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Growing seed

Editorial Board

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AL04475

LOW-LIGHT TOLERANCE IN RICE: DECODING ADAPTATION MECHANISMS

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Rice (*Oryza sativa L.*) is the staple food for more than 3.5 billion people and accounts for nearly 20% of global caloric intake. Rice is a sun-loving, photophilic crop and being a C_3 crop, requires high light intensity to achieve optimum growth and yield. The photosynthetic rate is strongly dependent on the solar radiation with peak light demands reaching up to 60,000–80,000 lux during tillering and booting stages. In most regions where rice is grown especially tropical and subtropical areas, light availability is naturally high. However, during the monsoons or wet season, where persistent cloud cover and high humidity prevails photosynthetically active radiation (PAR) can be reduced significantly by 30–70% and this significantly reduces the crop productivity. In eastern India, Bangladesh, and Southeast Asia, grain yield losses of 15–40% due to low light stress have been reported during the wet season. Besides the environmental paramaters, agronomic practices such as dense planting, growing of tall varieties and intercrop shading also exacerbate the problem.

Low light stress significantly reduces rice productivity by limiting photosynthesis, delaying tillering and impairing panicle initiation and grain filling. Reduced light availability leads to poor carbohydrate accumulation, lower spikelet fertility, and chalky grains, while also increasing susceptibility to fungal diseases such as sheath blight. Yield losses of 20–50% have been reported in wet-season rice where cloud cover coincides with reproductive stages. With climate change intensifying cloudy spells during monsoons, low light stress is emerging as a critical abiotic constraint to rice production and food security.

While substantial progress has been made in breeding for drought, salinity, and submergence tolerance, low light tolerance remains underexplored. However, advances in quantitative genetics, molecular breeding, and functional genomics are beginning to shed light on the physiological and genetic mechanisms that enable certain rice varieties to perform well

under shaded or cloudy conditions. Identifying, mapping, and deploying these traits could help close the wet-season yield gap and support sustainable intensification of rice systems.

Physiological and Proteomic Responses: Proteomic analyses under low-light stress (≈17% of control light) reveal a significant downregulation of chloroplastic proteins essential for photosynthesis. Specifically, components of the Calvin cycle, electron transport chain, and ATPase complexes were suppressed. Notably, overexpression of OsGAPB, the gene encoding the β subunit of glyceraldehyde-3-phosphate dehydrogenase, significantly improved CO_2 assimilation rates, chlorophyll content, and biomass under low-light conditions, without affecting plants under normal light (Liu et al, 2020)

Genetic Mapping of Low-Light Tolerance: A robust QTL analysis conducted across four consecutive wet seasons under artificially reduced light (≈35% of ambient) identified major yield-enhancing loci. The QTL qPNLL1.1 and qGYLL1.1, both on chromosome 1, showed high phenotypic variance explained (PVE > 30%) and consistent additive effects. Within this region lies MOC2 (*monoculm 2*, LOC_Os01g64660), upregulated in low-light tolerant genotypes—making it a promising candidate for marker-assisted selection to close the yield gap under shade (Ganguly et al 2024).

Subgenomic Resources and Photoreceptor Pathways: Recognizing the limited understanding of photomorphogenic adaptation, researchers constructed a subgenomic library from a low-light tolerant cultivar *Swarnaprabha*. This resource is intended to facilitate the isolation of genes related to light perception—such as phytochromes—and tailored photosensitivity, particularly focusing on phyA, phyB, and phyC, the dominant phytochrome types in rice (Sahu et al, 2023).

Implications for Breeding and Research

By Genetic improvement through incorporation of major QTLs (e.g., qPNLL1.1) via marker-assisted breeding approaches. Transgenic strategies can be adopted by exploring OsGAPB and other photosynthetic enhancement genes to increase the biomass under low light. Functional genomics can aim by utilization of subgenomic resources to dissect light perception pathways and develop varieties with optimized photoreceptors. Multi-omics profiling can be applied to integrate physiology and omics for comprehensive trait development, including grain quality under shade.

Conclusion

Low light stress is an underexplored but serious constraint in rice, causing 20–50% yield losses in monsoon regions due to reduced photosynthesis, poor grain filling, and higher disease incidence. Recent discoveries, including genes like OsGAPB and QTLs such as qPNLL1.1 (MOC2), show strong potential for breeding tolerant varieties. Marker-assisted selection, genomic tools, and gene-editing, combined with improved agronomic practices, can enhance resilience. Prioritizing low-light tolerance is vital for climate-smart rice production and global food security.

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DIVERSIFICATION OF FIN FISH & SHELLFISH SPECIES USED IN THE BRACKISH WATER AQUACULTURE IN INDIA

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Brackish aquaculture is play important role in all over the aquaculture industry. India has high brackish water resources around 8129km^2 of coastal length, 2.02million km^2 of Exclusive Economic Zone (EEZ), backwater & lagoon of about 0.9million ha, 3.9million ha of brackish water area, and 9million ha of salt-affected inland soil in the central highlands in Haryana, Rajasthan, Punjab, Utter Pradesh, Maharastra, Gujarat area to found suitable for used as brackishwater farming. In 1973, under the ICAR-CIFRI about 30 acres of the area were used for the first-ever experimental brackishwater farm in the country, after 1987, CIBA institutes started especially for the brackish water aquaculture in India. It CIBA organizations help invited the new environmentally sustainable and economically viable brackishwater aquaculture in India. About one decade CIBA & CMFRI are developing the breeeding and larval rearing technology of finfish like Seabass (*Lates calcarifer),* Milk fish *(Chanos chanos),* Grey mullet *(Mugil cephalus),* Pearlspot *(Etroplus suratensis),* cobia *(Rachycentran canadam),* Groupers (*Epinephalus sp*), Mangrove red snapper (*Lutjanus argentimaculatus*), etc and shellfish about shrimp (*Penaeus vannamei, P. monodon, P. merguiensis, Fenneropenaeus indicus, Penaeus semisulcatus), crabs (Scylla Serrata* (Mud crab) and *Scylla tranquebarica*) and mussels (*Perna viridis, Perna indica)* .

Species Used for Culture in Brackish Water

Finfishes

1. Asian sea bass (*Lates calcarifer*)

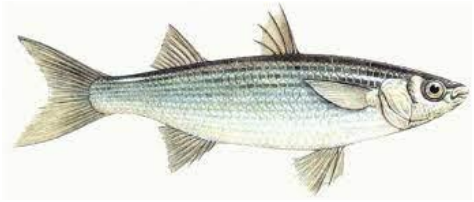
- Carnivorous, Protandrous hermaphrodite, Catadromous fish.
- Broodstock development - 5000 to 10000 brooders at a ratio of 1:3 (Female and Male).
- Spawn in the lunar cycle during the late evening (6pm - 10pm) and repeatedly in batches for 7 days.
- In nurseries, ponds are reared with tilapia before the 2-3 months of seabass larval rearing because tilapia fry is eaten by the seabass larvae and grading is needed to prevent the cannibalism.
- Grow out ponds, in monoculture 10,000 - 20,000 fingerlings per ha fish stocked and the polyculture 3,000- 4,000 fingerlings /ha.
- Daily feed @ 10% of the body weight
- Feeding using moist feed, trash fish and mollusks.
- Grow 500g within 6 months. It fetch 450 rupees per kg.

