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Growth Performance of *Clarias gariepinus* (Burchell, 1822) fed with Local Feed without Fish Meal

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Abstract In fish farming, feed accounts for a large proportion of production costs because of the use of fish meal and fish oil. The aim of this study was to develop a local feed from available local resources. To this end, a local feed balanced in essential amino acids and based on maggots (*Musca domestica*), earthworms *(Eisenia fetida*) and brewer's yeast as a total replacement for fishmeal was tested on *Clarias gariepinus* fry of average initial weight Pmi= 4.39± 0.01g for 90 days. Tested with three replicates, the feeds (control feed T0 - imported (*Gouessant*) and local feed T1) were used to feed fry distributed in tanks (volume 0.5m^3 each) with a density of 100 individuals / tank. Results showed that no significant differences were found in final weight and weight gain (p>0.05), whereas survival and protein intake differed significantly (p<0.05) between T0 and T1. Feed utilisation parameters showed better utilisation of the T1 local feed, with a consumption index of 1.01 and a protein efficiency coefficient of 1.9. Economic analysis showed that local feed T1 was about half the cost of commercial feed T0. Nevertheless, further investigations are required to determine the impact of using this local feed on the organoleptic quality and reproductive capacity of the products obtained.
Keywords *Clarias gariepinus*; Total replacement; Local feed; Reproductive capacity

1 Introduction

Demographic pressure and rising global fish consumption have encouraged intensive, and often irresponsible, fishing. This overfishing has endangered many wild fish species. Biodiversity is also under serious threat from pollution of the natural environment and overfishing with prohibited gear, leading to the disappearance of certain aquatic species (Welly et al., 2020)

In this context, aquaculture, and in particular fish farming, appears to be the answer to reducing overfishing and satisfying the growing consumption of fish. In many African countries, like Guinea, aquaculture is being developed (FAO, 2024). Despite Guinea's considerable potential, fish farming is practised extensively, seasonally in ponds, puddles and reservoirs (MPAEM, 2015).

Furthermore, the development of aquaculture in Guinea is coming up against a number of problems, including a lack of high-performance feed on the local market at prices that fish farmers can afford. The main activity of rural Guinean populations is agriculture, which plays an unprecedented economic and social role (MPAEM, 2015).

In West Africa, maggots or black soldier fly (*Hermetia illucens*) and housefly (*Musca domestica*) larvae are increasingly used in fish feed (Djissou et al., 2020; Gangbazo Kpogue et al., 2024). Known for their high nutritional quality (protein and essential amino acid content in particular), maggot meal is increasingly used in the manufacture of fish feed because of its short production cycle and affordable price. Maggots are also biodegraders of organic waste, the management of which is a major environmental concern in Africa (Odjo et al., 2018).

The economic interest of aquaculture is highly dependent on the availability and cost of feed (Djissou et al., 2016). Reducing feed costs, and consequently controlling the production cost of farmed fish, is therefore one of the priorities in aquaculture (Djissou et al., 2020). In fact, fish meal is an essential and practically unavoidable ingredient in aquaculture feeds due to its richness in Essential Amino Acids (EAA), the profile of which corresponds remarkably well to the needs of fish (Médale et al., 2013). However, according to Vodounnou et al (2025), the high cost of fish meal, coupled with its unavailability and variable quality on the local market, does little to improve the economic profitability of aquaculture. There is therefore an urgent need to find alternatives to fish meal for use in aquaculture. Increasingly, both plant and animal protein sources are being used as partial or total substitutes for fish meal (Médale et al. 2013; Djissou et al., 2020). The use of animal protein sources (termites, maggots and earthworms) and plant sources (peanut, sunflower and soybean cakes, bean meal and brewer's yeast) in aquaculture as substitutes for fish meal has thus been initiated (Gougbédji et al., 2020; Atchamou et al., 2024; Djissou et al., 2016) in several species, including *Clarias gariepinus*, with variable performance.

Clarias gariepinus is an omnivorous species with carnivorous tendencies and a high growth and economic potential. In Guinea, this species of great piscicultural interest is one of the species that fish farmers are most familiar with. Nevertheless, its production faces a number of difficulties, including the high cost and quality of the feed used, which is crucial to the development of the industry.

In replacement of the fish meal, the proteinic sources must bring the ten essential amino acids (EAA) required for fishes (Médale et al., 2013). To satisfy the essential amino acids requirements for *Clarias gariepinus* fingerlings, the experimental diets without fish meal based on a mixture of earthworm and maggots (proteinic sources) were tested on *Clarias gariepinus* (Djissou et al., 2016; 2025) and *Oreochromis niloticus* (Djissou et al., 2020) with good performances of growth and feed utilization for the pre-growing of fingerlings in Benin. This study was therefore initiated with the aim of promoting fish farming by developing a high-performance local feed that is free of fish meal and fish oil, and at a lower cost for the growth of fingerlings in Guinea.

2 Methodology

2.1 Experimental set-up

The experiment was carried out in an open circuit in six (06) circular above-ground concrete tanks, completely randomized, with a total volume of 0.5 m^3 each with of water supplied by borehole and a compressor (FIAC, axair 100L 2CV 10B 230 V) at a flow rate of 3 L min^{-1}. Half of the surface of each tank was covered with a screen to prevent direct sunlight penetration and, above all, the development of chlorophyll algae under the effect of solar radiation. A total of 600 *Clarias gariepinus* fingerlings, with an average initial weight of 4.39±0.07 g, were placed in the tanks at a stocking density of 100 fingerlings per tank. The fingerlings (tested with three replicates) were acclimatized for one week before starting the trial.

2.2 Obtaining the protein sources used to replace fish meal

The rearing of alternative animal protein sources was conducted at the experimental site. Earthworms (*Eisenia foetida*) were reared for 90 days (one production cycle) on a pig-manure substrate following the method described by Vodounnou et al. (2016). Maggots (*Musca domestica*) were reared on a substrate composed of soybean meal and chicken viscera, according to Odjo et al. (2018). Earthworm and maggot meals were processed in the same manner as the chicken viscera: the biomass was washed, drained, and gently cooked over low heat, then dried and ground into flour. The resulting meals were sealed in airtight plastic bags and stored under refrigeration until use.

2.3 Bromatological analysis

Diet T1 was analyzed according to AOAC (2005) procedures. Amino acids from diet were analyzed with a Waters HPLC method. These amino acid analyses were carried out using the method previously described by Bosh et al. (2006). Aminobutyric acid was added as an internal standard prior to hydrolysis. After experimentation, proteins, lipids and ash of 20 homogenized carcasses of fish taken randomly after 3 days from experiment in each diet. Crude protein (%N X 6.25) was determined by the Kjedahl method, fat by the hot method (Soxhlet type) and ash after incineration of the samples in a muffle furnace at 550 °C for 12 hours.

2.4 Feed formulation, manufacture and feeding frequency

The batches *of C. gariepinus* were fed two different diets during this experiment. The control diet T0 (*Gouessant*) is an imported commercial feed. The experimental diet is made up of ingredients including earthworms, maggots and brewer's yeast used as a source of protein that completely replaces fish meal (Table 1). With a feeding frequency of 4 times a day, the fish were fed for 90 days at a ration rate of 5% with the tested feeds.

Table 1 Feed composition of the imported feed (T0) and the local feed (T1) developed

Ingredients	T0 (%)	T1 (%)
Rice bran	-	5
Soy flour	-	25
Brewer's yeast	-	5
Cotton cake	-	15
Earthworm meal	-	12
Maggot flour	-	30.5
Palm oil	-	3
Vitamin	-	1
Minerals	-	1
Starch	-	2
Methionine	-	0.5
Crude protein	42	40
Fats and oils	11	12.9
Total ash	7.9	6.5

To make the food, the ground ingredients were weighed and mixed until a homogeneous powder was obtained, to which palm oil was added. Water was then added to obtain a malleable paste. A pelletiser with a mesh size of 1.5 and 2 mm was used to produce the pellets, depending on the development of the fish. The manufactured feeds were dried in the sun before being stored in boxes for conservation (-4 °C) before distribution (Table 2).

Table 2 Composition in essential amino acids (EAA) of the local feed developed (g.kg^{-1} of feed)

Essential amino acids	T1	EAA requirements of *C. gariepinus**
Threonine	8	5-5.6
Valine	7	7.1-8.4
Methionine	9	6-6.4
Isoleucine	11	6-7.3
Leucine	19	8-9.8
Phenylalanine	13	12-14
Histidine	9	4-4.2
Tryptophan	6	1.2-1.4
Lysine	14	12-14.3
Arginine	20	10-12

Table caption: : * NRC (2011)

2.5 Water physico-chemistry and biological monitoring

Water quality was monitored every 3 days by determining (twice a day) physico-chemical parameters such as temperature, dissolved oxygen, pH, conductivity and TDS using a multiparameter (ORCHIDIS SN-ODEOA-2138). Control fishing took place every two weeks, followed by emptying and cleaning of the tanks. The number and biomass of fish in each tank were determined by counting and using a centesimal- precision scale (TANITA KD-192).

2.6 Zootechnical and economic parameters

Growth, feed utilization and economic performances were determined by the average final weight (AFW), the Percentage Weight Gain (PWG), the Specific Growth Rate (SGR), the Survival Rate (SR), the Consumption Index (CI), the Protein Intake (PI), the Protein Efficiency Coefficient (PEC), the cost of manufacturing one kilogram of experimental local feed, the costs associated with manufacturing one kilogram of feed, the total production cost per kilogram of fish and the profit per kilogram of fish. The following formulas were used:

Pmf= Final biomass (g) / Final number of fish.

PGP= 100 x (Final average weight (g) - Initial average weight (g)) / Initial average weight

IC = Quantity of feed ingested(g) / Weight gain(g)

PI= Ration distributed x Crude protein / Final number of fish.

CEP= Weight gain(g) / Protein intake(g)

TCS (in %/d) = [Ln (Mf) - Ln (Mi) / t(d)] x 100

TS (in %) = (Number of final individuals / Number of initial individuals) x 100.

Cost per kilogram of feed from usual by-products =∑ (unit price of raw materials x proportions used)

Cost of manufacturing one kilogram of feed =∑ (cost of substrates+ milling price) x 100 / Rd with Rd the ration distributed

Total cost of a kilogram of feed= cost of a kilogram of feed from the usual sub-products + costs associated with manufacturing a kilogram of feed.

Total production cost per kilogram of fish= Total production cost per kilogram of feed x IC

Profit= Selling price per kilogram of fish - total production cost per kilogram of fish

2.7 Statistical analysis

Statistical analysis was carried out according to standard one-criterion analysis of variance (ANOVA) methods using Statistica version 6 software with a significance level of 5%. The Fisher LSD test was used for paired comparisons of means.

3 Results and Discussion

3.1 Farm water quality

Throughout the trial period, mean temperature values of around 28.4±0.6°C and 29.3±0.4°C were recorded at the T0 and T1 regime ponds, respectively. These measured temperatures are within the range (26 °C~30 °C) recommended by (Ipungu et al., 2019) for good growth of *Clarias gariepinus.* With regard to dissolved oxygen, the values recorded during the experiment were 4.22±0.9 $mg \cdot L^{-1}$ for regime T1 and 5.80±0.29 mg.L for regime T0. These recorded values are higher than the 3 mg/L reported by Ipungu et al. (2019) and are favourable for the growth of *C. gariepinus*. For pH, values of 5.38±0.42 and 5.68±0.31 respectively for T1 and T0 farm waters. The pH values indicate a slight acidity in the rearing water. However, they are likely to allow good growth of *C. gariepinus* (Ipungu et al., 2019). The values recorded for conductivity were 62.7±2.19 for the T0 regime and 72.6±1.26 µs/cm for the T1 regime, in contrast to TDS, where the values recorded were 42.9±1.11 and 49.2±1.37 ppm for the T0 and T1 regimes respectively.

3.2 Zootechnical and economic parameters

The zootechnical and economic performances obtained with the feeds tested after 90 days are presented in Table 3. Growth parameters such as Pmf, TCS, PGP reveal that there is no significant difference (p>0.05) in performance obtained between the local feed T1 and the imported feed (control - T0) with the exception of TCS. These results corroborate the work of Djissou et al. (2016) who used maggots and earthworms as a total replacement for fish meal to feed *C. gariepinus* fingerlings with similar growth performance (Table 3).

