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Global Marine Fisheries Bycatch Management: Strategies, Innovations and Contextual Lessons with a Focus on India

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Abstract

Bycatch—the unintended capture of non-target species—remains a critical challenge to marine biodiversity, sustainable fisheries management, and the livelihoods of coastal communities, particularly in developing regions. This review critically examines global strategies, technological innovations, and institutional responses to bycatch management, with a focus on their relevance and adaptability to India's complex, multispecies tropical fisheries. Through a comparative analysis of practices across both developed and developing contexts, the study highlights effective approaches such as gear modifications, digital monitoring tools, ecosystem-based frameworks, and community-led initiatives. While developed nations have made measurable progress through science-based governance and sustained investment, applying such models in India requires adaptation to local ecological diversity, socio-economic dynamics, and institutional settings. Strengthening areas such as inter-agency coordination, data availability, and enforcement mechanisms can further enhance India's capacity to implement effective bycatch management. Additionally, India's extensive trawling activities, the prevalence of juvenile catch, and the growing fishmeal industry underline the importance of integrated, adaptive strategies. The paper advocates for a mitigation hierarchy that balances ecological, economic, and social dimensions. Drawing on global experiences, it emphasizes the need for participatory governance, capacity building, and context-specific policy reforms to support a transition toward sustainable and inclusive bycatch management in India.

Keywords: Bycatch**,** Fisheries management**,** Technological innovations**,** Trawl fisheries**,** Policy frameworks

JEL Classification: Q22, Q28, O13, Q55

Introduction

Marine fisheries are among the most vital renewable resources available to humanity. They sustain millions of livelihoods, contribute significantly to food and nutritional security, and hold deep cultural and economic significance for coastal communities across the world. Today, more than three billion people rely on fish as a primary source of animal protein, and about 60 million are directly engaged in the fisheries and aquaculture sector (FAO, 2022). Clearly, marine resources are not just about food—they are central to development and poverty alleviation in many regions. Yet, the future of global fisheries is increasingly uncertain. Overfishing, habitat destruction, climate change, and one particularly persistent issue—bycatch—continue to place immense pressure on marine ecosystems. Bycatch refers to the unintended capture of non-target species during fishing, often including juveniles of valuable commercial fish, endangered marine animals like turtles and sharks, and species with little or no market value (Thavasi *et al*, 2025). The consequences of this are far-reaching. Bycatch undermines sustainable fisheries management, endangers biodiversity, disturbs marine food webs, and results in large volumes of waste—an especially troubling reality in a world still grappling with hunger and malnutrition.

Globally, bycatch is estimated to contribute over 10 million tonnes of discarded fish each year—roughly 10 per cent of total marine landings (Kelleher, 2005; Davies *et al*, 2009). In certain fisheries, especially those that rely on gear like bottom trawls and longlines, bycatch can make up more than half the total catch. The problem is not only ecological; it's also deeply economic and social, raising questions about waste, equity, and governance. Bycatch has been a major driver of population declines in vulnerable species such as sea turtles, sharks, marine mammals, and seabirds (Lewison *et al*, 2004; Dulvy *et al*, 2014; Wallace *et al*, 2010). These incidental catches contribute significantly to the depletion of

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non-target and threatened species, undermining ecosystem resilience and biodiversity (Baum *et al*, 2003; Hall *et al*, 2000).

In the Indian context, estimates suggest that bycatch accounts for up to 40 per cent of total marine landings, with significant regional variation depending on gear type and fishing grounds (Boopendranath *et al*, 2012; CMFRI, 2021). A study by Thavasi, 2021 estimated that 21 per cent of total marine fish landings in Tamil Nadu are bycatch during the years 2022 to 2023. Trawl fisheries, which dominate India's mechanized fleet, are particularly associated with high levels of bycatch, including juveniles of commercially important species. Much of this bycatch is either discarded or sold at low value, undermining both ecological sustainability and long-term economic returns.

While bycatch is often framed as a loss, in many small-scale and developing country fisheries, it also represents an important source of income and livelihood diversification. In regions where market systems are flexible, bycatch is frequently retained, sold, or processed into value-added products, contributing significantly to household earnings and food security (Clucas, 1997; FAO, 2011). For instance, species that were once discarded are now finding local or niche markets, especially in countries like India, Bangladesh, and Indonesia, where dried, fermented, or low-value fish products are in demand (Salagrama, 2006; Béné *et al*, 2010). In some coastal economies, the commercialization of bycatch supports ancillary industries such as fishmeal production, informal processing units, and street-level retailing, thus creating employment across the value chain (Kelleher, 2005; Aswathy *et al*, 2014). Moreover, with improved handling and cold storage infrastructure, bycatch utilization has seen upward trends in both volume and economic value, especially in tropical multispecies fisheries (De Silva and Yamao, 2006). Hence, under the right governance and market conditions, bycatch can enhance the resilience of fishing communities by providing alternative revenue streams and reducing economic waste.