2. Milk fish (*Chanos chanos*)

- The milkfish is a herbivore fish, with low production cost, and can form an ideal alternate species for shrimp farmers. Showing schooling behaviour.
- Milkfish can grow in brackish water, seawater, and freshwater ponds and lakes. Its easy adaptability to various salinity and temperature.
- The feeding input was reduced in the periphyton based nursery rearing in the milkfish culture about 50% of feed input reduced.
- Sexual dimorphisms - male have two urogential pores, where as female have three.
- Milkfish fry of 1-2 cm can be stocked at a density of up to 20-30 no/ m^2 (2-3 lakhs/ha) and can feed on lab-lab.
- In pen, Milkfish fingerlings of 40–60 g body weight can be stocked with the stocking density of 30,000–40,000 nos./ ha 10–20 tonnes/ha of Milkfish.
- In cages, Fingerlings of 40–60 g body weight are reared at a stocking density of 5 - 30 fingerlings/ m^3. Milkfish yield in cage culture could be 10-20 kg/m3.

- Milkfish fingerling of 7-15 cm body size can be stocked with a density of 8,000–12,000 nos/ha to the maximum density of 30,000 nos/ha in ponds.
- Marketable Milkfish are having a body weight of 200 - 300 g can be harvested after 3-4 months in a monoculture system
- Milkfish fetches Rs. 120-150/kg in the local market while the production cost is only Rs. 50-60/kg.
- The small-sized milkfish is also being used as a preferred live bait for the tuna fishing industry.

3. Grey mullet (*Mugil cephalus*)



- Grey mullets are distributed in tropical and sub-tropical areas, the fastest-growing species, and euryhaline fish can grow in fresh, brackish, and marine habitat.
- Breeding season - july to september, fecundity varies between 0.5 - 2.0 million eggs per female and oil globule there.
- Omnivorous feeding habits and acceptance of formulated pellet feed (35% of protein) make a good candidate fish for brackishwater farmer.
- Stocking density 10–15 g individuals at 6,175–7,410 nos/ha, a harvest of 4.3–5.6/tonnes/ha/crop can be obtained.
- In polyculture system with tilapia and carp, mullet fingerlings are stocked at 2,470–3,705 nos/ha together with 61,750–74,100 nos/ha 10–15g Nile tilapia fingerlings and 1,850–2 470nos /ha of 100g common carp juveniles. Total harvests are typically 20–30 tonnes/ha/crop and about 2–3 tonnes are mullet fish only.
- Production up to 3.5-4 tonnes per ha/crop .
- Due to the texture, taste, and free of spines, consumer preference is high and fetches a good market price, which is in the range of Rs.350 to Rs.500/kg.
- It is an ideal candidate species for polyculture and Integrated Multiprophic Aquaculture systems.

4. Pearlspot (*Etroplus suratensis*)

- Also called green chromite cichlids and "*Karimeen*" in Kerala.
- The State fish of Kerala, fast-growing and raid breeding brackish water fishes.
- Live in both brackish water and freshwater environments.
- In Kerala, pearl spot is farmed using wild seeds in traditional ponds . The average production is about 1 000 kg/ha/year over 8-10 month grow-out period.
- The fish can attain a marketable size of 120-150 g over 8-10 months.
- Monoculture at stocking densities ranging from 20,000 to 30,000 / ha, with an average production of 1,000 kg/ha/year can be obtained in brackishwater ponds.
- It attains sexual maturity within a year and shows parental care.
- This species can grow up to 8 inches (20 cm) in length and weight 1.5 - 1.8 kg.
- Prize of this fish differ in live and dead fish.

5. Cobia (*Rachycentran canadam*)

- Distributed in the tropical water of West & East Atlantic Caribbean sea and Indo-pacific region.
- Spawning period April to September.
- Opportunistic feeders and females grow faster than males.
- Eggs - 0.5 - 2.5 million eggs and newly hated larvae 2.2 - 2.7mm in length.
- While nursery rearing needs to do grading. because have high cannibalistic.
- It reaches about 2 – 6 kg in a year.

- In cages, an average weight of 6 kg has been reported with a stocking density of 13.3 fish/m^3, and 3.5 kg recorded with a stocking density of 23.3 fish/m^3 within 6-8 months.
- A lower stocking density would increase fish production with better FCR. The FCR value ranged from 1.3 – to 2.2.
- Cobia brood stock and breeding technology were standardized by the mandapam center of CMFRI.

Shellfishes

1. *Shrimps*

Many species are used like Penaeus vannamei, P. monodon, P. merguiensis, Fenneropenaeus indicus, Penaeus semisulcatus, etc.

➢ **White leg shrimp (*Penaeus vannamei)***

- *Mostly cultured species, because its seed availability is high and also SPF &SPR seeds also available in the hatchery. Its good disease resistance and high growth shrimp.*
- *Mature male and female respectively 20g and 28g at age of 6-7 months.*
- *35 - 45 g female spawn 1-2.5lakh eggs at 0.22mm diameter.*
- *12 larval stages (nauplius 6, protozoa 3, mysis 3).*
- *Stocking densities in extensive farms 4-10 PL/m^2, semi-intensive farms - 10-30 PL/m^2, Biofloc system at >10: 1 (C:N) for 80-160 PL/ m^2 and intensive farms at the range of 60-300PL / m^2.*
- *The price of shrimp depends on the count of species per 1Kg.*

➢ **Giant tiger prawn (*Penaeus monodon)***

- This is the fastest-growing shrimp of all penaeid shrimp.
- The giant tiger prawn is more of a predator than an omnivorous scavenger or detritus feeder than other penaeid shrimp. After molting, the new shell is still soft which causes prawns to become vulnerable and they may subsequently be eaten by their predators or companions. Adults are often found over muddy sand or sandy bottoms at 20-50 m depth in offshore waters.
- *Intensive* - Stocking density ranges from 20 to 60 PL/m².
- Feeding with artificial diets is carried out 4-5 times per day followed by feed tray checking. Final FCR is normally between 1.2:1 and 2:1.
- Semi-intensive at the rate of 5 to 20 PL/m².
- Pl 15 good stages for stocking its help to reduce the feed waste.
- Stock PL 15 prawns directly into the grow-out ponds.

2. Crab

- More economically important species used in the culture was *Scylla Serrata* (Mud crab) and *Scylla tranquebarica* comes under the Portunidae family. These crabs are found in the estuaries and mangroves of India.
- Mostly they prepare for the muddy and sandy bottom.
- In aquaculture of this species due to their high demand / price, high flesh content, and rapid growth rates in captivity.
- This is available worldwide and is mostly sold live in international markets.
- In India, mud crab farming started during the early eighties and now crab culture is developing very fast in the states of AP, Kerala, West Bengal, and Odisha.
- RGCA / MPEDA develops the mud crab hatchery in the Tamilnadu state in 2013.
- Crab fattening - done within 20-25 days, wild-caught crabs are fattened in cages or pen system feed with high feeding intensity. Feeding - @ 10% of body weight fed with trash fish and mollusks to prevent canabolism.
- In pond need to provide net fencing or a bottom coated with concrete.

- Culture period - 5-8 months and the survival rate - 30-70% .
- Harvest done by handpicking, only hard shell crab sold by live condition.

3. **Mussels**

- Mussel production is high in Kerala and CIMFRI also helps increase the production of mussels in Vembanad lake.
- Cultured species - *Perna viridis*, *Perna indica* belonging to the family Mytilidae.
- Mussel is a culture of two types, the bottom, and off-bottom culture.
- On bottom culture – The cheapest & simplest method and mussels are live on the bottom substrate. High mortality due to predation and siltation harvest done by handpicking.
- Off bottom culture - Costly, but high growth rate and production, where the bottom not good for the culture it very useful. It was done by using stake, raft, and rack culture.
- Food and feeding - No feed input because they are plankton feeders only depend on the phytoplankton.