Table 3 Zootechnical and economic parameters obtained with the experimental systems

Zootechnical parameters	Experimental regimes	
	T0	T1
Pmi (g)	4.40± 0.01a	4.39± 0.01a
Pmf (g)	140.30± 5.71a	139.68± 1.26a
TS (%)	98.33± 3.11a	93.00± 0.66b
IC	1.11± 0.04a	1.01± 0.02b
CEP	1.01± 0.24a	1.9± 0.05b
TCS (%/d)	4.23± 0.02a	4.10± 0.01a
PGP (%)	3091.14± 131.61a	3081.70± 23.85a
PI	50.99± 2.11b	61.18± 0.84a
Economic parameters		
Cost per kg (GNF/Kg)	-	5 265
Manufacturing costs per kg of feed (GNF/Kg)	-	2 860
Total cost per kg of feed (GNF/Kg)	15 052	8 125
Total production cost per kg of fish (GNF/Kg)	16 708	8 206
Selling price per kg of fish (GNF/Kg)	22 578	22 578
Profit (GNF/Kg)*	5 875	14 373

Table caption: T0= Control food, T1= Local food. Values with the same letters on the same line are not significantly different ($p>0.05$). Values are expressed as mean± standard deviation. * Prices are in GNF and are based on exchange rates in November 2025. Labour and processing costs were included by adding 20% to the ingredient costs (Azaza et al., 2006).

As for nutritional requirements, the crude protein content of the diet tested in this study (40%) is within the range of optimal requirements for catfish *(Clarias gariepinus, Heterobranchus bidorsalis and Heteroclarias)*, which is between 40% and 42.5% (Monebi and Ugwumba, 2013). Several studies have shown that total replacement of fish meal by maggot or earthworm meal reduced the growth rate of fish such as *Heterobranchus longifilis* (Sogbesan et al., 2007), *Heteroclarias* (Monebi and Ugwumba, 2013) and *Clarias gariepinus* (Djissou et al., 2016). The results of these studies contradict our results, which show good use of the local feed with a better consumption index (1.01) and ingested protein (61.18), in addition to the good growth performance obtained. Meeting the essential amino acid requirements of *C. gariepinus* also contributed to this performance. In fact, when formulating fish feed, meeting the growth requirements of fish depends not only on the quantity of protein provided by the feed, but also on its quality, i.e. the nature of the amino acids provided, particularly the essential ones. In our work, the results obtained are therefore explained by the quality of the feed (protein and essential amino acids) which satisfies the needs of *C. gariepinus* for good growth. Furthermore, Djissou et al. (2016; 2017) showed that fish meal can be completely replaced by a combination of *Azolla filiculoides*, brewer's yeast, maggot and *Dialium guineense* leaf in the diet of *Oreochromis niloticus* with good growth performance. However, when the essential amino acid composition of the feed does not meet the needs of the fish, this influences the net energy value of the proteins and increases the metabolism of the fish, as well as polluting the environment with nitrogenous waste (Medale and Kaushik, 2009).

It should be noted that the biological value of the protein source depends on its essential amino acid profile (Table 2) as well as its digestibility. The values of CEP and PGP (Table 3) recorded with the test feed are due not only to the protein sources used as total replacements for fish meal (earthworm, maggot and brewer's yeast), which are rich in EAA (Adesina, 2012), but also to the diet of *C. gariepinus*. The PER obtained are generally lower than those obtained by Nyinawamwiza (2007), who completely replaced fish meal with groundnut, soybean and groundnut meal in the diet of *C. gariepinus*. Nevertheless, the local feed would be well digestible for the fish in view of the feed utilisation parameters obtained.

An optimal profile of essential amino acids is a prerequisite for fish growth (Medale et al., 2013). The feed tested in this study is of high quality in protein value because it contains all the EAAs with higher values with the exception of methionine (Djissou et al., 2020). In fact, lysine and methionine are the first limiting EFAs in many fish feeds, mainly in those based on unusual protein sources. In addition, lysine is one of the amino acids involved in growth processes and is known to act together with arginine to increase the activity of the latter (Furuya et al., 2023). Its normal level in the local feed clearly explains the better growth rates recorded. Similarly, the better growth recorded with the tested feed can also be justified by the optimal level of phenylalanine, which is within the recommended range (NRC, 2011), an amino acid capable of increasing the growth rate of catfish (Furuya et al., 2023). The results indicate that *C. gariepinus* fingerlings efficiently utilized the local feed tested with total replacement of fish meal by the combination of earthworm, maggot and brewer's yeast meal.

Feed is the most expensive input in fish farming, accounting for up to 60% of total production costs (Gangbazo Kpogue et al., 2024). Analysis of the economic parameters showed that the cost of producing one kilogram of fish was 8206 GNF for the local feed, compared with 16708 GNF for the imported control feed. The profit obtained with the local feed was 14373 GNF per kilogram of fish produced, compared with 5875 GNF for the imported commercial feed. This shows the profitability of feeding *C. gariepinus* local feed without fish meal made from local by-products. Nevertheless, for industrial production of local feed T1, electricity, various taxes and transport must be taken into account in determining the production cost per kilogram of feed. The use of these proteins in fish feed helps to recover animal and industrial waste and to clean up the environment by recycling animal and industrial production waste.

The observed difference in survival could be attributed to the digestibility of feed T1, which was formulated using ingredients such as soybean and cottonseed meal. These ingredients contain antinutritional factors, such as gossypol, fibre and tannins (Imorou Toko et al., 2008). These factors lead to poor nutrient absorption or mortality related to digestive disorders.

4 Conclusion

Profitable fish farming requires the use of protein sources other than fish meal. However, large quantities of plant and animal proteins exist that are not used in human food and could partially, or even totally, replace fish meal in fish farming. Here, the results show that the use of local sources of protein (maggots, earthworms and brewer's yeast) as a total replacement for fish meal in the diet of *C. gariepinus* makes it possible to obtain good growth performance and feed utilization with improved profitability. These results are of great interest because they allow us to conclude that feed formulas based on local by-products can be developed without fish meal and fish oil with good performance. Nevertheless, further investigations are required to ascertain the impact of using this local feed on the organoleptic quality of the muscle of the fish produced, as well as the impact of this feed on the reproductive capacity of adult *C. gariepinus*, i.e. on the quality of the gonads of broodstock fed with this local feed.

References

Adesina A.J., 2012, Comparability of the proximate and amino acids composition of maggot meal, Earthworm meal and soybean meal for use as feedstuffs and feed formulations, Elixir Applied Biology, 51: 10693-10699

AOAC, 2005, Official Methods of Analysis, 18th ed. Washington DC.

Atchamou J.B.O., Tonoukouen R., Kpogue D.N.S., Djissou A.S.M., Aboh B.A., Sohou Z., Ndong D., Fall J. and Mensah G.A., 2024, Impact of different organic substrates on the productivity and nutritional composition of black soldier fly larvae (*Hermetia illucens*), European Journal of Nutrition and Food Safety, 16(11): 240-251.

Azaza M.S., Mensi F., Imorou Toko I., Dhraief M.N., Abdelmouleh A., Brini B., Kraiem M.M., 2006, Effets de l'incorporation de la farine de tomate dans l'alimentation du tilapia du Nil (*Oreochromis niloticus* L., 1758) en élevage dans les eaux géothermales du sud tunisien, Bull Inst Nat Sci Technol Mer, 33: 41-52

Djissou A.S.M., Adjahouinou D.C., Koshio S. and Fiogbé E.D., 2016, Complete replacement of fish meal by other animal protein sources on growth performance of *Clarias gariepinus* fingerlings, International Aquatic Research, (4): 333-341.

Djissou A.S.M., Odjo I., Godome T., Koshio S. and Fiogbé E.D., 2018, Amino acids composition of maggot, earthworm, termite and chicken viscera meals used as proteins sources in fish feeding, International Journal of Aquaculture, 8(1): 114-118.

Djissou A.S.M., Godome T., Fagbémi M.A.N., Bangoura Y., Konaté D., Kpoguè Gangbazo D.N.S., 2025, Total remplacement of fish meal by alternative protein sources in *Clarias gariepinus* (Burchell, 1822) feeds, Aquaculture Science and Management, 2(1): 13.

Djissou A.S.M, Tossavi C.E., Odjo N.I., Koshio S. and Fiogbé E.D., 2020, Use of *Moringa oleifera* leaves and maggots as protein sources in complete replacement for fish meal in Nile tilapia (*Oreochromis niloticus*) diets, Turkish Journal of Fisheries and Aquatic Sciences, 20(3): 177-183.

Djissou A.S.M., Ochiai A., Koshio S. and Fiogbé E.D., 2017, Effect of total replacement of fishmeal by earthworm and *Azolla filiculoides* meals in the diets of Nile tilapia *Oreochromis niloticus* (Linnaeus, 1758) reared in concrete tanks, Indian Journal of Fisheries, 64(1): 31-36.

FAO, 2024, The state of world fisheries and aquaculture: the blue transformation in action, pp. 40.

Furuya W.M., da Cruz T.P. and Gatlin III D.M., 2023, Amino Acid Requirements for Nile Tilapia: An Update, Animals, 13: 900.

Gangbazo Kpogue D.N.S., Tossavi N.D., Atchamou J.B.O., Decko Z.P.E., Djissou A.S.M., Danhossou G. and Imorou Toko I., 2024, The use of Black Soldier Fly Larvae meal *H. illucens* for the pre growth of *Oreochromis niloticus* (Linnaeus, 1758) fingerlings reared in floating cages i Benin, Journal of Aquaculture & Livestock Production, 5(6): 1-7.

Imorou Toko I., Fiogbe E.D., Kestemont P., 2008, Mineral statuts of African catfish (*Clarias gariepinus*) fed diets containing graded levels of soybean or cottonseed meals, Aquaculture, 275: 298–305

Ipungu L., Kayuma M., Labe N.N., Malangu B., Binemo K., Ompey I., Ilunga N.B., Numbi M., Kidinda M., Kapemba K. and Ngoy K. 2019, Étude comparative de la croissance de *Clarias gariepinus* et *Clarias ngamensis* en élevage semi-intensif de la ferme Mwema à Lubumbashi, J. Anim. Plant Sci., 41 (1): 6805-6809.

Médale F., Le Boucher R., Dupont-Nivet M., Quillet E., Aubin J. and Anserat J., 2013, Plant-based feeds for farmed fish, INRA Production Animale, 26 (4): 303-316.

Médale F., and Kaushik S., 2009, Les sources protéiques dans les aliments pour les poissons d'élevage, Cahiers Agricultures, 18: 103-11.

Monebi C.O., and Ugwumba A. A. A., 2013, Utilization of the earthworm, *Eudrilus eugeniae* in the diet of Heteroclarias fingerlings, International Journal of Fisheries and Aquaculture, 5(2): 19-25.

MPAEM, 2015, Document Cadre de Politique des Pêches et de l'Aquaculture. pp.25

NRC, 2011, National Academy Press Washington, D.C., USA, pp.405

Odjo I., Djissou A.S.M., Guezo C. and Fiogbé E.D., 2018, Optimization of maggot production from a mixture of chicken viscera and soya cake based on different ratios, International Journal of Biological and Chemical Sciences, 12(4): 1583-1589.

Vodounnou D.S.J.V., Kpogue D.N.S., Mensah G.A. and Fiogbé E.D., 2016, Culture of earthworm (*Eisenia fetida*), production, nutritive value and utilization of its meal in diet for *Parachanna obscura* fingerlings reared in captivity, International Journal of Fisheries and Aquatic Studies, 4(5): 1-5.

Vodounnou J.V., Iko R., Okou G., Kpogue D., Ahouansou Montcho S., and Micha J.C., 2025, Complete substitution of fish meal with black soldier lies *Hermetia illucens* (L. 1758) larvae meal at varying incorporation rates for feeding *Oreochromis niloticus* raised in captivity, Aquaculture Science and Management, 2(1): 1-9.

Welly Y., Supitriyani, Yusnaini and Surdirman A., 2020, Factors of using non-cash payments to the comsumption level of students, Jurnal Bisnis dan Manajemen, 7 (1): 61-68.