The Governance Challenge

Tackling bycatch isn't just about changing nets or techniques—it's about making complex decisions that affect ecosystems, economies, and people's lives. Policies such as the mandatory use of Turtle Excluder Devices (TEDs) in U.S. shrimp fisheries, real-time fishery closures in the North Atlantic, and individual vessel quotas in some EU nations offer some positive examples. These efforts are often supported by broader ecosystem-based management (EBM) frameworks and the work of Regional Fisheries Management Organizations (RFMOs) like the North Pacific Fisheries Commission or CCAMLR, which promote shared, science-driven governance of marine resources.

However, not all regions are equally equipped to handle this challenge. In many developing countries—where fisheries are critical for employment and food security—there are significant gaps in capacity. Weak enforcement, limited access to technology, lack of reliable data, and the prevalence of informal, small-scale fisheries all make bycatch management more difficult (Chuenpagdee & Jentoft, 2009; Pauly *et al*, 2002). In these settings, even well-intentioned policies can struggle to take root or have lasting impact.

Innovations in Bycatch Management

Despite the challenges, innovation has opened up new pathways for more responsible fishing. Modifications to fishing gear—like square mesh codends, sorting grids, or escape panels—are helping reduce the capture of undersized or non-target species, particularly in trawl fisheries. In longline fisheries, switching to circle hooks or using bird-scaring lines has proven effective in lowering the accidental deaths of seabirds and sea turtles.

Market-based mechanisms have also shown promise. Eco-labels, certification schemes like the Marine Stewardship Council, and traceability systems are allowing consumers to choose more sustainably caught fish. These initiatives can offer financial incentives for fishers to adopt better practices, especially in markets like Europe and North America. However, for small-scale or developing-country fisheries, high certification costs and bureaucratic barriers often stand in the way (Bush *et al*, 2013).

India's Bycatch Dilemma

India, with its vast coastline of over 8,000 kilometers and an EEZ spanning 2.02 million square kilometers, is one of the world's top marine fish producers (CMFRI, 2022). Its fisheries sector supports the livelihoods of over four million people. Yet, despite its importance, the sector is facing sustainability challenges—many of them linked to bycatch.

Trawling remains the dominant fishing method in India, particularly along the east and west coasts. In some states, trawlers contribute to nearly 70 per cent of marine landings (Vivekanandan *et al*, 2005). But with this dominance comes a downside: a significant share of trawl catches—up to 70 per cent in some harbors like Veraval, Malpe, Rameswaram, and Visakhapatnam—can consist of bycatch (Zacharia and Kizhakudan, 2012; CMFRI, 2021).

Fishmeal plants, while creating jobs and supporting industries like aquaculture, have added complexity to the issue. The use of juvenile fish and low-value catch in these plants raises concerns about overfishing, ecological degradation, and missed economic opportunities in the long run. Moreover, the carbon footprint and pollution generated by these facilities introduce additional environmental costs (Bhathal and Pauly, 2008; Lobo *et al*, 2010).

While bycatch reduction in India has gained attention, capital expenditure on supporting infrastructure—such

as BRDs, sorting facilities, cold chains, and processing units—remains poorly addressed. Small-scale fishers often lack resources for such investments, and while schemes like PMMSY highlight infrastructure development, specific funding for bycatch management is limited (CMFRI, 2021; DAHD, 2020; Srinivas *et al*, 2021). Pilot projects in Gujarat and Kerala show that valorizing bycatch requires targeted capital expenditure for equipment and logistics (Kripa *et al*, 2018). Internationally, similar challenges are noted. Gillett, 2011 and FAO, 2011 emphasize the need for financial support to install bycatch infrastructure, while the OECD (2006) highlights how public funding can bridge investment gaps. These insights underscore the importance of integrating capital expenditure planning into sustainable bycatch management.

Institutional and Policy Landscape

India has taken some steps toward addressing bycatch. The Ministry of Fisheries, working with state departments and research institutes like CMFRI and CIFT, has introduced draft guidelines for more sustainable trawling, promoted square mesh codends, and implemented seasonal fishing bans in certain areas. Community-based marine protected areas and fishery co-management efforts have also been piloted.

Still, enforcement remains patchy. Smaller motorized and mechanized vessels often operate with minimal oversight. Fragmented governance between central and state bodies has led to inconsistent policies and weak coordination. And while subsidies for fuel and gear help support fisher incomes, they can also inadvertently encourage overcapacity and unsustainable practices (Kumar *et al*, 2017).

Clearly, bycatch is not a standalone issue—it sits at the intersection of environmental health, economic strategy, and social equity. That's why this study seeks to examine the various global strategies and innovations developed to manage bycatch, evaluate their effectiveness, and explore how they can be meaningfully adapted to the Indian context.

The study specifically reviewed and analysed global bycatch management frameworks and tried to propose a set of evidence-based recommendations and governance strategies.