Other Species Used in Aquaculture

- Groupers (Epinephalus sp) - protogynous hermaphrodites (Serranidae family)
- Mangrove red snapper (*Lutjanus argentimaculatus*)
- Silver pompano (*Trachinotus blochii*)
- Gold Spot Mullet (Liza parsia)
- Yellowfin bream (Acanthopagrus australis)
- Blood clam (*Tegillarca granosa*)
- Indian backwater oyster (*Crassostrea madrasensis*)

Conclusion

The need of food increasing day by day but there availability of food materials are less because only depends on the agriculture, so we need to increase the fish culture also at mean while and the fish culture also growing fastly. Fish culture used in fresh water and brackish

water area, but freshwater land also decreasing day by day due to the building construction and industrial uses, So need an alternative source to need to focus the brackishwater culture by using advanced technologies. Many other brackish water species there for culturing, but the problem is their less availability of the seed and no breeding & hatchery technology for are these species, nowadays also people are collecting the seed from the wild only. Therefore need of new technology for breeding, larval rearing of cultivable to ensure the seed availability for the throughout the year. Recently many advanced technology are there for the culturing the brakishwater sp like pond system, RAS system, cage system, pen system, IMTAs and biofloc system are help to improving the less input to get high profit by using less culture area and also government also helping by providing subsides for start the cage system.

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FISH FARMING AS A BUSINESS: LESSONS FROM JAGATSINGHPUR

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Fish farming, or aquaculture, has emerged as one of the fastest-growing food production sectors globally, contributing significantly to food security, employment, and income generation in rural communities (FAO, 2022). In India, the sector has gained strong policy support under the Pradhan Mantri Matsya Sampada Yojana (PMMSY), which promotes scientific aquaculture for enhancing productivity and sustainability (GoI, 2020). Odisha, with its vast aquatic resources, has witnessed substantial growth in aquaculture, particularly in coastal districts like Jagatsinghpur, where fish farming has evolved from subsistence to a profitable enterprise (GoO, 2022; Giri et al., 2020). This article explores how Jagatsinghpur has transformed into a model for sustainable and business-oriented fish farming through scientific practices, women's empowerment, and market-driven approaches.

In the coastal heartland of Odisha, Jagatsinghpur district has quietly become a laboratory of change. Once known for traditional farming and fishing, it is now gaining recognition as a hub where fish farming is being treated not just as a livelihood, but as a thriving business. The district offers valuable lessons for farmers, policymakers, and entrepreneurs alike.

From Subsistence to Enterprise

For years, fish farming in Jagatsinghpur was modest. Small ponds stocked with local fish, harvested mainly for family consumption. But with the introduction of scientific aquaculture, farmers began to realize that ponds could yield more than food; they could yield profit. By adopting practices like proper pond preparation, predator eradication, and use of

quality seed, yields in the district have more than doubled, turning what was once a survival strategy into a business opportunity.

Women at the Forefront

A remarkable feature of Jagatsinghpur's fish farming success is the role of women. Self-Help Groups (SHGs) have taken charge of ponds, managing them with efficiency and care. For many women, this is their first step into entrepreneurship. Beyond adding to household incomes, fish farming has given them greater independence, decision-making power, and respect in their communities. Their success stories highlight how aquaculture can drive not just economic growth but also social change.

Keys to Business Success

Jagatsinghpur's experience highlights several factors that transform fish farming into a profitable venture:

1. **Scientific Practices:** Systematic pond management, quality fingerlings, and balanced feed are non-negotiable for high yields.
2. **Collective Action:** SHGs and cooperatives help farmers share resources, reduce costs, and strengthen bargaining power in markets.
3. **Access to Credit:** Microfinance and government schemes provide the initial push for farmers to invest in better inputs and infrastructure.
4. **Training and Extension:** Hands-on training from experts helps farmers overcome technical challenges and adopt new practices with confidence.
5. **Market Linkages:** Direct connections to traders, retailers, and cold storage facilities ensure that farmers earn fair prices for their produce.

The Business Mindset

Perhaps the biggest shift in Jagatsinghpur has been the change in mindset. Farmers no longer see fish farming as seasonal or secondary. Rather than relying on tradition alone, they adopt an entrepreneurial approach by analysing costs, assessing returns and strategically planning for the future. For many, the benefit-cost ratio is now competitive with or even better than traditional agriculture.

Case Study Snapshot: Fish Farming in Jagatsinghpur

- **Average Yield Increase:** From 2 tonnes/ha to more than 4 tonnes/ha with scientific practices.
- **Income Growth:** Household earnings up by 20–30% after adopting modern aquaculture.
- **Women's Empowerment:** Over 60% of SHGs in select blocks actively managing ponds.
- **Benefit-Cost Ratio:** Improved from 1.5 (traditional) to 2.3 (scientific methods).
- **Youth Engagement:** Rising participation of rural youth entrepreneurs treating aquaculture as a primary business.

Jagatsinghpur proves that fish farming is more than a livelihood, it's a business model that can deliver economic and social transformation.

Conclusion

Jagatsinghpur shows that with the right mix of science, support, and entrepreneurial spirit, fish farming can thrive as a business. The district's experience underscores the importance of seeing aquaculture not just as an add-on to farming but as a central driver of rural prosperity. As one farmer put it, *"Fish farming is no longer about survival, now it is about building a business and a better life."*

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MILLETS AND THE FUTURE OF FOOD: FROM CLIMATE RESILIENCE TO NUTRITIONAL WELL-BEING

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Millets are a collective term for various small-seeded annual grasses within the Poaceae family, cultivated primarily in dry, marginal lands across temperate, subtropical, and tropical regions (FAO, 2024a). They are highly tolerant to drought and extreme weather, requiring minimal chemical inputs. In India, they are celebrated as "Nutri-cereals" due to their rich nutrient content (ICMR-NIN, 2017).

Millets are broadly categorized into Major Millets and Minor Millets:

- **Major Millets** include Sorghum (jowar), Pearl Millet (bajra), and Finger Millet (ragi). Sorghum is a staple in Africa and South Asia, known for its drought tolerance and high protein, iron, and fiber content (AICRP-Millets, 2017). Pearl Millet, also from Africa, thrives in hot, dry regions and is rich in proteins (12-16%), lipids (4-6%), and dietary fiber (around 11.5%), along with niacin, folate, magnesium, and iron (ICMR-NIN, 2017). Finger Millet, native to East Africa, is exceptional for its calcium content (300-360 mg/100g), the highest among all cereals (ICMR-NIN, 2009/2024).

- **Minor Millets** encompass Foxtail, Little, Kodo, Proso, and Barnyard Millets. Foxtail Millet (kakum) is rich in protein (10-12.3%), fiber (8-19.1%), and various vitamins and minerals, with a low glycemic index. Proso Millet (china) is a good source of B-complex vitamins, magnesium, and dietary fiber (ICMR-NIN, 2017). Little Millet (kutki) is an excellent source of dietary fiber (15.9-18.1%) and minerals like iron, magnesium, and zinc (ICMR-NIN, 2017). Barnyard Millet (jhangora) is noted as the richest source of crude fiber and iron among millets (AICRP-Millets, 2017). Kodo Millet (kodon) is high in protein (8.3-11%), fiber (9-14.3%), B vitamins, and minerals, with strong antioxidant properties (Ghatak et al., 2024). Browntop Millet (korle) is rich

in crude protein (10.72-13.61%), crude fiber (7.2-16.08%), and diverse minerals (ICMR-NIN, 2017).