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A Review on Pearl Farming: the Rising Trend in India

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Abstract Pearl farming, the ideal blend of production of gems and water. It is being considered as a practice that has sustainability and innovation that is not only economically but ecologically helpful too. China is the most prominent producer by fresh water pearl cultures in large scale. Behind Japan, there are Akoya pearls- high quality pearls and the exotic black pearls of French Polynesia. These two countries have jointly established a multibillion-dollar pearl industry in the world. Pearl farming continues to be in its nascent stage in India with the initiatives that were taken by the CMFRI (Central Marine Fisheries Research Institute) in starting of 1970. Despite demonstrations that have shown that it is practical through successful experiences with *Pinctada fucata* and freshwater mussels such as *Lamellidens marginalis*, the uptake is low. Nevertheless, the prospects are in satisfying the increasing demand of the global and domestic market of ornamental pearl, diversification of aquaculture and the creation of jobs in the rural areas. The pearl farming business in India is facing major challenges such as the technical expertise in surgical nucleation, inadequate infrastructure and high start-up capital despite the potential of the industry being enormous. India can transform this sector by concentrating on research, skill building and by coming up with favourable government policies. This would not only tie in sustainable aquaculture with economic growth but also make the country one of the key international markets in terms of pearl.

Keywords Pearls; Aquaculture; *Lamellidens* spp.; Oysters; Sustainable marine farming

1 Introduction

A Pearl is naturally produced gem, or gemstone that is produced within the soft tissues of some mollusc species such as oysters in the sea waters and mussels in the freshwater environments. This gem is highly lustrous, or has an assortment of colours, and is often a perfect round. It consists of 85% calcium carbonate, 12 percent organic matrix and water. The primary constituent is calcium carbonate that may have the form of aragonite or calcite. It surrounds all foreign particles or irritants that might have entered and lodged within the interior of the shell of the mollusc. The pearl has hardness value between 3.5 and 4.5 and specific gravity 2.7. Any mollusc may produce any form of pearl; but the finest pearls are those produced by those which have nacre on the outer shell. Pearls are grouped into three categories of natural pearls, cultured pearls and artificial pearls (Alagarswami, 1974).

Pearl farming/pearl culture is a subdivision of aquaculture which denotes the cultivation of pearls in a controlled or semi-controlled environment through the rearing of pearl oysters or freshwater mussels. To make a pearl, a nucleus and mantle tissue transplantation is surgically inserted into the mollusc that then secretes shells of nacre (calcium carbonate and organic matrix) around the implant. There are several processes involved in pearl farming which requires 12~24 months to produce the first pearls.

2 Global History of Pearl Farming

The earliest, free and round man-made/cultured pearl of India was produced at Pearl Culture Laboratory, a division of the Central Marine Fisheries Research Institute, at Veppalodai, near Tuticorin in July 1973. It was prepared by using Indian pearl oyster *Pinctada fucata*. Cultural technology has now produced pearls of different sizes and colour. Pearls began to be cultivated first in Japan in 1893 when half-pearls on shells were produced, and then in 1907 with the successful breeding of spherical ones. It has since been dominated in the production, marketing and technology of cultured pearls, in the world. In 1956, Australia began to farm pearls with Japan, and

Philippines and Burma also joined in such partnerships. In Hong Kong, Palau, Celebes and some other South-West Pacific islands, limited-scale production has been taken up. In the majority of joint ventures, Japan exports technical knowledge and does marketing, whereas the host country contributes primarily to the creation and maintenance of farms. Past studies have identified the Japanese approaches and pointed out the possible potential of India in the cultured pearl (Nagai, 2013).

3 History of Pearl Farming in India

In the Gulf of Kutch and Gulf of Mannar, India has a history of pearl fishing of natural pearls. But there are ups and downs in oyster production in these regions, and between productive fisheries, there are some seasons when the oysters are barren. Since 1900 the Gulf of Mannar has had only 12 seasons of fishing, the seven-year grand series of 1955 to 1961. India has ceased pearl fishing in Gulf of Mannar (after 1961) and in Gulf of Kutch (1966-1967). Oysters were collected in the pearl banks of Tuticorin by means of diving and using SCUBA, and then transported to the farm where they were cleansed and measured. They were outlawed in rafts and placed in sandwich-like frame nets with repeat laboratory tests on purity and growth checks. Even though the oysters were fairly healthy, barnacle infestation became an issue of serious concern and resulted in certain mortality. The vigorous of shell margin indicates that the sea of Veppalodai is an appropriate location where oysters can grow. The Kallar River contributed to freshwater inflow during the northeast monsoon which reduced the salinity marginally but did not have any adverse effects. Light penetration was poor, in the 4-meter-deep farm field (approximately 1.5 meters) and total water clarity was poor (Alagarswami, 1974).

4 Major Species and Regions

The main species of pearl production that is cultivated in freshwater systems are the Indian pond mussel (*Lamellidens marginalis*). Its adaptability to the conditions of the Indian environment and the possibility to grow high-quality pearls under conditions characterized as controlled habitats (pond, tank, integrated multi-trophic aquaculture systems, etc.) contribute to its popularity (Saurabh et al., 2022). There are approximately 3,270 molluscan species that inhabit India, 1 100 of which are bivalves. These include 625 species of marine bivalves of which 88 are endemics. Approximately, 52 mussel species have been reported in freshwater ecosystems and these are found in both stagnant and low-moving water bodies. Large-scale pearl production in India, despite such diversity, is temperately reliant upon three freshwater mussel species that belong to the Unionidae family -*Lamellidens marginalis*, *Lamellidens corrianus*, and *Parreysia*.

CIFA (Central Institute of Freshwater Aquaculture), Bhubaneswar, has been a leader in establishing and distributing freshwater pearl culture technologies in India (Saurabh et al., 2022). Marine pearl farming is instead based on the Indian pearl oyster (*Pinctada fucata*), especially in coastal states (such as Tamil Nadu, Kerala, and Andhra Pradesh). In India, freshwater pearl mussels and marine pearl-producing oysters are very prolific. *Pinctada margeretifera* in Andaman and Nicobar Islands and *Pinctada fucata* in the Gulf of Mannar, Palk Bay, and the Gulf of Kutch are pearl-producing oysters (Sharma, 2005).

5 Classification of Pearls

5.1 Natural pearls

In a case of swallowing a foreign particle by a pearl oyster without any human intervention the natural pearl is formed. The natural pearls consist of nacre crystallized into pearls of greater thickness. It is unevenly shaped and comparatively smaller. The reason for its uneven shape is edge formation of covering crystals of aragonite (Birunagi et al., 2024).

5.2 Cultivated pearls

It is alike naturally occurring pearls but, the nucleus is surgically implanted into the mussel instead of natural swallowing of any foreign particle. This culturing technique of making natural pearls can yield the required size, shape, colour and lustre of the pearl. They can be spherical, semi-spherical or designer pearls depending on the size and shape of the nucleus (Alexander and Kumar Verma, 2023).

5.3 Imitation or artificial pearls

To replace actual or cultured pearls, imitation pearls are prepared by applying tough, round bases, with materials that mimic the qualities of pearls. The coating may show a difference in response to inexpensive glittering paints, imitated pearl essences crafted of fish scales, and so on. The artificial pearls leave a trace on their smooth surface when pressed against a sharp object in contrast to natural or cultivated pearls (Alexander and Kumar Verma, 2023) (Figure 1).

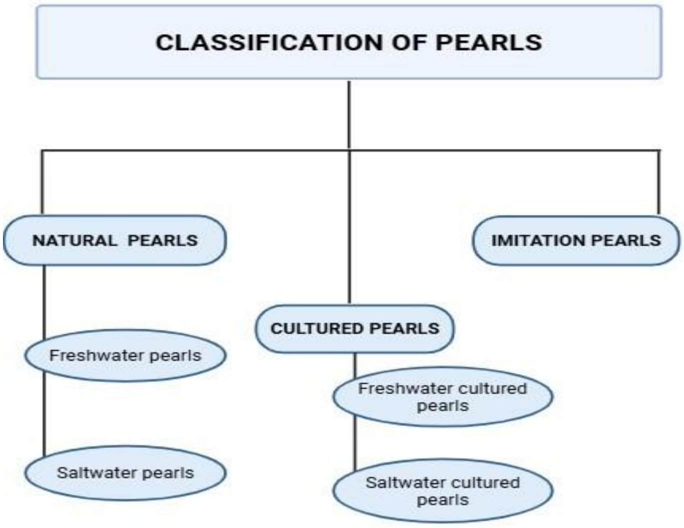

Figure 1 Classification of pearls

6 Biological and Technological Aspects

The pearls are formed by placing an irritant, usually a tiny bead or tissue lining, surgically into the mollusc into which the nacre is embedded to form the pearl in a few months to years (Saurabh et al., 2022). It is of paramount importance to maintain optimal water quality because physiological stress caused by such factors as ammonia may negatively influence the state of mussels and the quality of pearls. As an example, high levels of ammonia may disrupt important enzyme functions and antioxidation defences in *Lamellidens marginalis*, proving that the quality of water is reviewed and managed to ensure sustainable pearl culture (Chhandaprajnadarsini et al., 2025).

In order to facilitate operational efficiency, smart monitoring systems adoptions, including the use of IoT-enabled water quality sensors, application of machine learning models to predict the environment, etc. have become increasingly prevalent. Such technologies are able to forecast variations in such parameters as dissolved oxygen and pH to allow farmers to make appropriate interventions in time (Singh et al., 2022).

As part of its survival mechanisms, the marine oysters (particularly, *Pinctada spp*.) rely on their in-built immunity or an immune system to counter the environmental pressures like changes in temperature, salinity, the presence of pathogens and pollutants, etc. Antimicrobial peptides, lectins, heat shock proteins, and antioxidant enzymes are activated within them to sustain the cellular homeostasis. The pearl oyster can survive in unpredictable marine conditions with this capability. However, severe stress system may undermine the immunity of oysters and quality of pearls (Adzigbli et al., 2020).

7 Freshwater Pearl Culture

Pearl faming in freshwater involves the following steps sequentially:

7.1 Collection of mussels

The freshwater bodies have the mussels cleared manually and then transported to farm where they are harvested in a healthy manner. The habitats are primarily submerged in shallow peripheral regions and are primarily concealed by mud or sand. Habitats are in form of immobile stationary ponds, tanks, lakes, rivers, and reservations. Harvested pearl mussels on the natural bed are not always reliable because of their irregular harvest and contaminated water. The mussels seed grown in the hatcheries are much superior regarding the right supply of the pearls mussels to keep up the yearlong production. The mussels are grafted after growing such seed, according to weight, age, the degree to which they have sexual maturation and health in general (Ali and Rawat, 2023).

7.2 Pre-operative conditioning

The native pearl mussel species which were collected as freshwater are then subjected to the two-day pre-operative conditioning. They are kept in 200-liter ferro-cement tanks where the stocking density of the mussel is one mussel per litre. The pre-operative conditioning takes proper care of the relaxation of adductor muscles before surgery. This is important considering the low application of narcotizing methods that are used in the marine pearl production activities (Misra et al., 2009).

7.3 Selection and conditioning for surgery

Oysters that are 20 grams and above, are used to perform operational surgery with a goal of producing good outcome. They should be healthy and non-infected from borers. Oysters with maturing or mature gonads would be inappropriate because the gametes leak out during surgery and obscure the implantation site. Gametes may flow rapidly along the channel and the resultant graft tissue and nucleus may remain in place. Consequently, the selection of the oysters ought to be made of just oysters that are either at the initial stages of gametogenesis or recovering after spawning. The soft areas should be free of shells of sponge borers, polychaete blisters and trematode infections. The oysters should be stripped off all foul organisms.

The oysters are chemically conditioned to operate. Menthol crystals are added into the seawater in troughs of the oysters that are carefully selected. The oysters narcotize within 45~60 minutes and at this stage the valves are open because of adductor muscle’s loosening. Once each oyster is stripped, a wooden peg is placed between the valves and rinsed in sea water. The use of such narcotized oysters in the procedure should be as immediate as possible. When the oysters are put in pure seawater after surgery they will heal in 30~45 minutes (Victor et al., 1995).

7.4 Surgical implantation

Surgical implantations can take place in three sections of the mussel, which are of three different kinds depending on the kind of pearl being aimed at. A particular type of implantation is undertaken with each mussel. The mantle cavity insertion method is simple. The mussels of the weight and shell length required are collected prior to operation. They are appropriately opened with a 0.5 cm broad speculum that does not damage the soft tissues and adductor muscle of the mussels. An aperture the size and shape of a planned pearl, say 1 cm is cautiously inserted into the mantle cavity after a small section of the anterior side of the mantle has been detached, with care, at the top shell valve. Then it is driven in deep to avoid being rejected. One mussel may be implanted with the foreign organism that is desired in both of its valves.