Data Sources and Methodology

The study employs a case study methodology to explore the research objectives in depth. This approach allows for a detailed examination of the subject within its real-life context. The case study method is appropriate for gaining a comprehensive understanding of complex issues by focusing on specific instances or locations. It facilitates the collection of rich qualitative data through various sources such as interviews, observations, and relevant documents, enabling a thorough analysis of the topic under investigation. The countries selected for this study were chosen strategically to represent a broad spectrum of socioeconomic, ecological, and governance contexts in marine fisheries management. This diverse selection enables a comprehensive comparative analysis of bycatch management strategies and offers valuable insights for designing adaptable solutions suitable for developing countries like India (FAO, 2022; Pauly and Zeller, 2020). The countries selected for the case study approach represent two broad categories: developed countries and developing or least developed countries (LDCs) with multispecies fisheries. Developed Countries are known for advanced fisheries management systems, robust data reporting, and long-standing engagement with bycatch mitigation measures under ecosystem-based fisheries management (EBFM). Selected countries are:

United States: Leads globally in bycatch regulation through gear modifications, observer programs, and strong legal enforcement (NOAA, 2023).

New Zealand: Pioneers rights-based fisheries and electronic monitoring, aligning ecological and economic objectives (FAO, 2022).

Japan: Combines traditional knowledge with co-management in multispecies fisheries, emphasizing community-based governance (Pauly and Zeller, 2020).

Australia: Implements science-based TACs and transparent bycatch controls, setting global standards in sustainable fisheries (FAO, 2022).

France: Reflects the EU's regional governance under the CFP, focusing on bycatch mitigation in mixed-species fisheries (EU Commission, 2022). These countries were carefully chosen to ensure global representation—such as the United States from the West, France representing Europe, Japan from the East, and Australia from the South—covering all major regions of the world.

Developing and Least Developed Countries (LDCs) offer examples of fisheries with limited capacity, high dependence on marine resources for livelihoods, and gaps in bycatch governance—conditions comparable to India's (MRAG, 2016; FAO, 2022). Selected countries are:

Madagascar: A biodiversity hotspot with high bycatch in artisanal fisheries, facing weak enforcement and pressure from foreign fleets (Pauly and Zeller, 2020).

Taiwan: A major distant water fishing nation addressing IUU and bycatch through recent regulatory reforms (MRAG, 2016).

Thailand: Former IUU-listed country now implementing strong port state measures and inter-agency reforms, showing regulatory progress (EU Commission, 2022; FAO, 2022).

Vietnam: High bycatch and weak enforcement across multispecies fisheries underscore governance challenges in both small- and large-scale sectors (Pauly and Zeller, 2020).

China: The largest marine capture producer, balancing global leadership with ongoing IUU concerns and recent governance improvements (FAO, 2022; MRAG, 2016).

All the selected countries primarily operate in multispecies fisheries, which are often characterized by significant bycatch and discards. However, they tend to have relatively better governance frameworks and management strategies in place to address these issues. This ecological complexity mirrors the operational and ecological conditions prevalent in Indian trawl and gillnet fisheries, making them ideal for comparative assessment.

The study is based entirely on secondary data collected from various sources, including Publish or Perish, Google Scholar, ResearchGate, Sci-Hub, ICAR-CIFT, ICAR-CMFRI, FAO, and BMIS database. The keywords used for literature retrieval included "bycatch management," "bycatch mitigation measures," "bycatch reforms," and "bycatch case study." A total of 70 research papers were referred to for this analysis. A critical component of sustainable fisheries management is managing the incidental capture of non-target species (Reeves *et al*, 2013). Globally, every country is facing challenges in formulating and implementing effective frameworks to address bycatch issues (Kiszka *et al*, 2009). While only a few countries have succeeded in this effort, most are still striving to achieve effective solutions. Some of the mitigation measures adopted by different countries are discussed in the paper.

Results and Discussion

Institutional Frameworks

Several international organizations address bycatch within their mandates, notably the Bycatch Management Information System (BMIS) and Regional Fisheries Management Organizations (RFMOs). These bodies contribute through guidelines, gear regulations, and research coordination (Fitzsimmons *et al*, 2015; Lodge *et al*, 2017).

Regional Fishery Management Organisation (RFMO)

The key actors in the management of high seas and international fisheries are regional fisheries management organizations (Lodge *et al*, 2017). It is an Intergovernmental organisation and a type of RFB (Regional Fisheries Body) entrusted with the sustainable management of fish stocks in a particular region, or of highly migratory species. RFMOs are, in turn, more politicised, so the science-focused recommendations issued by the relatively independent RFABs often constitute the scientific input to the RFMOs, where they are subject to political negotiations between the members, in order to adjust them to social and economic reality. Figure 1 depicts the RFMO's situated across the world.