It's important to distinguish millets (true cereals, members of the grass family Poaceae) from pseudocereals like Amaranth, Buckwheat and Quinoa, which are cultivated for similar purposes but belong to different plant families (FAO, 2024a).

Nutritional Powerhouse and Health Benefits

Millets are a nutritional powerhouse, offering a comprehensive profile of macronutrients, micronutrients, and bioactive compounds. They typically contain 7-12% protein, 2-5% fat, 65-75% carbohydrates, and 15-20% dietary fiber (ICMR-NIN, 2017). They are rich in B vitamins, beta-carotene, vitamin E, and vitamin B12, along with essential minerals like calcium, phosphorus, magnesium, iron, zinc, potassium, and copper (ICMR-NIN, 2024).

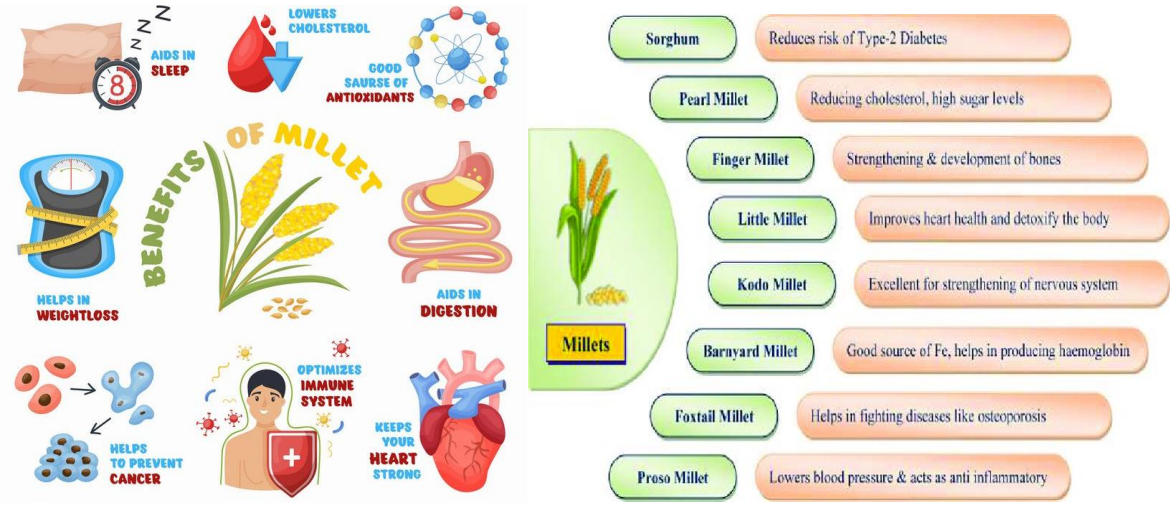
Beyond basic nutrition, millets are abundant in bioactive compounds such as phytates, polyphenols, tannins, anthocyanins, phytosterols and pinacosanols, contributing to their high antioxidant activities (AICRP-Millets, 2017). These compounds offer therapeutic benefits, including anti-microbial, anti-biofilm, and anti-cancer effects (Ghatak et al., 2024).

The consumption of millets is linked to numerous health benefits:

- **Cardiovascular Health:** Millets help decrease triglycerides and C-reactive protein, lower cholesterol (due to niacin), and regulate blood pressure (due to magnesium) (Anitha et al., 2021c).
- **Diabetes Management:** Their low glycemic index (GI) ensures slow glucose release, preventing blood sugar spikes, making them ideal for managing type 2 diabetes.

Minimally processed millets are 30% more effective in lowering meal GI compared to milled rice and refined wheat (Anitha et al., 2021a; University of Reading, 2021).

- **Digestive Health:** High dietary fiber promotes healthy digestion, reduces the risk of inflammatory bowel disease, and acts as a prebiotic, stimulating beneficial gut bacteria (Silva et al., 2024).
- **Weight Management:** The high fiber content promotes satiety, aiding in weight management (Silva et al., 2024).
- **Bone Health:** Millets, especially Finger Millet, are excellent sources of calcium, magnesium and phosphorus, crucial for bone strength and preventing conditions like osteoporosis (ICMR-NIN, 2009/2024).
- **Anti-Cancer and Anti-Inflammatory Effects:** Antioxidants combat inflammation and oxidative stress, factors linked to chronic diseases and cancer (Ghatak et al., 2024).



While millets contain antinutrients (e.g., phytates, polyphenols, tannins, lectins) that can hinder nutrient absorption, traditional and modern processing techniques effectively reduce them. Methods like decortication/dehulling, soaking, germination/sprouting, fermentation, and various heating methods (cooking, roasting, boiling) can significantly enhance nutrient bioavailability (Misra et al., 2016; Sharma & Singh, 2021).

Cultivation and Agricultural Practices

Millets are highly resilient and adaptable, making them crucial for sustainable agriculture (Govindaraj et al., 2022).

- **Climate and Soil Adaptability:** They thrive in low rainfall (200-700 mm annually) and warm climates (20-32°C, tolerating up to 42-50°C), often being the "last crops standing in droughts" (FAO, 2024b). They grow well in various soil types, including poor, sandy, loamy, and clay soils, and even those with low fertility or high salinity. Their deep root systems and C4 photosynthesis contribute to their drought resistance and efficient water use (Ghatak et al., 2024).
- **Water Requirements:** Millets require approximately 70% less water than rice and considerably less than wheat, thriving under rainfed conditions (FAO, 2024a). Adequate moisture is crucial during germination, early vegetative growth, and especially during flowering and grain-filling.
- **Sowing Techniques:** Both traditional (broadcasting, dibbling) and modern (line sowing with seed drills, transplanting) methods are used. Optimal sowing depth is 2-3 cm (AICRP-Millets, 2017).
- **Crop Management:** Millets have low fertility requirements but respond well to balanced nutrient application. They are generally less susceptible to pests and diseases due to natural defences, making Integrated Pest Management (IPM) effective. Effective weed management is critical, as millets compete poorly with weeds in early stages.
- **Harvesting and Post-Harvest Handling:** Grains should be harvested when mature and dry to prevent shattering. Post-harvest processes like threshing and drying (to 10-12% moisture) are vital for quality preservation. The labour-intensive nature of traditional dehulling, especially for minor millets, is a significant bottleneck (ICRISAT, 2022).

Global Production and Market Dynamics

Millets are cultivated in over 100 countries. India is the world's largest producer, contributing approximately 38.4% of global production, with 15.38 million metric tonnes in FY 2024. Other top producers include Nigeria, Niger, Sudan, and Mali. Within India, Rajasthan leads in production and cultivation area (FAO, 2024b). Pearl millet accounts for 60% of cultivated millets in India, followed by sorghum (27%) and finger millet (11%).

Globally, the area under millet cultivation has marginally declined (from 35 to 32 million hectares between 2011-2020), leading to a slight reduction in overall production. However, Asia has seen consistent productivity growth (from 800 kg/ha to nearly 1400 kg/ha between 2000-2019) due to improved cultivars and management, while Africa's productivity has declined. In India, pearl millet productivity increased by 244% between 1963-2020, comparable to wheat, yet cultivation area decreased due to lack of sustained demand and policy support.