Before surgery in the mantle tissue procedure, the mussels that are to be operated upon (the recipient mussels) and those sacrificed (the donor mussels) are separated into two categories. The pallial mantle ribbon of the living donor mussels is excised, clipped to grafts of the appropriate size and c alone or together with a small nucleus (2 mm in diameter). This kind of grafting is performed on both of the mantle lobes. There can be two to eight implantations depending on the size and thickness of the mantle of the recipient mussel.

In preparing the live graft parts to be implanted through the gonadal procedure, the recipient mussels are opened carefully to a depth of about 0.5 cm with a shell opener. Another end of the graft needle has a specialized knife that makes a tiny, precisely calibrated slit when he is making the incision beneath the outer membrane of the gonad. Caution should be observed that one does not make deep cuts into the gonadal tissue in order to avoid injuries to the intestinal coils. Only one implantation per oyster is to be done (Misra et al., 2009).

Precautions: 1) Wash the instruments properly, before and after use. 2) Avoid the use of mature oysters for nucleus implantation. 3) Avoid harming the stomach, heart, or intestine. 4) Make the incision or cut according to nucleus size.

7.5 Post-operative care and culture

Oysters are maintained in a flow-through system after operation until they are narcotized, or frequent water changes are done where flow-through system is not accessible. They spend three to four days in the lab in order to reduce stress by being observed in filtered clean water. Once they have been stabilized, they are taken to the farm and kept in fitting cages. Oysters are kept to low densities, suspended at lower levels and are treated sparingly to avoid stress during the post-operative stage. The period of culture on the nuclei with size in the range 2-5 mm takes 3-12 months in Indian conditions. The last harvest period is based on the harvests that are experimental and monthly observed (Victor et al., 1995).

7.6 Pearl formation

7.6.1 Natural pearl formation

Pearl formation in pearl oysters begins with organic or inorganic nucleus (e.g. sand grains, parasites, molluscan eggs, plant debris, epithelium cells of same animal etc.). These particles invade the oyster during feeding or breathing and sink in between shell and mantle. As an answer, mantle epithelium invaginate the foreign body and create a pearl-sac surrounding it.

Pearls only form after a pearl-sac has been formed, which is formed out of the interior or exterior epithelium of the mantle or gill plate. The secreted nacre of the epithelial cells of the pearl-sac increasingly coats the foreign object to form a pearl. There are seldom natural pearls between the mantle and shell, in the mantle, or in other soft tissues; these pearls tend to be small and irregular-shaped. Large pearls of round shape are very rare. When the irritant is stuck on the shell, forming a blister pearl is possible that only reflects the irritant on the exposed surface (Victor et al., 1995).

7.6.2 Cultured pearl formation

Their creation is anthropogenic. In any form of pearl development two things are indispensable, the outer epithelium of mantle lobe and a nucleus. The human made nucleus is gently inserted into the oyster tissue through appropriate surgery procedure. Grafted oysters are returned to the water in order to keep growing. As the inner epithelium and connective tissue of the mantle is absorbed, the outer cells of the graft tissues divide and form a pearl-sac around the nucleus. The pearl-sac cells produce a nacre (mother-of-pearl) in concentric micro-layers over the nucleus and get nourished by the adjacent tissues. Nacre is made up of aragonite (0.29 0.60 mm thick) and conchiolin, an organic mucopolysaccharide binding layer that is alternately and interchangeably composed of these components. Farmed pearls recreate the same process as nacre deposition and creation of pearls. A covering a few of the nuclei upon the inner of the shell gives half-pearls, the mantle epithelium forming a pearl-sac upon the top of the bare nucleus (Victor et al., 1995).

7.7 Harvest of pearls

The pearl culture period is short in tropical India in comparison with temperate locations. It may take up to 12 months in pond culture, each pond varying in the duration of time according to the size and number of nuclei, the well-being of the mussels and the conditions of the pond. The pearls that are formed as a result of gonadal implantation or grafting of mantle tissue are affected by the mother mussel and the donor mantle graft, and have a colour of silvery white to golden yellow and deep pink. The harvesting involves either killing of the mussel or extracting of the pearls in live mussels at the end of the culture period (12~14 months). Even though the freshwater mussels can produce pearls of gem quality, the size, shape, and colour may change because of natural variation. Pearls that are harvested are often washed, whitened, or dyed to ensure uniformity and value addition (Victor et al., 1995).

7.8 Grading of pearls

Grading of natural cultured pearls according to their quality (Glover et al., 2006) (Table 1).

Table 1 Grading criteria and quality characteristics of cultured pearls

Grading	Properties
AAA	Absolute shine, zero surface irregularities, and a perfect symmetry
AA	Good shine, quality and homogenous in colour with some irregularities on surface
A	Average quality, good shine but poor symmetry, uneven coloration with a few imperfections on surface
B	Good shine with uneven coloration and edgy surface
C	Low shine, weak nacre layer and serious surface flaws, no economic value

7.9 Culture in ponds

India Freshwater mussel is implanted to pearl culture year-round except during the hot months of May-June to reduce post-operative mortality and nucleus rejection. Traditional culture ponds are the most suitable since they are approximately 2.5 meters in depth, have a clay-soil foundation, are slightly alkaline and lack algae blooms and aquatic weeds. Implanted mussels are placed on bamboo rafts of nylon mesh bags (30 × 13 cm, 1.5 cm mesh) at a density of 50 000 mussels/ha (Figure 2).

Figure 2 Pond Culture of Pearl farming in India (Source: The Better India, 2021)

Pond management is vital in an attempt to maximize the yield of pearl, as well as to maintain the health of mussels. Ferro-cement tanks are fed with algae such as Chlorella, Chlorococcum and Scenedesmus (water green) and fertilized with 10 000 kg/ha cow dung, 100 kg/ha urea and100 kg/ha single super phosphate (SSP) every year to enhance natural food production. Water is fertilized and pumped to ponds when it is green. Freshwater mussels are able to consume a wide range of particulate organic matter as mucoid filter feeders; however, their preferred food items are diatoms, green algae and blue-green algae (Spirulina).

To reduce the cases of death due to parasite infections, inadequate food or internal injuries, frequent health examinations are done after every two weeks. Mussels are removed, checked and washed prior to being repacked in net bags. Physio-chemical factors such as temperature, water level, and nutrient load are all constantly checked; optimum growth occurs at 25 °C~30 °C. Excessive algal growth due to accumulation of nutrients is prevented (Misra et al., 2009).

8 Important Parameters for Pearl Farming

Soil and water quality are critical determinants of successful pearl farming because they directly influence mussel health, nacre secretion, and ultimately pearl quality and yield. Suitable pond soils should maintain a near-neutral pH, adequate organic carbon, and sufficient available nitrogen to support natural productivity, while the absence of hydrogen sulphide is important to avoid toxic stress in bottom conditions (Table 2). In addition, stable water quality is required throughout the culture period; a slightly alkaline pH, appropriate total alkalinity and hardness, and sufficient dissolved calcium provide favorable conditions for shell growth and nacre deposition, since calcium availability is closely linked to biomineralization processes (Table 3). Maintaining these parameters within the recommended ranges helps reduce environmental stress, improves survival and growth performance of cultured mussels, and supports consistent pearl formation and overall production efficiency.

Table 2 Recommended soil quality parameters for pearl farming

pH	6.5~7.5
Organic carbon	1.0%~2.5%
Available nitrogen	25 to 75 mb/100 gm of soil
Hydrogen sulphide	Nil

Table 3 Recommended water quality parameters for pearl farming

pH	7.5~8.5
Total alkalinity	75 ppm~150 ppm
Total hardness	40 ppm~75 ppm
Dissolved calcium	25 ppm~50 ppm

9 Socioeconomic Significance

Pearl farming also offers some form of diversification of income to fishers and the rural population especially where other stable sources are unavailable. The level of adoption among farmers has gone up due to training, government subsidies, and technology transfer efforts, but issues of water quality, technical expertise, and markets have become more difficult (SATHIADHAS, 2009). The break-even analysis of the aquaculture practices reveals that pearl culture is a lucrative activity particularly where it is integrated with fish, crops and livestock.

Farmers in developing countries such as India lack the understanding of the modern aqua farming methods, such as pearl farming that should be used in their respective sectors. There are already many women, farmers, and business people, interested in this topic, who expressed their interest in the Grade "AAA" that is the highest grade with such wonderful properties as excellent shine, non-existence of surface faults, and needed symmetry. Surface of AA has couple of marks on its surface, even colour, and lustre is good. A medium quality, colour variation, medium lustre, few surface flaws, poor symmetry A B good lustre with some imperfections and an uneven surface and colour (Singh et al., 2023).

10 Environmental and Sustainability Challenges

Productivity and sustainability have also been affected by not only the quality of water but also climate change, unpredictable rainfall, and gaps in skills when managing aquaculture (Singh et al., 2022). In reaction to this, integrated aquaculture such as multi-trophic systems that combine fish, mussels and other aquatic plants or animals is suggested to recycle nutrients and minimize environmental impact, which increases system resiliency and sustainability (Saurabh et al., 2022).

10.1 Impacts of ocean acidification on calcium carbonate deposition in pearls

Near-future ocean acidification (pH ~ 7.6) can cause disruption in nacre deposition in pearl oysters. SEM observations shows that lower pH levels can lead to the production of irregular and disorganized nacre tablets, reducing overall strength of oyster shell. This not only degrade the pearl quality but also increases the vulnerability of oysters to predation. As the cultured pearl industries depends on production of high-quality nacre from cultured oysters, the ocean acidification may lead to devastating effects for them (Welladsen et al., 2010). Increased temperatures can accelerate the impacts of ocean acidification by altering cell membrane permeability, impairing protein activities linked in acid-base regulation and defence, and leading to metabolic stress in marine calcifers (Li et al., 2015).

10.2 Impacts of accelerating sea temperature on quality and growth of pearls

Temperature significantly affect the pearl growth rate in *Pinctada margaritif*era, fastest growth rates are observed between 26 °C~30 °C while the rate declines significantly at 34 °C, followed by reduction in biomineralizing capacity of pearl sac. According to the polynomial equation: G=0.05T2+ 2.65T–33.34 (r=0.81), the optimum temperature for pearl growth is 27.1°C. Lustre or shine of pearls is also temperature dependant (lower the temperature, higher the lustre) (Le Moullac et al., 2018). Additionally, the Marine Heat Waves (MHWs) can cause damage of tissue in *P. maxima* (especially the gills' tissue) (Xu et al., 2022).

10.3 Importance of pearl farming in carbon sequestration and blue economy

Unlike some edible oysters, pearl oysters support ecosystem by providing services specifically through high filtration capacity. Water filtration capacity varies with size, life stage and species. Juvenile oysters can filter 2-4 litres of water per hour; adults can filter up to 22 litres and large *Pinctada margaritifera* and *Pinctada maxima* oysters have the capacity to filter 50~100 litres water per hour. Along with filtration, pearl faming also contributes to carbon sequestration and nutrient bio-extraction through shell formation. By extracting large quantities of organic nutrients and heavy metals, pearl oysters play a significant role in bioremediation (Farming, 2024).

11 Policy and Technology Transfer

The development of pearl cultivation in India is frequently dependent on the specific training, the sharing of technologies, and the localization. The Central Marine Fisheries Research Institute (CMFRI) and ICAR have played a key role in breeding, seed production, farming methods, training small-scale self-help groups to enhance quality and productivity at small and commercial levels (Jagadis et al., 2018).

Pearl culture has been transferred in India where the method has proved crucial in the transition to commercial application. It has now been possible due to the specialized training programs, on-field demonstration and participatory strategies whereby small farmers and rural self-help organizations have been able to integrate pearl production in their lives. The survival rates and the overall quality of pearls have improved due to diffusion of standard practices that include surgical implantation, pond and water quality management, and post-harvest value addition. Most importantly, such endeavors have shown that pearl farming can be an additional profitable activity to support the normal aquaculture and agriculture, and it can earn additional income. The report, however, notes that long-term sustainability would require uniform technical support, reliability in accessing the market, and sound policy support to encourage the wider adoption (Jagadis et al., 2018).

