

[11] Baiju KK, Parappurathu S, Ramachandran C, Kaleekal T. Non-state legal systems and their role in governance of small-scale marine fisheries along the south west coast of India. Ocean & Coastal Management. 2020 Feb 1;184:105020.

[12] Vincent SG, Jennerjahn TC, Kunjupillai S, Chattopadhyay S. Ecohydrology of river catchments and coastal backwaters in Kerala, India: An introduction and synthesis. InEcohydrology of Kerala 2025 Jan 1 (pp. 1-6). Elsevier.

[13] Davies M, Béné C, Arnall A, Tanner T, Newsham A, Coirolo C. Promoting resilient livelihoods through adaptive social protection: Lessons from 124 programmes in South Asia. Development policy review. 2013 Jan;31(1):27-58.