The global millet market is experiencing robust growth, valued at USD 11.24-11.31 billion in 2024 and projected to reach USD 15.10-16.93 billion by 2030-2033, with a CAGR of 4.6% to 10.54%. Key growth drivers include:

- Increasing health consciousness and demand for gluten-free and plant-based diets.
- Rising prevalence of lifestyle diseases.
- Government initiatives and policy support (e.g., IYM 2023).
- Environmental sustainability concerns.
- Product innovation and value addition.

Asia-Pacific leads the global millet market (over 60% share in 2025), driven by India, China, and Nepal. Europe and North America are also experiencing steady growth (WITS, 2023).

Global trade in millets reached approximately $258 million in 2023. Top exporters include India ($41 million), Uzbekistan ($40.5 million), and the United States ($33.8 million). Major importers are Pakistan ($37.1 million), Indonesia ($31 million), and Germany ($12.4 million). A significant challenge is that over 80% of India's millet exports are in raw, unprocessed form, and Indian companies hold less than 2% of the global branded millet product market, representing a missed opportunity for higher value capture (WITS, 2023).

Policy Landscape and Research & Development

The global resurgence of millets is significantly shaped by policy and R&D.

- **International Year of Millets (IYM 2023):** Declared by the UN General Assembly at India's initiative, IYM 2023 aimed to raise global awareness of millets' contribution to food security and nutrition, inspire sustainable production, and enhance investment in R&D. It aligns with UN Sustainable Development Goals (SDGs) like Zero Hunger (SDG-2) and Climate Action (SDG-13) (UNGA, 2021).
- **National Government Initiatives:** India declared 2018 as the "National Year of Millets" and classified them as "Nutri-cereals," integrating them into nutrition programs like "Poshan Abhiyaan". Key initiatives include the National Food Security Mission, Rashtriya Krishi Vikas Yojana, and the Millets Mission, aiming to expand cultivation and production. Financial incentives, subsidies for seeds and equipment, and integration into the Public Distribution System (PDS) and Integrated Child Development Services (ICDS) are also part of the strategy. State-level projects like the Odisha Millets Mission (OMM) have shown success in increasing cultivation and yield (Government of India, 2018).
- **Role of International Organizations:** The FAO, as the lead agency for IYM 2023, promotes sustainable production and consumption and collaborates on genetic improvement projects for climate change adaptation. ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) is a pioneering organization in dryland farming, actively involved in millet research and breeding. Their impacts include "Rapid-Ragi" speed breeding protocols for finger millet, reducing its growth cycle from 100-135 days to 68-85 days. ICRISAT has also developed high-protein and high-yielding varieties, improved disease and striga tolerance in pearl millet, and led the pearl millet genome sequencing (Varshney et al., 2017; Kumari et al., 2023).
- **Challenges in Policy Implementation:** Despite efforts, challenges persist, including limited awareness in rural areas, difficulties in processing, lack of established markets, and inconsistent supply and demand. The high cost of millets compared to traditional cereals can also pose accessibility challenges for low-income consumers. The scarcity of high-quality seeds and high-yielding varieties also limits productivity (FAO, 2024a).

Processing, Value Addition, and Product Innovation

Transforming millets into modern food ingredients relies on processing and innovation.

- **Traditional Processing:** Historically, millets were dehulled manually using pestle and mortar, a labour-intensive and time-consuming process, especially for minor millets with tightly adhering husks. Lack of local processing infrastructure remains a challenge (AICRP-Millets, 2017).
- **Modern and Innovative Processing:** Modern techniques aim to remove inedible portions, enhance nutrient bioavailability, and reduce antinutrients. Primary processing includes cleaning, destoning, washing, soaking, germination, and decortication (dehulling), often using modified rice milling machinery like emery or centrifugal mills. Secondary processing converts grains into "ready-to-eat" (RTE) or "ready-to-cook" (RTC) products through extrusion, flaking, popping, and baking. Innovative non-thermal technologies like cold plasma treatment can enhance seed growth, reduce antinutrients (e.g., tannin by up to 57%, phytic acid by up to 18%), and improve nutrient bioavailability. High-Pressure Processing (HPP) can significantly reduce phytate content (up to 80.61%) and increase free iron content (Misra et al., 2016; Sharma & Singh, 2021).
- **Diversification of Millet-Based Products:** Millets are versatile, used in traditional dishes like roti and porridge. Modern value-added products include gluten-free flours for baked goods (breads, pancakes, muffins), breakfast cereals (flakes, puffs, granolas), healthy snacks (puffed millet bread, chips, bars), noodles and pasta, and plant-based milks and smoothies (ICMR-NIN, 2024).
- **Challenges and Opportunities in Value Chain Development:** Challenges include labour-intensive processing, lack of affordable dehullers, inconsistent supply, poor market linkages, low price realization for farmers, and consumer perception issues. Opportunities lie in creating D2C "superfood" brands, leveraging global health trends (clean-label, plant-based, gluten-free), integrating technology (traceability, AI), and strengthening Farmer-Producer Organizations (FPOs) to build robust "farm-to-brand" supply chains.

Environmental Sustainability and Climate Resilience

Millets are a cornerstone of environmental sustainability and climate resilience.

- **Low Water and Input Footprint:** They require significantly less water (approx. 70% less than rice) and fewer chemical inputs (pesticides, fertilizers) than conventional staple grains, making them eco-friendly and cost-effective.

- **Contribution to Soil Health and Biodiversity:** Millets enhance soil fertility by adding organic matter and improving soil structure. Their deep root systems reduce erosion, and they are excellent for crop rotation, promoting soil biodiversity and nitrogen fixation (some varieties).

- **Role in Climate Change Adaptation and Mitigation:** Millets are exceptionally resilient to higher temperatures and extreme weather (droughts, floods). Their short life cycle (60-120 days) allows for "drought escape". As C4 crops, they efficiently use carbon dioxide, contributing to carbon sequestration in the soil and producing lower greenhouse gas emissions compared to high-input crops like paddy rice (Varshney et al., 2017).

Future Prospects and Investment Opportunities

The future of millets is promising, driven by evolving consumer preferences and their critical role in addressing global challenges.

- **Evolving Consumer Preferences:** Growing awareness of millets' health benefits (gluten-free, high fiber, low GI) and a global shift towards sustainable, plant-based diets are driving demand (FAO, 2024b).
- **Investment Avenues:** Significant opportunities exist in (Govindaraj et al., 2022):
    - **R&D:** Developing improved, climate-resilient, and nutritionally superior varieties through genomics and speed breeding.
    - **Processing Infrastructure:** Investing in modern, energy-efficient, and solar-driven processing technologies, especially dehullers for village and micro-enterprise levels.
    - **Startups and Entrepreneurship:** Creating D2C "superfood" brands, developing innovative millet-based products (snacks, cereals, baked goods, beverages), and leveraging technology for traceability and quality checks.
    - **Farmer-Producer Organizations (FPOs):** Strengthening FPOs to build robust "farm-to-brand" supply chains, ensuring quality sourcing and fair prices for farmers.
    - **Market Development:** Facilitating market linkages, establishing quality standards, and promoting millets through consumer awareness campaigns.
- **Contribution to Global Food Security and SDGs:** Millets are vital for combating hunger and malnutrition due to their high nutrient density and affordability. Their

climate resilience ensures food production in erratic weather, making them indispensable for climate change adaptation. Environmentally, they reduce water use, chemical inputs, enhance soil health, and contribute to carbon sequestration. Economically, they provide income and employment for smallholder farmers, contributing to rural development and poverty reduction. Millets directly align with SDGs, including Zero Hunger (SDG-2), Good Health and Well-being (SDG-3), Responsible Consumption and Production (SDG-12), and Climate Action (SDG-13) (FAO, 2024a).