11.1 Pradhan Mantri Matsya Sampada Yojana (PMMSY)

It is a large initiative to modernize the fishing sector in India in a sustainable way. It was introduced in May 2020. The capital injection would be 20 crores of production, technological, and post-harvest infrastructure deficits over 5 years. The program empowers farmers and fishermen, promotes entrepreneurship and overall development of sectors through financial aid to the fish farming, fish hatchery, fish seeding, and capacity building programs.

11.2 NABARD's support for pearl culture

Cultivation of pearl is eligible to bank loans and NABARD refinance. The NABARD facilitates to qualified organizations such as Agriculture Development Finance Corporation (ADFC), State Cooperative Agriculture and Rural Development Bank (SCARDB), Regional Rural Banks and Commercial Banks to provide their loans on pearl culture facilities. The loan brings a maximum term of 15 years. The ultimate beneficiaries of the investment finance may be cooperative societies, firms, state or individuals and partnership firms (Sharma, 2005).

12 Future Aspects

In India, most farmers do not know much about the modern modes of aquaculture, such as pearl farming. Research and training institutions, especially ICAR-CIFA have eased the transfer of technology with farmers, entrepreneurs and women being trained. There are now freshwater pearl farms situated in states like Odisha, Maharashtra, Gujarat, West Bengal, Bihar, Uttar Pradesh, Chhattisgarh and Kerala. There is a large demand of big and designer pearls and even religious designs. The creation of more employment and more advanced methods of freshwater pearl farming can increase employment, wages and yielding high-quality freshwater pearls within a shorter cultivation cycle (Saurabh et al., 2022).

Indian government has provided subsidies and incentives to pearl farmers in order to reduce the financial risk associated with farming of pearl. Programs that are provided by different state fisheries departments differ. The technology diffusion programs of ICAR-CIFA, can be considered highly favourable to the farmers, fishery stakeholders, and businessmen who seek to initiate freshwater pearl farms. In its yearly training program, the candidates are taught practically how to practice the various techniques of implantation besides the technology of the culture of the culture which includes the water quality, mussel nutrition and feeding, pre and post care as well as the best conditions to achieve the pearl culture (Alexander and Kumar Verma, 2023).

13 Benefits of Pearl Culture

13.1 Non-perishable output

Production of pearls has benefit that the product is light, non-perishable, and it does not need much processing. Pearl oysters have flourished in isolated tropical atolls where the traditional fisheries are at logistical disadvantage. Pearl farming, with the exception of the grafting process or surgery, is not very complicated and requires no artificial feed, sophisticated infrastructure, or sustained supervision. It is also compatible and is also accessible by people who are adept at boating, diving, and fishing and so on, as an aquaculture occupation (Haws, 2002).

13.2 Revenue generation

The quality of pearls is highly priced hence; pearl farming is a profitable business. Although the prices depend on size and quality, large, round black pearls are priced highly such as an 8 mm good black pearl costing about $40 in 2000 and a 12 mm pearl of the same quality costing as high as $120. Even as prices of smaller, poorer quality pearls have dropped over the past years, large high-quality pearls have been comparatively stable (Haws, 2002).

13.3 Overcoming biodiversity loss

Climate change, overfishing, unregulated coastal development are the major threats to marine biodiversity. Conservation can only be effective when the local communities are involved and economic incentives are incorporated together with preservation of the ecosystems. The practice of cultured pearl farming is a good example of this practice, as environmental management has been a crucial aspect to ensure that production is economically successful (Cartier and Saleem, 2012).

14 Challenges and Constraints

Growing pearls has a number of challenges despite the fact that the pearl farming is a highly profitable business. Among the most significant factors is the capability of the mussel to survive after the implantation. It is another challenge to determine the right quality of the pearl once it has been purchased. Breeding technique standardisation is of great importance to freshwater mussels as successful breeding occurs, but mussel larvae survival is one of the greatest challenges. The attachment of Glochidia to secondary host fish is problematic. The mussel larval cycle requires a secondary host, e.g., a fish. Lack of expertise in pearl farming methods is one among the major problems (Saurabh et al., 2022).

14.1 Constraints for commercialization

Due to the low returns, commercial scale pearl growing has proved challenging to the entrepreneurs in India, despite the successes in the introduction of freshwater and sea pearl cultures in 1989 and 1973 respectively. Some of the challenges include unfavourable biological factors, absence of sheltered bays, turbulent waters, sediment, high oyster mortality, low implantation rates of the oysters, and labour-intensive processes. Moreover, the volume and the quality of the pearls produced in India attract decent prices in the outside world. It is important to save on costs, enhance production and make pearl production profitable, Pinctada maxima beds, local production of high-quality nuclei and development of steel black pearl of *Pinctada margaritifera* of Andaman and Nicobar Islands are all essential (Sharma, 2005).

15 Conclusion

Farming of pearls is a traditional activity in India that is at the cross road of tradition and modernity. Biological knowledge, technology use and policy reinforcement have led to amplified pearl production, rural wellbeing and provision of cultured pearls with confidence in the domestic and export market (Saurabh et al., 2022).

Nevertheless, further focus on water quality, climate adjustment, agriculture education, and market incorporation is necessary in order to realize the full capacity of this aquaculture industry (Chhandaprajnadarsini et al., 2025).

References

Adzigbli L., Hao R., Jiao Y., Deng Y., Du X., Wang Q., and Huang R., 2020, Immune response of pearl oysters to stress and diseases, Reviews in Aquaculture, 12(2): 513-523.

Alexander K., and Verma D.K., 2023, High-tech and beneficial agriculture: PEARL CULTIVATION IN INDIA,

Ali S., and Rawat R.S., 2023, A review on global status of fresh water mussel: pearl culture, International Journal of Creative Research Thoughts, 11(8): 2320-2882.

Birunagi S., Patil S., and Katkar N.S.D., 2024, Pearl farming: a review of farming in the future, International Journal of Research in Agronomy, 7(6S): 478-485. https://doi.org/10.33545/2618060x.2024.v7.i6sg.920

Cartier L., and Saleem H., 2012, Solutions: For a sustainable and desirable future, Solutions, 3(4): 30-34.

Chhandaprajnadarsini E.M., Maharana S., Tiwari P.K., Choudhary P., Sahoo S.N., and Saurabh S., 2025, Physiological impact of ammonia-induced stress in freshwater pearl mussel, *Lamellidens marginalis* (Lamarck, 1819), Molluscan Research, 45(1): 27-38. https://doi.org/10.1080/13235818.2024.2444185

Glover K.A., Skår C., Christie K.E., Glette J., Rudra H., and Skaala O., 2006, Size-dependent susceptibility to infectious salmon anemia virus (ISAV) in Atlantic salmon (Salmo salar L.) of farm, hybrid and wild parentage, Aquaculture, 254(1-4): 82-91. https://doi.org/10.1016/j.aquaculture.2005.10.041

Government of India Ministry of Fisheries, Animal Husbandry and Dairying Department of Fisheries, 2020, PRADHAN MANTRI MATSYA SAMPADA YOJANA OPERATIONAL GUIDELINES.

Haws M., 2002, The Basic Methods of Pearl Farming: A Layman's Manual, pp. 5-13.

Jagadis I., Kripa V., Mohamed K.S., Koya K.P., Mohanraj T., Sajikumar K.K., and Pradeep S., 2018, Technology transfer, adoption and performance evaluation of pearl culture technology at selected ecosystems of India, Journal of the Marine Biological Association of India, 60(1): 40-47.

Alagarswami K., 1974, Development of cultured pearls in India, Current Science, 43(7): 205-207.

Le Moullac G., Schuck L., Chabrier S., Belliard C., Lyonnard P., Broustal F., Soyez C., Saulnier D., Brahmi C., Ky C.L., and Beliaeff B., 2018, Influence of temperature and pearl rotation on biomineralization in the pearl oyster, Pinctada margaritifera, Journal of Experimental Biology, 221(18): jeb186858.

Li S., Liu C., Huang J., Liu Y., Zheng G., Xie L., and Zhang R., 2015, Interactive effects of seawater acidification and elevated temperature on biomineralization and amino acid metabolism in the mussel Mytilus edulis, Journal of Experimental Biology, 218(22): 3623-3631.

Farming M.P., 2024, A CASE STUDY FOR REGENERATIVE AND RESTORATIVE AQUACULTURE.

Misra G., Jena J., and Kumar K., 2009, Freshwater pearl crop: an emerging enterprise in the Indian subcontinent, Aquaculture Asia, 14(4): 26-27.

Nagai K., 2013, A history of the cultured pearl industry, Zoological Science, 30(10): 783-793. https://doi.org/10.2108/zsj.30.783

Sathiadhas R., Najmudeen T.M., and Prathap K.S., 2009,, Break-even analysis and profitability of aquaculture practices in India, Asian Fisheries Science, 22(2): 667-680.

Saurabh S., Pradhan S., and Suman S., 2022, Recent Trends in Freshwater Pearl Farming in India, in Update on Malacology, IntechOpen. https://doi.org/10.5772/intechopen.99281

Sharma M.R., 2005, ROLE OF NABARD IN CREDIT SUPPORT FOR DEVELOPMENT OF HORTICULTURE, Acta Horticulturae, 696: 577-581. https://doi.org/10.17660/ActaHortic.2005.696.101

Singh M., Sahoo K.S., and Nayyar A., 2022, Sustainable IoT Solution for Freshwater Aquaculture Management, IEEE Sensors Journal, 22(16): 16563-16572. https://doi.org/10.1109/JSEN.2022.3188639

Victor A.C.C., Chellam A., Dharmaraj S., and Velayudhan T.S., 1995, Manual on pearl oyster seed production, farming and pearl culture, CMFRI Special Publication, 63: 1-53.

Welladsen H.M., Southgate P.C., and Heimann K., 2010, The effects of exposure to near-future levels of ocean acidification on shell characteristics of Pinctada fucata (Bivalvia: Pteriidae), Molluscan Research, 30(3): 125.

Xu Y., Liang J., He G., Liu X., Yang K., Masanja F., and Zhao L., 2022, Responses of pearl oysters to marine heatwaves as indicated by HSP70, Frontiers in Marine Science, 9: 847585.

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Smart Technologies in Fisheries: Innovations in Monitoring, Management, and Sustainability

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Abstract This study mainly explores the core challenges during the global fishery transformation period, such as overfishing, deterioration of marine ecology, environmental pressure from aquaculture, and the problems of data deficiency and lag in fishery management. Why can intelligent technology become a key breakthrough for the sustainable development of the fishery industry? I have summarized the main technologies and application scenarios of intelligent fishery, such as Internet of Things sensing, artificial intelligence and big data, remote sensing and blockchain, as well as their practical application effects in resource assessment, water environment monitoring, IUU fishing identification, and precise aquaculture. I have also clarified the roles of these technologies in protecting fishery resources, improving production efficiency and industrial chain benefits, as well as their comprehensive impacts on the sustainability of the fishery environment, economy and society. Additionally, I have also paid attention to related issues such as international governance norms, national policy supervision and data ethics. I have also discovered that factors such as technology, economy and others have hindered the popularization of intelligent fishery, possibly exacerbating the uneven development of the industry. Intelligent fishery will integrate deeply with "Fishery 4.0" and AIoT. This study aims to combine technological innovation with inclusive development, people-oriented concepts and ecological protection, and promote the deep integration of technology with fishery systems and interests relations, so as to fully unleash its potential. This study provides practical theoretical and practical references for building an intelligent sustainable fishery industry globally.

Keywords Intelligent fisheries; Sustainable fishery development; Artificial intelligence; The Internet of Things; Fishery management

1 Introduction

In recent years, the global fishing industry has been in a critical transformation stage. Overfishing has put wild fish resources at risk, and climate warming and marine pollution have further damaged the ecological foundation of the fishing industry, directly affecting food security and the livelihoods of fishermen. Aquaculture has alleviated the pressure of fishing, but it also faces issues such as diseases and environmental burdens; while fishery management has always lacked data and the data is lagging behind, making resource assessment and law enforcement very difficult.

permeated every aspect of the fishing industry, becoming an important helper in the transformation of the industry. In marine fishing, electronic monitoring and remote sensing equipment can accurately collect data related to fishing, which is very helpful in combating illegal fishing (Barreiro et al., 2025); in aquaculture, the combination of the Internet of Things and artificial intelligence can automatically monitor water quality and identify fish diseases, not only improving the farming efficiency but also reducing carbon emissions (Lv, 2025); in the supply chain， the combination of blockchain and the Internet of Things can clearly trace the entire fishing process， and a new model of intelligent fishing is gradually taking shape.