Status of Indian Bycatch Management

As India is a multispecies fisheries nation, management of bycatch becomes very complex and ineffective (Prakash *et al*, 2019). As a part of resource management, nationwide fishing ban period is followed in different seasons for the two different coasts (East Coast - April 15 to June 14 and West coast - June to July 31). In some states, there exist a ban on usage of purse seine, as it has the highest bycatch ratio compared to other fishing gears (Ramesh *et al*, 2018). There has been a drastic increase in the research field on bycatch mitigation measures/bycatch management measures in the past two decades which indicates the importance its effect and existence (Naidu *et al*, 2017). Table 1 presents an overview of India's membership status in selected global and regional fisheries organizations that play significant roles in marine resource management and policy development.

Several bycatch mitigation reforms and measures have been introduced by ICAR-CMFRI and ICAR-CIFT. ICAR-CMFRI has contributed through innovations in trawl fisheries of Gujarat by altering the cod-end design, the development

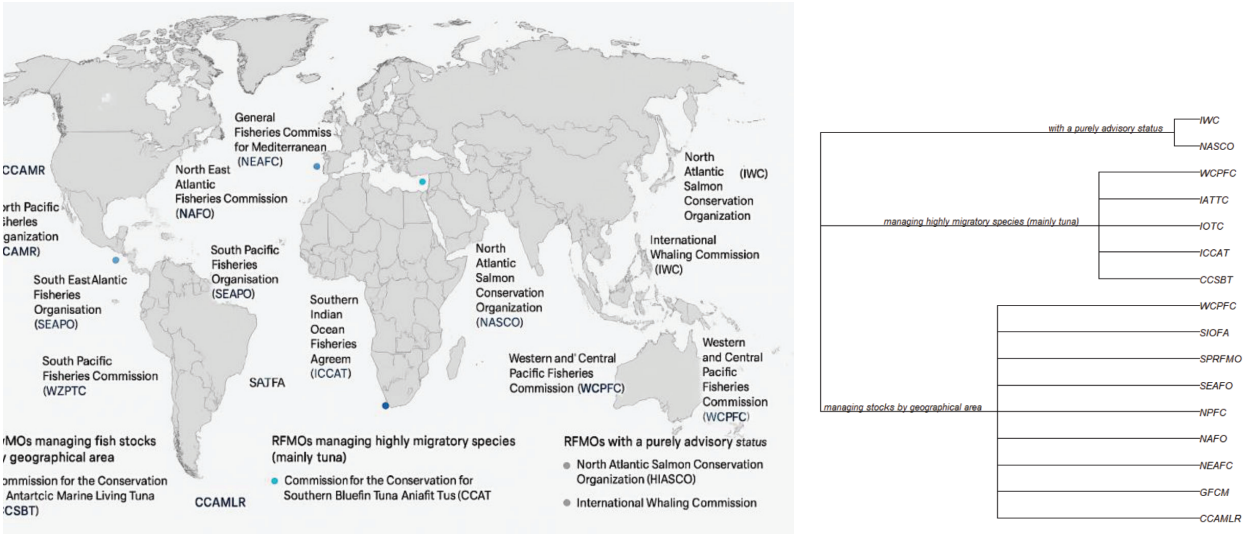

Fig 1. Regional Fishery Management Organisations (RFMO) Across the Globe

of a specialized trawl net for octopus' fishery along the southwest coast of India, and the introduction of a square mesh cod end which is more selective than the traditional diamond mesh. ICAR-CIFT has designed and developed selective pentagonal-shaped fish traps operated along the Gulf of Mannar, changed the colour of gillnets used in the southwest coast of India to reduce unwanted catch, and developed species-specific longline gear to avoid shark bycatch.

Several non-governmental organizations (NGOs) in India are actively working to reduce bycatch. Dakshin Foundation is a non-profit organization that works on conservation and sustainable use of marine and coastal ecosystems in India, with one of its focus areas being the reduction of bycatch in Indian fisheries. The TerraMar Project is a global non-profit organization that works towards ocean conservation and sustainable use, and it has initiatives in India to reduce bycatch in fisheries.

Global case studies in bycatch management

Developed Countries

The United States, with a marine capture production of ~4.23 million metric tons, has adopted diverse bycatch mitigation strategies across taxa such as seabirds, sharks, sea turtles, and cetaceans. For seabirds, bird-scaring (tori) lines deter access to baited hooks (Melvin *et al*, 2014), while night setting further reduces interactions (Department of Fisheries). Hook-shielding devices prevent birds from accessing bait at depth (Scott and Lopez, 2017), and bird deterrent curtains minimize scavenging during gear retrieval (Jordan *et al*, 2013). In shark bycatch management, the U.S. has banned wire leaders (DOF) and encourages reduced soak times (Robbins *et al*, 2020). Circle hooks have proven effective, reducing blue shark bycatch by 17–28% (Yokota *et al*, 2006; Walsh *et al*, 2005; Ward *et al*, 2009; Curran and Bigelow, 2011; Beverley and Curran, 2009). To mitigate sea turtle bycatch, regulations mandate large circle hooks (≥16/0) and deep-setting gear below 40 meters (FAO, 2011). Gear deployment before sunrise further reduces turtle interactions. For cetaceans, the Medina panel allows dolphin escape from nets (Clarke *et al*, 2014), while hook-shielding barriers minimize depredation and mortality.