Conclusion and Recommendations

Millets are poised to become a cornerstone of future food systems, offering solutions to global challenges of food security, malnutrition, and climate change. Their exceptional nutritional value, climate resilience, and environmental benefits are undeniable. However, realizing their full potential requires overcoming significant hurdles, particularly in post-harvest processing, market access, and economic viability for farmers.

To accelerate the mainstreaming of millets, a holistic, concerted effort is needed:

- **Governments and Policymakers** must strengthen policy coherence, invest in decentralized processing infrastructure, enhance market linkages (including PDS integration), support farmer empowerment through FPOs and extension services, and increase R&D investment in improved varieties.
- **International Organizations** should sustain the momentum from IYM 2023, facilitate technology transfer to lower-yielding regions, and continue interdisciplinary research into millets' nutraceutical and climate adaptation properties.
- **The Private Sector and Investors** should capitalize on the growing market for health-conscious and convenience foods by investing in modern processing facilities, innovative product development, and D2C "superfood" brands. They should also foster agri-tech innovation and collaborate with FPOs to build robust, remunerative value chains.

By collectively addressing these recommendations, stakeholders can transform millets into a widely consumed, economically viable, and environmentally sustainable food source, contributing significantly to a healthier planet and more secure food future.

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BREEDING AND FARMING OF STRIPED CATFISH (*Pangasianodon hypothalamus*, Sauvage 1878): SUSTAINABLE PRACTICES FOR GLOBAL AQUACULTURE

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Pangasianodon hypophthalmus also known as striped catfish or iridescent shark and, plays a vital role in food security across many Asian countries, including Bangladesh, Thailand, Vietnam, India, and Malaysia. This catfish is ideal for inland aquaculture because it proliferates and is in high demand in European markets. Pangas is native of Mekong basin of Indochina. Its fast growth, strong market, and well-established farming methods have made it the third most farmed freshwater fish in India. This species was introduced into India clandestinely through Bangladesh around 1997 and began to be cultured in West Bengal. In India, about 300 to 500 million pangasius seeds are produced in West Bengal, with a significant amount sent to Andhra Pradesh for farming. Other states involved include Karnataka, Bihar, Chhattisgarh, Kerala, Rajasthan, and Uttar Pradesh. This species is widely cultivated in various aquaculture systems, including ponds, cages, and raceways, particularly in Southeast Asia. Pangasius is popular because it can reach 1.5 kg in six months, lower production costs, and thrive in varying oxygen levels. Consumers appreciate pangasius for its tender flesh and fewer bones.

In 2009, the Government of India officially recognized pangasius farming by establishing guidelines for its cultivation. Commonly referred to as the tiger shark, iridescent catfish, or Siamese catfish in the ornamental fish industry, *P. hypophthalmus* is highly valued for its attractive shape and graceful movement, particularly at the juvenile stage. Various fingerling varieties, including striped and albino, are cultivated for the aquarium trade. In their juvenile stage, they are primarily carnivorous and exhibit cannibalistic behavior. However, as they mature, their diet shifts to omnivores, predominantly comprising algae, plant matter, zooplankton, insects, fruits, crustaceans, and smaller fish. In aquaculture, the production of *P. hypophthalmus* is significant, ranging from 7 to 20 tonnes per hectare per year, and the average production is higher than carp production in the same areas, so farmers can get higher

production in the lower areas with low cost of production and also it will increase the economics of the farmer.

Maturity, Breeding, and Seed production

P. hypophthalmus usually matures after three years in the wild, but it can reach maturity in captivity as early as two years. The sexes can be easily differentiated. Females have large, soft, and swollen bellies that are reddish-pink, while males have reddish genital openings and release milt when their abdomens are gently pressed. Breeding occurs from April to mid-September, and a single brooder can be used at least twice during the same season. After hormone injection (Ovatide, Pituitary extract, or Ovaprim), the fish release eggs within 12-13 hours, which are then fertilized or by striping method. The fertilized eggs are rinsed in a milk powder solution in an aluminum 'hundi' to remove the adhesive gelatinous coating. After fertilization, the eggs go through water hardening within 20 minutes. The "blastodisc stage" developed at approximately 25 minutes' post-fertilization, followed by the "morula stage" at 3 hours and 45 minutes. The "blastula stage" was observed at 5 hours and 30 minutes post-fertilization. Twitching movements began between 24 and 26 hours after fertilization, while hatching occurred between 34 and 36 hours post-fertilization.

The newly hatched larvae measured about 3.80 mm in length, with a slightly bent head and a compact, yellowish yolk sac. Between 5 and 10 days of age, the pectoral, caudal, ventral, and dorsal fins began to develop. Boiled egg yolk supplemented with multivitamins was recognized as an optimal initial feed, introduced approximately 40 hours post-hatching at intervals of 3–4 hours. Between 60 and 96 hours post-hatching, the gradual incorporation of freshly filtered zooplankton (Rotifer and Artemia nauplii), in combination with diluted boiled egg yolk, administered at 3–4-hour intervals, resulted in enhanced larval growth. From the fourth day post-hatching until days 12–14, larvae were provided with a diet of diluted boiled chicken liver enriched with multivitamins. Furthermore, the administration of a combination of live *Tubifex* and Artificial Plankton Rotifer (APR) at 3–4-hour intervals between 36 and 40 hours post-hatching was found to be more effective than blended *Tubifex* alone, yielding significantly lower larval mortality rates.

Fig 1: Pangasius fingerlings (8-10cm)

Grow out Culture

Two types of pangasius fish cultivating are practiced by farmers. One uses monoculture, while the other practices polyculture with carp and other species. Monoculture is often preferred due to its easier maintenance compared to polyculture.

i) Stocking density

In India, fingerlings of ***P. hypophthalmus*** typically range from 4 to 5 inches in length, with corresponding weights between 50 and 100 grams. Farmers commonly stock around 25,000 fingerlings per hectare, with stocking densities not exceeding 30,000 per hectare. To minimize management challenges, most farmers prefer a single stocking of pangus fingerlings. The recommended stocking density for *P. hypophthalmus* culture in cages is about 40nos/ m^3.

Fig 2: 2-Month-old *Pangasianodon hypophthalmus*

ii) Feeding

Farmers use various local ingredients to feed the cultured pangus fish. Most commonly, they provide cooked de-oiled rice bran (DOB) and broken rice at a rate of 5% of the fish's body weight. They also incorporate locally available agricultural waste products and even discarded

potatoes into the feed. Additionally, bag feeding is a common practice among many farmers. Pangasius feed also commercially available in floating feed with 28 to 33% of crude protein (4 mm), where two times morning and evening per day.

Fig 3: Floating pellets for *P. hypophthalmus*

iii) Disease management

P. hypothalamus is a hardy species that can be cultured at high stocking densities. However, it is vulnerable to various microbial and parasitic diseases. Notable among these are bacillary necrosis in pangasius (BNP) caused by *E. ictaluri* and motile aeromonas septicemia (MAS) caused by *Aeromonas* species, primarily *A. hydrophila*. Additionally, as a scaleless fish, Pangasius is particularly susceptible to the protozoan parasite *Ichthyophthirius multifiliis*. To avoid these diseases frequent check-up the fish and reduce the over stocking.