In real-world settings, bringing intelligent technologies into use is rarely just a matter of choosing the most advanced option on offer. Much of the existing literature concentrates on what these tools can achieve in principle, but pays less attention to how they perform once they are introduced into established social arrangements and management routines. When projects move from the planning stage into everyday operation, practical difficulties tend to appear quickly. High initial costs, uncertainty over data ownership, and reluctance to change long-standing management habits often turn out to be more disruptive than expected, slowing implementation or, in some cases, causing projects to stall altogether (Barreiro et al., 2025).

Regional differences add another layer of difficulty to this process. In some areas, relatively advanced and integrated applications are already being tested in practice, while in others progress is still constrained by basic infrastructure limitations. This uneven development has gradually exposed gaps in access to digital tools and has prompted ongoing discussion about who is able to use new technologies and who ultimately benefits from them (Wang et al., 2025). In this context, focusing only on technological advancement is unlikely to bring about stable outcomes. What matters more in practice is whether these tools can be adjusted to fit local ecological needs, governance arrangements, and social conditions, allowing them to become part of routine work rather than remaining symbolic additions with limited real impact.

This study will explore the resource, environmental and governance challenges faced by global fisheries, and analyze the reasons why intelligence and data-driven approaches have become the key to sustainable development. At the same time, it will review the current intelligent technologies related to fisheries, analyze their application value and the path of integrating them into an eco-oriented management system, and combine cross-border cases to provide theoretical and practical references for building an intelligent sustainable fishery.

2 Common Intelligent Technologies in the Fishing Industry and Their Operating Modes

2.1 Internet of things and sensing technology

In day-to-day work, many fish farmers still rely on fairly familiar routines to judge what is happening in their ponds. They walk along the edges, watch the color of the water, pay attention to any strange smells, and now and then pull up a few fish to check their condition. This way of working has been passed down for a long time and is not completely unreliable, but its limitations are obvious. It requires time and constant presence, and much depends on whether someone happens to be on site. Changes that take place late at night are especially easy to overlook. When water temperature drops suddenly or dissolved oxygen falls quickly, the signs are often noticed only after the fish have already been affected, leaving little chance to react early. Precisely because of this, the Internet of Things and sensing technologies have gradually been introduced to the livestock farming sites. In simple terms, some devices are installed in fish ponds or near-sea farming areas to enable them to "keep an eye" on the water conditions. Data such as water temperature, pH value, and dissolved oxygen, which previously required manual monitoring, can now be continuously recorded. Even minor fluctuations are not easily overlooked (Huang and Khabush, 2025). After preliminary processing of the data, it will be transmitted to the platform. Farmers do not necessarily have to go to the pond; they can roughly grasp the situation from their offices or mobile phones (Huang and Han, 2025).

In real settings, this type of system is rarely tied to just one kind of farming environment. How it is used often depends on where it is deployed. Along coastal waters, it tends to function mainly as an early warning tool. Events such as red tides can be picked up earlier than before, giving managers at least some time to respond instead of reacting after the fact (Adnan et al., 2025). In inland ponds, however, the focus is more on everyday control. When water quality starts to shift, equipment like aerators or water exchange systems can be activated in time, helping fish and shrimp remain in relatively stable conditions. There are also cases where monitoring does not stay in one fixed location. With the use of mobile devices, for example unmanned boats, areas that were previously difficult to cover can now be checked more easily, and the overall monitoring range becomes wider. Of course, there will also be problems in actual use. Sensors may be blocked by mud or algae, and power supply instability occurs from time to time. These are not the "ideal conditions" mentioned in the technical promotion, but some targeted improvement methods have emerged now, such as self-cleaning probes and solar power supply. In the end, it is precisely because these data come more promptly and in greater detail that fishery management can gradually shift from "based on experience" to a more precise approach.

2.2 Artificial intelligence and big data

Collecting the data is merely the first step. What really causes headaches is how to determine what to do next when faced with a bunch of numbers. At this point, artificial intelligence and big data analysis come into play. They are more like a "background system", specifically responsible for identifying patterns from the chaotic data and providing relatively clear instructions. Nowadays, many breeding farms are attempting to use models to predict changes in water quality or assist in assessing the risk of fish diseases (Idoko et al., 2025). Some situations that were previously difficult to explain, such as sudden deaths of fish and shrimp, or oxygen deficiency in the water body in the morning, can also be detected in advance through data backtracking and trend analysis, thereby reducing losses. This does not mean that the problems can be completely avoided, but at least it is no longer necessary to make remedial efforts after the fact.

If artificial intelligence is directly linked with existing Internet of Things systems, which is often described as AIoT, its use is no longer limited to simple monitoring. In practice, this connection allows farming operations to respond more flexibly to what is actually happening in the pond. For example, feeding does not have to follow a fixed schedule. It can be adjusted according to how fast the fish are growing and how actively they are feeding. In some cases, different pieces of equipment can also be connected and respond automatically when conditions change (Chen and Huang, 2025).

These adjustments do not attract much attention, and taken individually they are easy to pass over. With time, however, their influence on everyday work becomes harder to ignore. Tasks that once required repeated manual handling are now performed less often by hand, feeding decisions are approached with more caution, and the most obvious forms of waste are easier to pick out and keep under control. Gradually, this changes how feed and related inputs are managed, weakening routines that were largely built on habit and accumulated experience rather than deliberate planning (Huang and Khabush, 2025).

Seen from a wider angle, the introduction of intelligent technologies into traditional fisheries is clearly not driven by sudden breakthroughs. Instead, small adjustments are made one after another, and many of them blend into existing practices without drawing much attention. What stands out is a change in how decisions are made. Choices that once relied almost entirely on personal judgment are now more often compared with data before action is taken. The process is slow and uneven, but it is beginning to influence everyday operational decisions in a steady way. In the fishing industry, AI can process data such as vessel tracking and satellite images to achieve intelligent identification of fishing vessels and fish stocks, estimate the catch volume, and detect traces of illegal fishing. Globally, AI can uncover the patterns of fishing activities and provide a basis for regulation and policy-making. However, the application of AI is constrained by issues such as data acquisition and standardization. It requires collaboration among fishery administrators, fishermen, and developers, and adaptation to actual needs, in order to transform AI from experimental applications into reliable fishery information systems.

2.3 Synergistic integration of remote sensing, unmanned systems and blockchain technology

Remote sensing, unmanned systems, and blockchain are integrating with the Internet of Things and AI to build a complete intelligent fishery system. Satellite remote sensing and drone images can make up for the shortcomings of on-site monitoring. Combined with ship data and AI, it can enhance the scope and efficiency of fishery supervision. Drones and unmanned ships are becoming increasingly common in the fishing industry and are quite practical. For instance, fishermen often use them to inspect fish cages and estimate the number of fish, and the operation is very convenient. As a result, the coverage of the Internet of Things becomes wider, and staff no longer need to frequently go to sea, which not only reduces operational risks but also significantly saves monitoring costs. What's more noteworthy is that if multiple devices work together, even those more complex monitoring tasks can be successfully handled (Idoko et al., 2025).

Blockchain has also begun to find its place in fisheries, although its role is sometimes easier to see in practice than in theory. Put simply, it offers a way to make fishery-related data more reliable and easier to trace. In seafood trade, for example, information can be recorded from the moment the catch is landed through processing and finally to the market. Once these records are uploaded, they cannot be altered at will and can be checked whenever needed. When blockchain is used together with the Internet of Things and artificial intelligence, it becomes harder to falsify records or hide inaccurate reports, and in real applications this combination has shown promising results. Similar blockchain-based IoT systems are not limited to fisheries. They have also been tested in agricultural production, where production data can be securely stored and protected from tampering. This makes certification of agricultural products more transparent, as the supporting evidence is clearer and easier to verify. In some pilot projects, such as quota trading, these systems have played an additional role by helping keep supply chains more stable and reducing the risk of disputes. For small-scale fishers in particular, this kind of transparency can translate into more predictable income and better livelihood security (Nandhini et al., 2025).

3 Innovation in Fishery Monitoring under Intelligent Technologies

3.1 Rethinking fishery resource monitoring and population assessment

For many years, estimates of fish populations were often based on broad impressions rather than solid numbers. In quite a few regions, surveys were carried out only occasionally, data accumulated at a slow pace, and by the time results were finally compiled, conditions in the water had already changed. This was especially common in small-scale fisheries, where staff numbers were limited and technical support was hard to come by. The shift away from this situation did not happen all at once. In the early stages, new monitoring tools were tested only in a small number of pilot sites and attracted little attention. Their value became clearer only over time. Today, monitoring is no longer restricted to short field surveys conducted once in a while. In some coastal fisheries, artificial intelligence–based image recognition has gradually entered routine work, making it possible to identify and count fish and invertebrates directly from images. In the Pacific region, for instance, a cloud-based platform has been developed that can recognize more than 600 coastal fish species. By handling large volumes of uploaded images, the system has sped up resource assessments and, in some cases, helped relieve pressure caused by shortages of specialists and long-term data records (Figure 1) (Kharabsheh and Bdour, 2025).

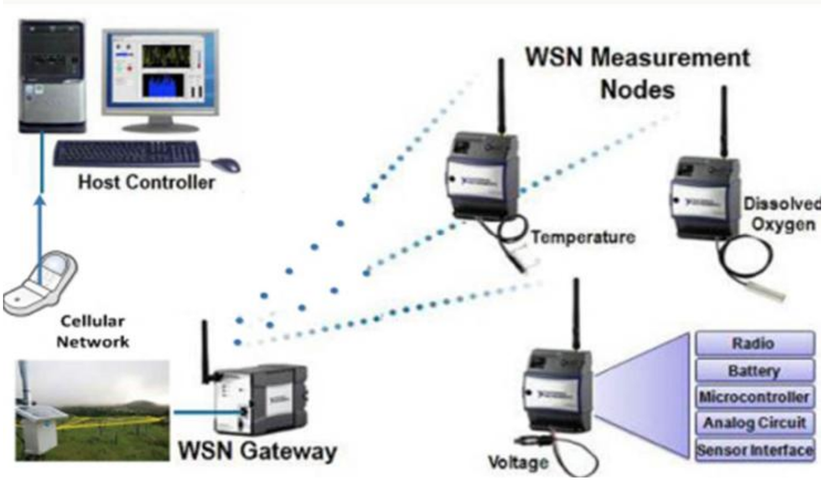

Figure 1 Illustration of the communication method embedded in the developed system (Adopted from Kharabsheh and Bdour, 2025)

These approaches are not only useful for species that are easy to spot. Evidence from Europe suggests that they also work for organisms that tend to remain hidden. Studies on Norwegian lobster populations combined underwater video, environmental DNA, and image analysis to locate individuals and their burrows directly in the field. Compared with earlier methods, this combination produced population estimates that were closer to actual conditions. At the center of these systems is not a single technology, but the ability to bring different types of information together. Images, catch records, and spatial data are uploaded to a central cloud platform, where learning algorithms extract indicators such as species composition and size structure. In many developing regions, this level of integrated analysis was previously difficult to achieve. If sensor networks and prediction models are added to the process, assessments can move closer to reflecting the condition of the wider ecosystem, rather than isolated snapshots.

3.2 From fish ponds to oceans: real-time monitoring of water environments

In many cases, changes in water environment monitoring came quietly rather than through any clear turning point. Across aquaculture operations, long-used practices were usually kept in place, with new tools added around them rather than replacing them outright. Low-cost sensors were introduced gradually and, over time, became part of everyday management routines. Once installed in ponds, they began to record basic conditions such as water temperature and dissolved oxygen on a continuous basis. Compared with earlier methods that depended heavily on manual checks, this approach reduced repeated measurements and, when problems occurred, left behind records that could be reviewed later instead of relying solely on experience or recollection (Kharabsheh and Bdour, 2025; Sharma, 2025).

As data continued to build up, the way they were used began to change almost without being noticed. In some systems, monitoring gradually moved beyond simply recording conditions and started to offer rough indications of survival rates, or to issue warnings when key indicators were approaching critical levels. Under relatively stable management settings or controlled trials, reported accuracy can be very high, sometimes above 99%. In a few cases, systems are also able to react automatically to changes in weather by adjusting water quality parameters, which has helped ease daily workloads and made routine management a little more efficient for farmers (Baena-Navarro et al., 2025). At the same time, results are far from consistent. Differences in data quality, local environmental conditions, and management practices still play a major role, and performance can vary markedly from one farm to another.