New Zealand, producing ~0.3 million metric tons, uses both input and output controls to reduce bycatch, especially of endangered sea lions. Trawling is banned within 12 nautical miles of the Auckland Islands, a key habitat, and the Maximum Allowable Level of Fishing Related Mortality (MALFIRM) limits seasonal sea lion bycatch, triggering fishery closure if exceeded (DOF). Marine protected area expansion further supports broader bycatch reduction efforts.

Japan, with a marine capture production of ~3.13 million metric tons, operates under a highly regulated fisheries management system to control bycatch. Core mechanisms include vessel registration, national licensing, and enforcement of vessel capacity and gear restrictions. Total Allowable Catch (TAC) and Total Allowable Effort (TAE) systems regulate both harvest volumes and fishing intensity. Destructive gear is legally prohibited. In 2021, the Japanese government invested 16 million Yen in improving bycatch mitigation measures (Jimenez *et al*, 2012; DOF Japan).

Australia, producing ~0.5 million metric tons, prioritizes bycatch reduction of marine mammals and sea turtles. Pingers are widely used to deter cetaceans from gill and trawl nets (Mackay and Knuckey, 2013), while green-coloured nets exploit species' visual sensitivities to reduce entanglements. Square mesh gear, preferred over diamond mesh, aids in non-target species escape (Smith *et al*, 2021). For sea turtles, TEDs are mandatory in trawl fisheries (DOF), and buoyless nets have shown bycatch reduction benefits (Peckham *et al*, 2007). Additionally, trawl bans in coral reef zones protect sensitive habitats from degradation.

France, with ~0.7 million metric tons in marine capture, enforces spatial and gear regulations to limit bycatch and habitat damage. Seine net deployment is prohibited over seagrass beds and coral reefs—critical dugong habitats. On Mayotte and Reunion Islands, hand lining has been restricted to ease pressure on local stocks. The French government has also invested in R&D and technology transfer to advance sustainable fishing and develop effective bycatch mitigation

Table 1: Membership of India in Key Global and Regional Fisheries Organizations

Organization	Headquarters	Membership
International Whaling Commission: IWC	Impington, UK	Yes
International Council for the Exploration of the Sea: ICES	Copenhagen, Denmark,	No
The International Center for Living Aquatic Resources Management (ICLARM)	Penang, Malaysia	-
Inter-American Tropical Tuna Commission: IATTC	California, US	No
International Pacific Halibut Commission: IPHC	Seattle, Washington	No
Pacific Islands Forum Fisheries Agency: FFA	Honiara, Solomon Islands	No
Bay of Bengal Programme: BOBP	Chennai, India	Yes

tools (Amande *et al*, 2010).

Developing Countries

With a marine capture production of approximately 0.1 million metric tons, **Madagascar** has implemented a mix of conservation incentives and community-based approaches to reduce bycatch, particularly of marine mammals. Incentive programs encourage fishers to release incidentally caught marine mammals safely (DOF). Additionally, the promotion of eco-tourism activities such as whale and dolphin watching provides alternative livelihoods for local fishing communities, thereby reducing fishing pressure and bycatch risks (DOF). Understanding fishers' perceptions and attitudes toward bycatch and its management has also been a focus, as studies indicate that engaging fishers is critical for effective implementation of mitigation measures (Razafindrainibe *et al*, 2010).

The Union of the Comoros reports cetacean species frequently as bycatch, prompting regulatory and community-led actions. National policies prohibit destructive fishing methods such as dynamite fishing and the use of poisons (DOF). Furthermore, an official ban on gillnets has been enacted to limit bycatch (DOF). In addition to formal regulations, some local communities enforce informal bans on harmful fishing gear through village associations and fishing syndicates, highlighting the role of traditional governance in bycatch management.

Taiwan has adopted a structured approach to bycatch mitigation through a national observer program that places onboard observers to collect reliable bycatch data (DOF). Government investment in the program rose significantly from US$166,000 in 2002 to over US$5 million by 2013, highlighting increased commitment. The use of circle hooks over J-hooks is promoted to reduce sea turtle bycatch (DOF), supported by nationwide education and outreach campaigns aimed at fostering sustainable fishing practices (Michel and Van Bree, 2015). Strict enforcement, including criminal penalties for the illegal capture of endangered species, further underscores Taiwan's focus on compliance (DOF).

Thailand, with a marine capture production of approximately 1.52 million metric tons, employs a regulatory and technological mix to manage bycatch. The issuance of fishing licenses is carefully regulated to align with the natural productivity of fisheries resources (DOF). The country operates a Fisheries Monitoring Center (FMC) that continuously oversees fishing vessels through a Vessel Monitoring System (VMS), enhancing enforcement and compliance (DOF). Larger vessels, specifically those over 30 gross tonnages, are required to operate outside Thai waters to reduce pressure on domestic stocks (DOF). Innovative gear such as Juvenile and Trash Excluder Devices (JTEDs) has been studied and is increasingly adopted by fishers, helping to reduce unwanted catch (Chokesanguvan *et al*, 2020). However, co-management frameworks remain inadequate, with ongoing conflicts and a heavy dependence of artisanal fishers on fishing as their sole livelihood, posing challenges to sustainable bycatch management (Chanrachkij *et al*, 2022).