Heavy mortalities have been observed, with affected fish showing symptoms such as off-feeding, circular motions, and other signs of distress. Fish of all sizes, ranging from 5 g to 1.5 kg, have been impacted, leading to significant losses for farmers. Parasitic diseases are prevalent, and occurrences of "red disease" a form of hemorrhagic septicemia, have also been confirmed in *P. hypophthalmus* from grow-out farms. In some cases, swelling of the liver has been noted. Microscopic examinations of the gills using squash preparations from infected fish reveal a moderate presence of *Trichodina* parasitic infection.

Various chemicals have been tested to prevent Ichthyophthiriasis, including malachite green, malachite green combined with salt or formalin, formalin alone, chloramine-T, potassium permanganate, and copper sulfate. Several reports indicate that combining malachite green and formalin is the most effective alternative. Additionally, salt is one of the most commonly used treatments in freshwater tropical fish culture.

iv) Harvesting and Marketing:

P. hypophthalmus weighing over 1.5 kg is preferred for harvest and sale. In some regions, these fish are typically marketed at ages 8 months and 1 year, though farmers may start harvesting as early as 6 months. Many farms implement multiple harvests throughout the year. Chilled storage is the most commonly used active packaging technology, extending the product's shelf life to 20 days.

Fig 4: Harvest

Conclusion

The culture of *P. hypophthalmus* has gained substantial economic importance due to its fast growth, high adaptability, and market demand. Its ability to thrive in different water conditions and its omnivorous feeding habits make it a cost-effective option for commercial fish farming. Economically, *P. hypophthalmus* plays a key role in the global seafood trade. It is a major export product, contributing to employment, food security, and foreign exchange earnings in many countries. The species' affordability and good taste have made it popular among consumers worldwide, additional increasing its market price. Despite its economic welfares, the sustainability of *Pangasius* farming depends on responsible and sustainable aquaculture practices. Ongoing research and improvements in breeding, nutrition, and disease management are going to be key for keeping the industry growing and sustainable.

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PROTEASE INHIBITORS IN FISH FEED: CHALLENGES AND STRATEGIES FOR DETOXIFICATION

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The increasing replacement of fishmeal with plant-derived ingredients in aquafeeds has raised concerns about the presence of anti-nutritional factors, among which protease inhibitors (PIs) are particularly significant. Found abundantly in soybean meal, groundnut meal, and other legumes, protease inhibitors interfere with digestive enzymes such as trypsin and chymotrypsin, thereby reducing protein digestibility, amino acid availability, and overall feed efficiency. Their action often results in impaired growth, pancreatic hypertrophy, altered gut morphology, and compromised health in sensitive fish species. The challenges posed by protease inhibitors are further amplified when plant protein inclusion levels are high, especially in carnivorous species with limited tolerance. Strategies to mitigate these effects include thermal processing (toasting, extrusion, autoclaving), fermentation, enzyme supplementation with exogenous proteases, genetic selection of low-PI crop varieties, and optimized feed formulations combining plant and animal protein sources. Recent advances in biotechnological approaches and enzyme supplementation have shown promise in reducing PI-related effects while supporting sustainable aquaculture. This review highlights the sources, mechanisms, and impacts of protease inhibitors in fish nutrition, and discusses current and emerging strategies for their detoxification to ensure efficient and sustainable fish feed formulation

The rapid expansion of aquaculture as the fastest-growing food production sector has significantly increased the demand for nutritionally balanced and cost-effective fish feeds. Traditionally, fishmeal has been the primary protein source in aquafeeds due to its high digestibility and balanced amino acid profile. However, sustainability concerns, rising costs, and limited availability of fishmeal have driven the industry toward greater reliance on plant-

derived proteins such as soybean meal, groundnut meal, lupin seed, peas, and other legumes (Krogdahl et al., 2010; Francis et al., 2001).

Despite their advantages, plant ingredients are often limited by the presence of anti-nutritional factors (ANFs), which interfere with nutrient utilization and fish health. Among these, protease inhibitors (PIs)—including trypsin inhibitors (TI) and chymotrypsin inhibitors (CI)—are particularly important because they directly affect protein digestion, the most critical nutrient for fish growth and metabolism. By binding to digestive enzymes in the gastrointestinal tract, PIs reduce protein hydrolysis, leading to poor amino acid availability, pancreatic stress, impaired growth, and overall reduced feed efficiency.

Given the increasing use of plant proteins in aquafeeds, understanding the role, mechanisms, and consequences of dietary protease inhibitors is vital. Equally important are strategies to mitigate their negative effects through processing, enzymatic supplementation, biotechnological innovations, and feed formulation approaches. This review highlights the sources, mechanisms of action, health impacts, challenges, and recent advances related to protease inhibitors in fish feed, with a focus on practical solutions to improve fish performance and ensure the sustainability of aquaculture.

Sources of Protease Inhibitors in Fish Feed

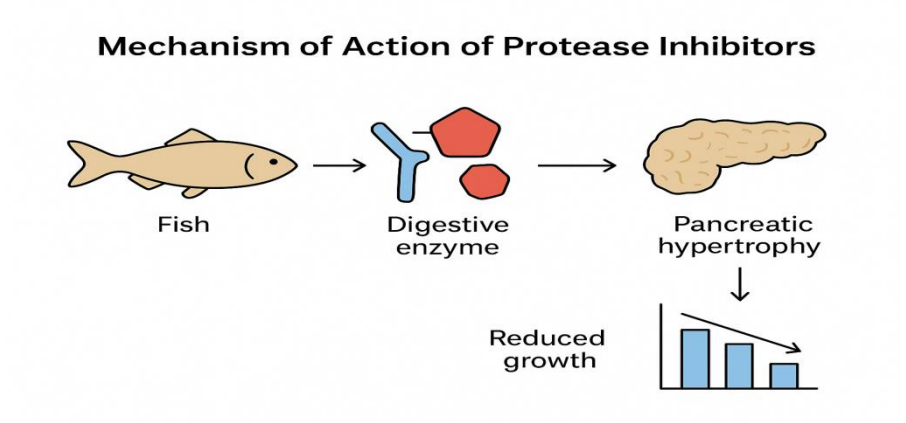
Protease inhibitors (PIs) are widely distributed in plant-derived protein sources commonly used in aquafeeds. Soybean meal is the most significant source, containing both trypsin inhibitors (TI) and chymotrypsin inhibitors (CI), which can account for up to 6–7% of total protein in raw soybeans (Krogdahl et al., 2010). Other legume-based ingredients such as groundnut meal, lupin seed, beans, and peas also contain varying levels of PIs that interfere with protein digestion in fish (Francis et al., 2001). Additionally, processing residues from oilseed cakes and meals may retain residual protease inhibitor activity depending on the extent of heat treatment applied during processing.

Mechanism of Action of Protease Inhibitors

Protease inhibitors exert their anti-nutritional effects primarily by binding to digestive enzymes such as trypsin and chymotrypsin in the gastrointestinal tract of fish. This binding forms stable enzyme–inhibitor complexes, thereby inactivating the enzymes and reducing their ability to hydrolyze dietary proteins (Krogdahl et al., 2010). As a result, the efficiency of

protein digestion is compromised, leading to poor amino acid availability for metabolic processes, growth, and tissue development.