Related approaches are now being tested outside pond-based aquaculture as well. At a larger scale, projects such as those carried out in the Gulf of Aqaba have combined sensor networks with machine learning tools to track water quality in real time and assess the risk of coral bleaching. Available reports suggest that this setup has maintained monitoring effectiveness while reducing overall costs by around 30% (Kharabsheh and Bdour, 2025). Satellite remote sensing has also been drawn into this process. Although its spatial resolution is limited and the results are not always precise, it remains one of the few workable options for observing large marine areas at the same time. When satellite data are used together with nearshore sensor observations, monitoring begins to span multiple scales, gradually linking aquaculture management with broader assessments of ecosystem conditions.

3.3 Intelligent detection of illegal, unreported, and unregulated fishing

When it comes to dealing with illegal fishing, intelligent technologies are often appreciated because they make monitoring possible over a much wider area than manual inspection alone. In real situations, however, using these tools is rarely simple. Machine learning systems are typically applied to vessel movement data alongside satellite observations, with AIS signals used to identify routes or behaviors that appear unusual in timing or pattern. In Southeast Asia, for instance, studies have relied on vessel trajectory data to highlight zones where the risk of illegal fishing is relatively high, rather than to confirm individual violations outright (Sharma, 2025).

Some systems go a step further by assigning risk scores to vessels, suggesting whether they may be operating outside permitted waters. Others focus on identifying particular patterns, such as extended periods of loitering, through tools sometimes described as a "fishery prediction guardian." These systems can issue timely alerts that help enforcement agencies decide where closer attention may be needed (Sharma, 2025). They are not intended to replace inspectors working on the ground, but rather to filter large amounts of information and highlight cases that warrant further checking.

Despite these advances, a number of limitations remain difficult to avoid. One long-standing issue is that some vessels intentionally switch off their AIS transmitters, leaving sizeable gaps in monitoring coverage. To work around these blind spots, researchers have increasingly experimented with remote sensing and the joint use of multiple data sources. The INSURE system deployed in Ghana is often cited in this context, reporting an identification accuracy of around 91%. Even so, existing studies indicate that close to 75% of observed vessels still lack AIS records, which highlights how incomplete current surveillance efforts remain. As monitoring tools continue to be introduced more widely, other challenges have also become harder to ignore. Access to reliable data is uneven across regions, and false alarms occur often enough to remain a practical concern. In response, researchers have begun exploring a range of possible directions, including the combination of different image sources to enable more continuous, all-weather monitoring, as well as the use of blockchain-based tools to strengthen the credibility of operational records. These approaches are still being tested, but they suggest several possible paths for improving future responses to illegal, unreported, and unregulated fishing (Sharma, 2025).

4 How Intelligent Technologies Are Reshaping Fishery Management

4.1 Decision support systems and the shift away from pure experience

For a long time, fishery management followed a fairly familiar routine. Records were written by hand, figures were arrange and checked later, and decisions were usually made after the fact rather than during the fishing process itself. In some situations, by the time all the notes had been reviewed and compared, the season was already nearing its end. This way of working was not useless, but it was slow, and it rarely reflected what was actually happening at sea at that moment. The shift away from this approach happened step by step. Decision support systems were not introduced as a complete replacement from the start. Instead, they were added gradually and used alongside existing practices. As they improved, information that had once been scattered across different logbooks and reports began to appear in one place. Today, electronic logbooks, vessel position data, and catch records can be viewed together on a single platform, making it easier to follow fishing activity as it unfolds. The iFIMS system used by members of the Pacific Nauru Agreement is a typical example. With fishing volumes available almost in real time, routine assessments are now faster, and much of the repetitive manual data work has been reduced (Agmata and Guðmundsson, 2025).

These systems do not have to stop at basic data integration. In some cases, machine learning and image analysis have been added, making it possible to extract indicators like catch per unit effort automatically. This opens the door to more flexible management responses, such as temporarily closing certain fishing areas when environmental conditions change. At the same time, cloud-based deployment has made two-way communication easier. Fishers upload data, while managers send back forecasts or catch trend charts, which can help crews adjust their schedules. If vessel data and environmental information are further combined, the system may even estimate fishing probabilities, balancing quota control with ecosystem protection. That said, technology alone does not guarantee good management. Without clear governance arrangements, shared data standards, and proper privacy protection, even the most advanced system can fail to function as intended. Effective fishery management still depends on coordination across sectors and on fitting these tools into existing legal and institutional frameworks.

4.2 Moving toward more precise fishing and aquaculture practices

In recent years, fishing and aquaculture have started to look a bit more like carefully managed farming systems, although this change has not followed a single path. The underlying goal is fairly straightforward: increase output while avoiding extra pressure on natural resources. How this goal is approached, however, differs noticeably between capture fisheries and aquaculture. In capture fisheries, artificial intelligence is generally used as a point of reference rather than as a substitute for human decision-making. In routine practice, managers often look at historical catch records together with basic ocean conditions—such as variations in water temperature or salinity—to form a rough impression of where fish may be gathering. These models are not meant to remove uncertainty, and in practice they do not. What they tend to offer instead is a way to narrow down options, limit avoidable bycatch, and give managers more room to adjust quotas as conditions change (Agmata and Guðmundsson, 2025). At the same time, monitoring gaps that have existed for a long time are gradually being reduced. In many coastal areas, information on species distribution and market trends is now collected more regularly, while the combined use of remote sensing and vessel tracking has made coordination across regions more manageable, especially as marine ecosystems continue to shift at a faster pace.

Aquaculture follows a different logic. Here, the emphasis is less on prediction and more on keeping daily conditions within a manageable range. Sensors are usually installed for long-term use, continuously recording environmental indicators, while automated systems respond by fine-tuning feeding schedules and oxygen supply.

This does not mean that farming conditions are always optimal, but it does help keep biomass estimates more stable and reduce obvious feed losses. Ideas such as "intelligent fish farms" or automated production lines have become increasingly familiar, and in some cases digital twin technologies are already being used to simulate farming environments and coordinate equipment through cloud platforms. These approaches are not without limits. High upfront costs and a lack of trained personnel remain common obstacles. Still, with careful system design, wider adoption is possible, and over time such tools may contribute to both higher productivity and more environmentally responsible aquaculture practices.

4.3 Intelligent platforms and collaborative governance

An intelligent fishery platform should not be understood as nothing more than a data collection system. In real settings, it often plays a much broader role. It becomes a place where different groups are brought together. In several offshore fisheries in the Pacific, for example, monitoring systems were created through joint efforts by government agencies and local communities. Rather than dismantling existing arrangements, these systems were designed to work with local practices. Community-generated data were also incorporated, which made it easier for groups that are geographically dispersed to share experience, compare situations, and coordinate their actions. At a broader level, this type of cooperation is sometimes described using a "four-spiral" framework, which links academia, industry, government, and civil society. The emphasis is on moving innovation, financing, and training forward together, while connecting fishery management with wider concerns such as climate adaptation and food security.

Platforms built in this way rarely stay the same once they are put into use. As people interact with them, their role often shifts. Experiences from local fishery committees in Chile, as well as co-management practices in the Catalan Sea, suggest that bringing different stakeholders into the process can make a real difference. Community involvement helps preserve local autonomy, while state oversight remains in place, and tensions over how marine space is used become easier to handle. Seen from this angle, intelligent fisheries are not shaped by technology alone. Participation, mutual trust, and day-to-day cooperation matter just as much. When these elements are missing, even carefully designed systems tend to remain on paper rather than becoming part of practice. This is why future research and policy may need to spend less time on technical performance by itself, and more on how intelligent systems fit into participatory governance arrangements, with data managed in a fair and transparent way to support long-term social and ecological sustainability.

5 Application of Artificial Intelligence Video Monitoring in Fisheries

5.1 Application background, scenarios and system composition

In fishery management, the observer system has always faced a practical contradiction: when people go on board, the number is limited, and thus the coverage is naturally restricted; but if cameras are used instead and the footage is recorded and then reviewed by humans, with more videos, people will actually become even busier and unable to handle it all manually. Especially now, many long-distance and line-trawl fishing fleets have installed electronic monitoring equipment, and the amount of data is so large that it is almost impossible to fully process it manually. It was precisely under the circumstances where "there weren't enough people but there was too much data", that artificial intelligence video surveillance began to be taken seriously. Some research teams attempted to use deep learning models to directly process onboard videos, allowing the system to automatically identify fish species and judge fishing behaviors. The entire process hardly relied on manual intervention (Figure 2) (Khiem et al., 2025). Currently, such systems have been applied in various scenarios, such as nearshore resource assessment, deep-sea species observation, and even the automatic counting of crustacean catches from small fishing vessels. In the end, its key lies not in "taking videos", but in converting continuous videos into standardized data that can be used for management.

In routine use, this kind of system does not feel especially complicated to operate. Cameras mounted on fishing vessels simply record what happens during normal work, and the footage is later handled in the background rather than being reviewed manually. During processing, the models go through the video by identifying what appears on screen, following movement patterns, and sorting different elements into broad groups (Khiem et al., 2025). On a number of Australian longline vessels, this setup has already become part of regular practice. Fishing records are produced as trips are still underway, so crews no longer need to wait until returning to port to complete their logs. Other systems place their emphasis elsewhere. AI-RCAS, for instance, is built around speed rather than post-trip analysis. Instead of waiting until fishing operations are finished, it delivers information while work is still in progress. This makes it possible for crews and managers to respond to on-board situations as they unfold, adjusting actions in real time rather than relying only on later reviews. Beyond deck-level cameras, underwater imaging and towed cable observation devices are also used to turn raw video into useful population data. With these components working together, a clear pattern has emerged in recent applications. Most fishery AI video monitoring systems now follow a structure in which data are collected at the front end and processed centrally at the back end, a setup that has gradually become the common approach in practice.

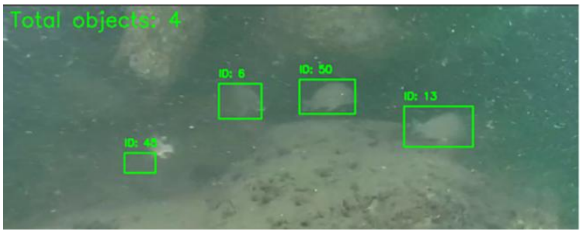

Figure 2 Fish counting results show the number of objects with bounding boxes in each frame (Adopted from Khiem et al., 2025)

5.2 Actual performance in resource assessment and law enforcement

Judging from how these systems are currently used, AI-based video monitoring can generally cope with everyday resource assessment tasks, even though its limitations are well recognized. In most routine situations, it provides information that is sufficient for basic management needs. On Australian trawler vessels, for example, early versions of the models produced catch counts that were broadly consistent with manual observations, with only small differences between the two approaches (Khiem et al., 2025). Similar technologies have also been applied to monitoring black cod populations and documenting underwater coral habitats, often without requiring major changes to existing equipment or operating procedures. Once the systems are in place, day-to-day operation tends to be relatively uncomplicated.

The value of video-based monitoring is often felt most clearly during enforcement work. Conventional observation relies largely on on-site personnel, and records usually have to be reviewed after the fact, which can take time. By comparison, AI-supported systems operate continuously in the background, so footage does not need to be examined from scratch once an issue arises. When real-time analysis is added, these systems can also support the management of total allowable catch limits and, in certain situations, help flag fishing activity occurring in areas where access is restricted. However, this technology is not perfect. In situations with insufficient light or turbid water bodies, the recognition effect will significantly decline; for some uncommon species that are also caught incidentally, the model is prone to make incorrect judgments. Therefore, if the goal is long-term and stable supervision, relying solely on algorithms is clearly insufficient. Establishing a dedicated quality control process is still necessary.