Vietnam's marine capture production stands at about 3.27 million metric tons. The country has developed a multidisciplinary approach to bycatch management, integrating ecological, technical, and socio-economic considerations. However, the practical application of many mitigation measures faces significant obstacles due to socio-economic constraints among fishing communities (Vu *et al*, 2025). Vietnam has established a common legal framework targeting bycatch reduction in trawl fisheries (DOF). In some provinces, alternative livelihood programs have been introduced to improve the socio-economic status of fishers, aiming to reduce their dependence on bycatch for income stability (Thanh *et al*, 2014).

China leads in marine capture production with an estimated 11.7 million metric tons. It initially introduced incentive-based programs in 2008 aimed at reducing bycatch, but these were discontinued in 2013 due to a paradoxical increase in bycatch despite the initiatives (Innes *et al*, 2010). Subsequently, China implemented indirect incentives, including subsidies, to encourage fishers to minimize bycatch. Traditional voluntary measures also play a role; customary taboos that temporarily close coral reef areas to fishing are widely practiced, serving as informal conservation tools. To protect dolphins, China enforces a prohibition on "sundown sets" — fishing operations conducted at dusk — which have been linked to increased dolphin mortality during the capture of large yellowfin tunas in the Eastern Pacific Ocean.

Key takeaways from case studies

A comparative analysis of bycatch management strategies reveals stark contrasts between developed and developing countries, shaped by governance, resources, and socio-economic contexts. Developed nations like the U.S., New Zealand, Japan, Australia, and France emphasize science-based regulations, advanced technologies (e.g., circle hooks, pingers, TEDs), spatial protections, and strong enforcement frameworks. These approaches are backed by significant public investment and legal mandates, ensuring effective bycatch reduction across diverse species.

In contrast, developing countries often rely on community-based management, incentives, and gradual reforms due to limited resources. Madagascar and Comoros integrate local stewardship and alternative livelihoods like eco-tourism. Taiwan and Thailand demonstrate progress through improved monitoring, gear innovation, and international compliance efforts. Vietnam and China blend policy reforms with socio-cultural mechanisms, though enforcement challenges persist.

Bycatch rates are strongly influenced by demand and

resource abundance. Developed countries often report lower demand for bycatch species and enjoy relatively abundant marine resources, supported by robust monitoring, enforcement, and penalties that ensure regulatory compliance (Kjeld *et al*, 2016). In contrast, developing or multispecies fishery nations face more complex challenges, requiring species-specific and multidisciplinary mitigation strategies that address both ecological and socio-economic dimensions. However, factors like poverty, fishery complexity, low literacy, and limited investment frequently hinder effective implementation.

Countries like Vietnam and Thailand have struggled with these constraints, yet many of their bycatch management strategies mirror those adopted in India. These include bans on destructive fishing methods (Comoros), promotion of turtle-friendly gear like circle hooks (Taiwan), legal penalties for capturing endangered species (Taiwan), seasonal fishing bans in breeding zones (China), unified legal frameworks for key gear types (Vietnam), and technical measures such as mesh size and vessel size restrictions.

Overall, while developed countries focus on top-down, tech-driven solutions, developing nations prioritize participatory, adaptive strategies. Effective bycatch management ultimately hinges on aligning ecological goals with economic and social realities in context-specific ways.

Global Technological Innovations in Bycatch Mitigation

GoPro has developed a range of waterproof, shock-resistant digital and 35mm film cameras. These cameras come with various mounting options, making them wearable—such as wrist- and helmet-mounted—or attachable to different surfaces. Some GoPro models are capable of functioning at depths of up to 200 meters. In the Netherlands, a study conducted by Peike Molenaar (WMR) explored the effective application of GoPro technology in fisheries. His research led to the innovation of integrating GoPro cameras with a downrigger system. While echo sounders or sonars can detect fish shoals and represent them as white lines, they are unable to differentiate between species. This limitation could lead to resource wastage, especially when the detected shoals consist of juveniles or non-commercial species. The use of GoPro cameras allows for real-time visual identification of shoals. If the fish are deemed commercially viable, fishing operations can then commence promptly.

A three-year research study by Mattias Van Opstal (ILVO, Belgium) investigated the potential of **green LED lights** in reducing flatfish bycatch in bottom trawling. The lights were affixed to the ropes of trawl gear. Flatfish, being sensitive to green spectrum light, were repelled by the illumination. The results demonstrated a significant reduction in by-catch, approximately 80%.