To compensate for the loss of active enzymes, the pancreas increases enzyme secretion, which can cause pancreatic hypertrophy and hyperplasia (Francis et al., 2001). While this compensatory mechanism temporarily maintains digestive capacity, it imposes a significant energy cost, diverting resources away from growth and other physiological functions. Chronic exposure to dietary protease inhibitors thus leads to reduced feed conversion efficiency, growth retardation, and nutrient wastage, which may ultimately affect fish health and aquaculture profitability.



Effects on Fish Health and Performance

The presence of protease inhibitors (PIs) in aquafeeds has several detrimental effects on fish health and overall performance. The most direct consequence is growth reduction, caused by poor protein digestibility and decreased amino acid availability. This reduced nutrient utilization translates into nutrient wastage, which is reflected in a higher feed conversion ratio (FCR), lowering feed efficiency and increasing production costs.

Chronic ingestion of PIs may also lead to gut irritation and morphological changes, including shortened microvilli, altered intestinal mucosa, and compromised absorptive capacity. At the same time, continuous over-secretion of digestive enzymes to compensate for enzyme inhibition places the pancreas under heavy stress, leading to pancreatic hypertrophy and hyperplasia.

Nutrient deficiencies caused by impaired protein digestion can also result in indirect immune suppression, as essential amino acids are critical for the synthesis of immune-related

proteins and enzymes. Consequently, fish exposed to high PI levels often show reduced resistance to infections and environmental stressors.

Importantly, the severity of these effects is species-dependent. Carnivorous fish such as salmonids and seabass are more sensitive to dietary PIs due to their higher reliance on efficient protein digestion, whereas omnivorous and herbivorous species like tilapia and carp generally show greater tolerance, though still with measurable performance losses at high inclusion levels of plant proteins.

Challenges in Fish Feed Formulation

The incorporation of plant-derived protein ingredients in aquafeeds presents several challenges due to the presence of protease inhibitors (PIs). One major issue is that high inclusion levels of soybean meal, the most common fishmeal replacer, substantially increase the dietary PI burden. This reduces protein digestibility and can significantly impair fish growth performance, particularly in carnivorous species.

Another complication is the variability of PI content across feed ingredients. Factors such as plant variety, cultivation conditions, and processing methods (e.g., oil extraction, heat treatment) strongly influence residual PI levels. This inconsistency makes it difficult to predict the exact impact of PIs on feed performance.

Species differences add to the challenge. Carnivorous fish such as salmonids and seabass are more sensitive to dietary protease inhibitors, while omnivorous and herbivorous species like tilapia and carp show relatively greater tolerance. Feed formulators must therefore account for species-specific nutritional requirements and digestive physiology when determining inclusion levels of plant proteins.

Finally, there is an economic trade-off between cost and nutritional safety. Plant proteins are cheaper and more sustainable than fishmeal, but excessive reliance on them can reduce feed efficiency due to PI-related issues, ultimately negating cost savings. Optimizing feed formulations to balance affordability, nutritional quality, and fish health remains a critical challenge for the aquafeed industry

Strategies for Detoxification of Protease Inhibitors

Effective management of protease inhibitors (PIs) is essential to ensure the nutritional safety of plant-based aquafeeds. Several strategies have been developed to reduce their

negative impact on fish growth and health, ranging from feed processing to advanced biotechnological approaches.

Processing Techniques

Thermal processing methods such as toasting, extrusion, and autoclaving are widely used to inactivate protease inhibitors. Heat denatures the inhibitor proteins, thereby reducing their capacity to bind digestive enzymes. However, excessive heating may also destroy essential amino acids, lowering the nutritional value of feed. Other methods such as soaking, germination, and microbial fermentation can also reduce PI levels. Fermentation with beneficial microbes not only decreases inhibitor activity but may also enhance the digestibility and palatability of plant ingredients.

Enzymatic Approaches

The supplementation of aquafeeds with exogenous proteases offers a promising strategy to overcome PI effects. These enzymes help to compensate for inhibited endogenous proteases, improving protein digestion and nutrient utilization. When combined with other feed enzymes such as phytase, synergistic benefits on nutrient availability have been reported.

Biotechnological Strategies

Advances in crop biotechnology have enabled the development of genetically modified soybean and legume varieties with reduced protease inhibitor content. Such innovations provide long-term, sustainable solutions by reducing the need for extensive processing, although acceptance and regulatory approval remain major challenges.

Feed Formulation Approaches

Balanced feed formulation can also help minimize the impact of PIs. Strategies include blending plant proteins with animal proteins such as fishmeal or insect meal to dilute inhibitor concentrations. Additionally, the inclusion of functional feed additives like probiotics, prebiotics, and organic acids can improve gut health and enhance the digestive capacity of fish, indirectly alleviating the adverse effects of protease inhibitors.

Recent Advances & Case Studies

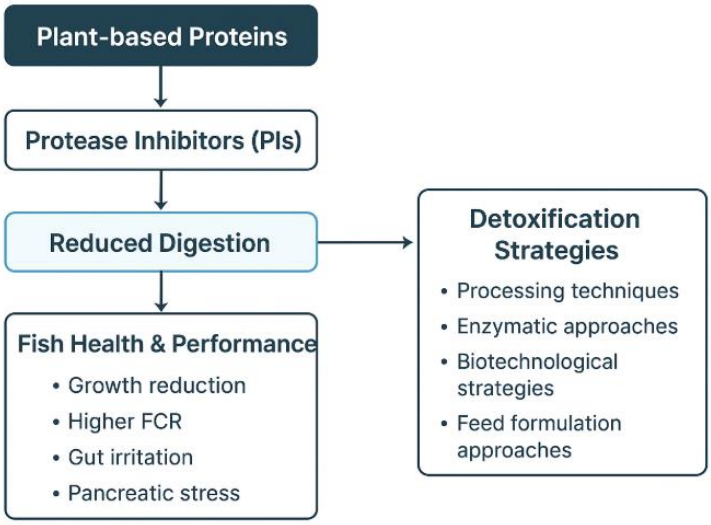
Recent studies highlight multiple approaches to mitigate protease inhibitors (PIs) in aquafeeds. Enzyme supplementation, particularly with proteases, improves protein

digestibility; when combined with phytase, synergistic gains in nutrient utilization and growth are observed (Xue et al., 2024). Microbial fermentation of soybean meal using *Bacillus* or *Aspergillus* can reduce trypsin inhibitor activity by >80%, while also enhancing palatability and amino acid availability (Fermentation MDPI, 2024). Advances in breeding low-KTI **(**Kunitz Trypsin Inhibitor) soybean cultivars offer long-term solutions, though regulatory and adoption challenges remain (USDA/ARS, 2024).

Case studies show species-specific responses: tilapia and carp benefit significantly from protease supplementation or fermented soybean meal; salmonids remain highly sensitive, requiring thorough PI reduction; and catfish/shrimp show improved growth with protease–phytase blends (Krogdahl et al., 2010; Francis et al., 2001). Collectively, combining processing, fermentation, enzyme supplementation, and genetic improvement provides the most effective strategy for controlling PIs in aquafeeds.

Conclusion

Protease inhibitors (PIs) continue to pose a significant challenge in the utilization of plant-based proteins for aquafeeds. Their interference with digestive enzymes reduces protein utilization, compromises fish health, and increases feed costs through poor efficiency. Adoption of effective detoxification techniques—such as heat processing, fermentation, enzyme supplementation, and selective breeding of low-PI crops—offers practical solutions to mitigate these effects. Integrating such strategies into feed formulation is essential not only for improving fish growth and welfare but also for ensuring the long-term sustainability and economic viability of aquaculture



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