Researcher Fernandez from Spain introduced modifications to traditional bottom otter boards to mitigate bycatch and minimize environmental degradation. The redesigned boards initiate a "flying" motion immediately after contacting the seabed, lifting the gear slightly above the ocean floor. This alteration aids in reducing flatfish bycatch by preventing the net from dragging along the bottom. Additionally, the **flying otter boards** lessen disturbances to benthic flora and fauna. The study reported a 55% reduction in flatfish catch.

Research conducted by Mangel *et al,* 2013 has shown that the use of **green colored gill nets** results in higher target catch efficiency and a reduction in bycatch across various global fisheries. The coloration helps to optimize visual detectability for non-target species, thereby minimizing incidental captures.

Calderan and Leaper, 2019 highlighted the effectiveness of **square mesh cod ends** in fishing nets. This modification allows non-target and undersized species to escape more efficiently due to the larger and more stable opening of the mesh, in contrast to traditional diamond-shaped designs.

Elsa Cuende from AZTI, Spain, demonstrated that using **shortened last ridge ropes in the cod end of trawl nets** creates more escape openings for fish species that are not the primary target. This structural adjustment helps in minimizing bycatch while maintaining the effectiveness of target species capture.

Valentina Melli from DTU, Denmark, introduced the concept of **generating low flow zones inside and around trawl boundari**es. These zones encourage non-target fish species to escape by offering lower resistance pathways, enhancing selectivity during trawling operations.

Baldwin *et al,* 2018 emphasized the use of **Whalesafe gear** designed specifically to prevent whale entanglement. These include modifications and materials that are less hazardous to large marine mammals.

Research by McLellan *et al,* 2018 supports the use of **low breaking-strength ropes** or links engineered to break at 1,700 lbs. of force. This feature enables entangled whales to more easily free themselves, significantly lowering the chance of severe injury.

Innovative systems have been developed to eliminate vertical lines in the water column. These include **rope-on-demand systems**, which store buoy lines on the seafloor, and inflatable bag systems that replace traditional buoy lines. The following table 2 summarizes key global studies that have assessed the effectiveness of various bycatch reduction measures across different marine species and geographic regions.

Bycatch Management: Challenges and Strategies

While progress is being made, India's efforts in managing bycatch present important opportunities for further development. Several critical areas have been identified where

Table 2: Effectiveness of Bycatch Reduction Measures Across Species and Regions

Author	Country	Species	Measures	Bycatch reduction %
Mangel *et al* (2013)	California	Dolphin	Pingers	40%
Bordino *et al* (2013)	Argentina	Dolphin	Pingers	68%
Gearin *et al* (2000)	Washington state	Porpoise	Colored nets	50%
Trippel *et al* (2019)	Bay of Fundy	Porpoise	Pingers	88%
Kraus *et al* (1999)	Gulf of Maine	Porpoise	Coloured nets	92%
Gilman *et al* (2010)	N. Pacific (Hawaii)	Seabird	Operational depth	82%
Melvin *et al* (2001)	N. Pacific (Alaska)	Seabird	Use of Acoustic devices	47%
Boggs (2007)	N. Atlantic	Sea turtle	TED	30%
Cherel *et al* (1996)	S. Indian	Sea turtle	TED	68%

focused attention could enhance outcomes. For instance, the availability of comprehensive and standardized data on bycatch remains limited. As noted by Kizhakkudan *et al,* 2013, the lack of consistent, large-scale information constrains the formulation of targeted, evidence-based management strategies. India's predominantly multispecies fisheries pose additional challenges, as species-specific mitigation measures are more complex to design and implement in such contexts (Eliasen *et al*, 2014). There is also scope for greater innovation in bycatch management practices. While some measures have been trialed, broader adoption and scaling of novel strategies remain limited. In many cases, fishers may not be fully aware of the long-term ecological and economic impacts of high bycatch levels (Johnson *et al*, 2004), which underscores the importance of strengthening outreach and awareness initiatives. Additionally, the observed decline in certain commercially important species highlights the need for proactive management. Expanding the role of governmental and research institutions in conducting dedicated bycatch and discards studies would be a significant step toward building a stronger foundation for sustainable fisheries governance in India.

Most existing bycatch studies in India have emphasized environmental and ecological impacts, often overlooking the crucial socio-economic factors that drive fishing practices and influence bycatch levels (Gupta *et al*, 2019). The vastness of India's coastline, with widespread fishing activity, complicates monitoring and enforcement efforts. Post-harvest technology and bycatch management are underdeveloped. Research by Amande *et al,* 2016 shows that fish waste generated by processing industries exceeds bycatch discards by fourfold, pointing to inefficiencies and wastage in the system. The socio-economic status of the fishing community, marked by low literacy and poverty, limits the acceptance of new technologies that might reduce immediate incomes. This resistance causes innovations to stall before they reach the ground level. Interestingly, bycatch and fish waste form key raw materials for India's fish meal and poultry feed industries (Salagrama *et al*, 1998). As one of the world's leading poultry feed producers, India sees a growing demand for fish bycatch, which undermines bycatch reduction efforts (Anwar *et al*, 2021). Given bycatch's socio-economic significance and the vulnerability of many species caught incidentally, it is imperative to develop regulations that address the ecological, economic, and social dimensions of this issue. Without integrated management approaches, bycatch will continue to threaten fisheries sustainability and marine biodiversity (Dulvy *et al*, 2014).

The core constraint of bycatch management lies in the simultaneous convergence of two major challenges: the decline of commercially important fish species and the rising global demand for fish protein. This dual pressure has left fishers with limited choices, often compelling them to harvest all available species without discrimination. Therefore, any effective bycatch mitigation measure must also account for the demand side, as the market for fish protein continues to grow substantially. Addressing only the supply or technical aspects, while ignoring the consumption and economic drivers, would result in an incomplete strategy. One potential approach to alleviate this burden is through the provision of incentives to fishers or by developing alternative livelihood options, which may reduce their dependency on

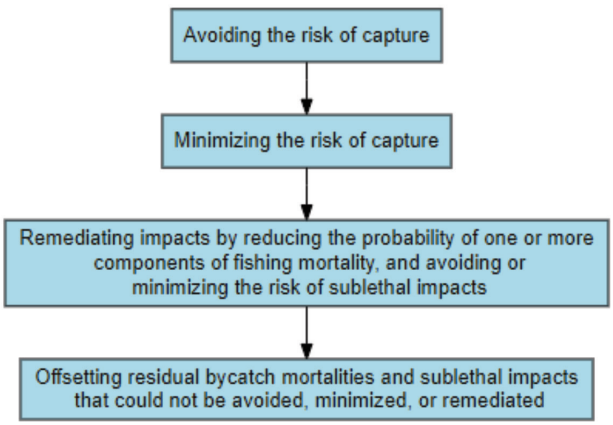

Fig. 2. Bycatch Mitigation Hierarchy (Gilman *et al*, 2022)

indiscriminate fishing. Given the complex and ground-level challenges associated with bycatch, a sequential mitigation hierarchy offers a promising framework. The mitigation hierarchy is defined as the sequence of actions to anticipate and avoid impacts on biodiversity and ecosystem services; and where avoidance is not possible, to minimize those impacts; and when impacts occur, to rehabilitate or restore; and finally, to offset any significant residual impacts (Cross Sector Biodiversity Initiative). In the specific context of bycatch, the mitigation hierarchy (Gilman *et al*, 2022) can be followed. This framework emphasizes a comprehensive and phased approach to bycatch management, offering a structured way to address ecological, economic, and social complexities simultaneously.

Conclusions and Policy Implications

Given that India is a multi-species fishery nation situated in the tropics, the formulation of species-specific bycatch mitigation measures poses significant challenges. The diversity of species, combined with a large and dispersed fishing fleet, necessitates substantial investment and manpower. The capital expenditure required to implement such targeted measures would be enormous. Nevertheless, global experiences offer insight into possible directions. For instance, countries like the USA and Australia have developed species-wise bycatch management strategies led by government research institutions, although such approaches are difficult to implement in the Indian context. France has demonstrated that increasing capital investment in both infrastructure and innovation can be feasible through government and private project funding. Thailand has introduced vessel monitoring systems, though implementation remains complex due to institutional constraints. Countries such as Vietnam, China, and Thailand have shown that promoting and normalizing co-management strategies involving governments, NGOs, and private organizations is not only viable but urgently necessary. Drawing from these international experiences, India must selectively adapt strategies that balance practicality with effectiveness, especially those that consider its scale, resource limitations, and ecological complexity. Given India's vast coastline, ecological diversity, and resource constraints, bycatch mitigation must balance practicality with effectiveness. Low-cost gear modifications like BRDs and TEDs—proven effective in Tamil Nadu and Odisha—can be gradually introduced in trawl fleets (Boopendranath *et al*, 2012). The use of circle hooks in longline fisheries offers a simple, scalable solution to reduce turtle and shark bycatch. Valorizing unavoidable bycatch through cold chain integration and fishmeal markets, as seen in Gujarat and Kerala, can enhance economic returns (Kripa *et al*, 2018).

Strengthening community-led monitoring and leveraging tools like the Fisher Friend Mobile App (FFMA) can improve compliance and awareness. Seasonal and spatial closures, based on ecological data, can protect vulnerable species if implemented with fisher cooperation. Furthermore, seasonal and spatial fishing closures based on scientific assessments of spawning or migratory patterns offer ecological benefits, provided they are well-communicated and enforced with stakeholder buy-in. India can also selectively replicate international models—such as Taiwan's observer program or New Zealand's input-output control mechanisms—on a pilot basis in high-risk zones like the Gulf of Mannar or Sundarbans, scaling up only after context-based evaluation. Ultimately, a hybrid strategy, combining indigenous knowledge, technological innovation, and strong institutional support, is essential for sustainable and practical bycatch management in India.

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