5.3 Key technical points and promotion potential

Looking at how AI video monitoring performs in everyday use, its effectiveness often comes down to a series of quite ordinary details. Model choice plays a role, but it is rarely decisive on its own. In routine operation, the size of the training dataset and the amount of effort put into labeling tend to have a visible impact on results. Under suitable conditions, recognition accuracy for some commercially important species can reach close to 90%, although this level is usually the outcome of repeated adjustment rather than a one-off installation (Khiem et al., 2025). Practical experience also shows that decisions made during system design can matter just as much as the algorithm. Camera placement is a typical example. It is easy to treat as a secondary concern, yet it strongly affects both species recognition and the stability of body length estimates (Baker et al., 2025). Hardware adds another layer of constraint. Smaller fishing vessels often have to work with low-power devices, while deep-sea observation platforms, despite stronger computing capacity, still struggle with the sheer volume of video data that needs to be processed.n terms of wider application, AI video monitoring appears easier to adapt than many other digital technologies. Approaches first tested in Australia are now being discussed for use in other offshore fisheries, and in some cases have also been applied to recreational fishing. At the same time, core detection modules are becoming more standardized, which makes it possible to use similar systems across aquaculture facilities, nearshore fisheries, and mixed-catch monitoring settings (Khiem et al., 2025; Baker et al., 2025; Al-Abri et al., 2025). Even so, technical readiness alone rarely leads to smooth adoption. Questions around privacy, access to data, and coordination among different stakeholders tend to emerge during implementation. In practice, setting clear goals for how systems are meant to be used, building open and comparable benchmark datasets, and involving fishers directly in system design often prove more helpful for real-world uptake than continuing to focus only on improving algorithm performance (Afrifa-Yamoah, 2025).

6 Intelligent Technologies and Sustainable Fisheries Development

6.1 How intelligent monitoring supports resource conservation and ecological restoration

In fisheries management, recent changes are driven less by specific devices than by continuous data collection and use. Previously, data were scattered and infrequent, and problems were often identified only after damage occurred. With the gradual adoption of intelligent monitoring, sensors deployed at sea, on vessels, and around aquaculture sites now regularly record key indicators such as temperature, salinity, dissolved oxygen, and fish distribution. While individual measurements may seem ordinary, together they provide managers with a clearer picture of fishing pressure and help identify areas requiring protection (Li et al., 2025; Lu, 2025). When combined with satellite data and automated analysis, these systems also make illegal fishing harder to conceal, while selective fishing gear has further helped reduce pressure on certain fish stocks (Wang et al., 2025). Although not immediate solutions to overfishing, these tools allow earlier and better-informed management responses.

Marine protected areas follow a different approach, where limiting disturbance is often more important than increasing monitoring frequency. Technologies such as underwater robots, biological tagging, and automated stations enable long-term observation of species behavior and habitat recovery with minimal human interference, providing more stable references for restoration decisions (Masmitja et al., 2025). Management has gradually shifted from reacting to damage toward earlier risk identification, as AI and large-scale data analysis can detect early signs of stock decline (Wang et al., 2025). At the same time, cleaner farming practices and blockchain-based traceability are beginning to influence production choices, placing greater emphasis on long-term sustainability (Li et al., 2025).

6.2 Improving efficiency without focusing on output alone

Innovation in fisheries has never been only about producing more. As resource limits become increasingly clear, attention has shifted toward how efficiency can be improved without adding further pressure on ecosystems. In aquaculture, cloud platforms, Internet of Things technologies, and artificial intelligence are gradually finding their way into everyday management. Feeding and aeration decisions are no longer guided solely by experience. Instead, systems adjust settings in response to real-time data, which helps reduce feed waste and lower mortality under typical operating conditions (Briones et al., 2025). AI-supported biofloc systems provide a practical example of this trend. By automatically fine-tuning culture conditions, these systems help maintain fish health even at relatively high stocking densities, while keeping costs within a manageable range (Alghamdi and Haraz, 2025). They are not suitable for every situation, but they illustrate that improvements in efficiency do not necessarily have to come at the expense of environmental performance.

Changes can also be seen in capture fishing, although they are often less visible. With IoT-based monitoring tools, fishers are increasingly able to plan routes based on real-time sea conditions and market information, reducing unnecessary travel and fuel consumption caused by limited or outdated data (Li et al., 2025). In several developing regions, relatively simple technologies-such as solar-powered equipment and mobile information platforms-have already made a noticeable difference to household incomes (Hungevu et al., 2025; Chandravanshi et al., 2025). Experience from coastal areas of China further suggests that, when systems are designed with care, intelligent technologies can support economic returns while remaining broadly compatible with environmental protection goals.

6.3 Beyond environment or economy alone

Whether fisheries supported by intelligent technologies can genuinely be regarded as sustainable is difficult to judge if attention is placed on environmental indicators alone. In practice, economic and social considerations are closely intertwined and rarely easy to separate. From the environmental side, intelligent systems have been linked to more efficient use of resources, lower levels of waste during farming and processing, improved oversight of illegal fishing through continuous monitoring, and conditions that are more favorable for ecosystem recovery (Wang et al., 2025; Li et al., 2025; Lv, 2025). Economic impacts are also becoming increasingly apparent. Digital tools are helping reduce transaction costs along the supply chain and, in some cases, lowering barriers for small-scale fishers to reach markets. Evidence from China's coastal regions suggests that economic growth and environmental improvement do not always stand in opposition, as long as management arrangements take local circumstances into account (Li et al., 2025).

Social effects, however, are often less straightforward. On the positive side, intelligent systems can help ease labor shortages, improve safety during offshore operations, and provide fishers with more opportunities to participate in management processes (Chandravanshi et al., 2025; Briones et al., 2025). At the same time, several studies caution that unequal access to technology and insufficient policy support may widen existing gaps within the sector or lead to an overreliance on automated systems (Jang et al., 2025). Seen from this angle, the key issue is not simply whether intelligent technologies are available, but how they are introduced, shared, and governed in ways that remain fair, inclusive, and balanced over time.

7 Policy and Regulatory Framework for the Development of Intelligent Fisheries

7.1 International governance and institutional support for intelligent fisheries

International laws and governance initiatives provide the overall direction for the development of intelligent fisheries. Key frameworks such as the United Nations Convention on the Law of the Sea and the FAO Code of Conduct for Responsible Fisheries emphasize monitoring, control, and the use of advanced scientific methods, including digital and AI-based technologies. These principles are further operationalized by regional fishery management organizations through standards such as electronic monitoring and satellite vessel tracking. In addition, the proposed Biodiversity Beyond National Jurisdiction agreement highlights electronic monitoring as a core tool for high-seas protection, offering legal support for the wider adoption of intelligent systems.

At the same time, governance challenges emerge early and are difficult to avoid. As intelligent technologies shape fisheries management, debates quickly focus on system transparency, data access, and decision-making authority. Research shows that data accessibility and transparent processes are essential for trust and accountability. The Global Fisheries Watch initiative illustrates this tension: while it enables public, real-time tracking, it has also raised questions about data ownership and enforcement authority. Similar issues appear in broader international discussions, where AI governance remains fragmented and fishers' practical concerns are often underrepresented. Without parallel efforts to ensure fair access and participation, new technologies risk reinforcing existing geopolitical and economic inequalities.

7.2 National-level policies, regulations and governance practices

At the national level, governments operate between international commitments and everyday management needs. In practice, the pace of intelligent aquaculture development depends less on technological readiness than on whether policies allow flexible yet well-defined use. Many countries have revised aquaculture laws to promote monitoring and traceability, increasing regulatory pressure while also improving efficiency and product quality.

Comparable patterns exist in capture fisheries. Some regions mandate electronic logbooks and vessel monitoring, while others still rely heavily on rigid paper-based systems. These contrasts highlight how regulatory design shapes technology adoption. For example, the United States emphasizes performance outcomes rather than specific equipment, whereas the United Kingdom continues to debate mandatory remote electronic monitoring. Studies suggest that voluntary systems often yield uneven results, making standardized approaches such as “SMART” mechanisms more effective. Evidence from countries like Indonesia and Pakistan further shows that lasting improvements depend on both reliable data and coordination across governance levels. Where legal, administrative, and technical systems are misaligned, effective governance is difficult to sustain (Suherman et al., 2025; Lina and Butt, 2025).

7.3 Data governance, ethical issues and regulatory challenges

The development of intelligent fisheries requires robust data governance frameworks that balance innovation with confidentiality, fairness, and ethical use. AI systems rely on large volumes of vessel, catch, and image data, yet privacy concerns and legal restrictions often limit data sharing. Even where technology is mature, paper-record requirements and strict confidentiality rules continue to constrain digital applications, while dedicated regulatory standards for fishery AI-such as algorithm transparency and accountability-remain underdeveloped.

As intelligent monitoring becomes more widespread, ethical concerns are increasingly visible. Technologies like remote sensing and drones expand regulatory capacity but also raise questions about privacy and data ownership. Governance research emphasizes that fishers and local communities should be active participants in decisions about how data are collected and used, rather than merely serving as data sources (Montana, 2025). At the operational level, weak coordination among institutions remains a key vulnerability. Inconsistent terminology and unclear standards can create confusion once data flow across agencies. Studies warn that rigid quota rules or poorly designed data systems may generate unintended ecological and social effects, underscoring the need for cautious, preventive policy approaches rather than overreliance on rapid technical fixes (Radi et al., 2025). Ultimately, successful governance depends not only on technology, but also on whether intelligent systems function fairly and effectively in real-world practice.

8 Challenges, Future Trends, and Prospects

The adoption of intelligent technologies in fisheries and aquaculture is constrained by a combination of technical, economic, and operational factors. These barriers slow implementation and may widen existing development gaps within the sector. Technically, intelligent systems depend on reliable sensors, networks, and data transmission, yet many aquaculture sites and small-scale fisheries are located in remote areas with weak infrastructure, making long-term maintenance difficult. Economically, high upfront costs, uncertain returns, and limited financing channels—especially in developing countries-restrict wider uptake. Operationally, limited digital literacy among fishers and managers, along with continued reliance on paper records and the lack of recognition of third-party data, further hinders implementation. As a result, fisheries digitalization cannot be treated as a simple technological upgrade, but must account for the diverse capacities and needs of different actors.

Looking ahead, intelligent fisheries are likely to evolve toward deeper integration between “Fishery 4.0” and AIoT systems. By combining artificial intelligence, the Internet of Things, and edge computing, future systems will increasingly link production, monitoring, processing, and marketing. In aquaculture, intelligent fish farms are expected to become more common, using sensors, computer vision, and digital twins to optimize water quality and feeding in real time, while edge computing helps address connectivity challenges in remote areas. At the same time, advances such as deep-sea intelligent aquaculture will continue to emerge. Successful implementation will depend heavily on cross-disciplinary and cross-institutional cooperation, enabling data sharing, regulatory coordination, and alignment with real production needs. Future research is also expected to move beyond small-scale pilots and focus more on long-term impacts and governance frameworks that support sustained application.

Despite these challenges, intelligent fisheries still hold significant potential to support sustainable development when technological innovation is combined with inclusiveness, people-centered approaches, and ecological protection. Existing applications of IoT monitoring, AI analysis, and blockchain traceability have already improved efficiency, reduced waste, and increased transparency, while helping small-scale fishers access data and markets more effectively. AIoT and marine intelligent technologies can support adaptive management and ecological restoration by providing real-time information on resources and fishing intensity, and Industry 4.0 approaches may further reduce environmental impacts. Nevertheless, intelligent technologies are not a universal solution. Their long-term value depends on lowering application costs, improving digital skills, and establishing fair data-sharing mechanisms that reflect the realities of small-scale fisheries. Ultimately, intelligent technology is a tool for transformation, and its effectiveness rests on how well it is integrated into institutional reforms and evolving interest relationships within the fishery sector.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Adnan J., Ishak M., Hashim F., Saad M., and Rahman M., 2025, IoT-based coastal fisheries monitoring system, Advances in Agricultural and Food Research Journal, 10: a0000499.
https://doi.org/10.36877/aafrj.a0000499

Afrifa-Yamoah E., 2025, Digital transformation in recreational fisheries monitoring: A framework for data integration, analysis, and management applications, Fisheries Management and Ecology, 10: 70023.
https://doi.org/10.1111/fme.70023

Agmata A., and Guðmundsson S., 2025, Convolutional-LSTM approach for temporal catch hotspots (CATCH): An AI-driven model for spatiotemporal forecasting of fisheries catch probability densities, Biology Methods & Protocols, 10: bpaf045.
https://doi.org/10.1093/biomethods/bpaf045

Al-Abri S., Keshvari S., Al-Rashdi K., Al-Hmouz R., and Bourdoucen H., 2025, Computer vision-based approaches for fish monitoring systems: A comprehensive study, Artificial Intelligence Review, 58: 11180-3.
https://doi.org/10.1007/s10462-025-11180-3

Alghamdi M., and Haraz Y., 2025, Smart biofloc systems: Leveraging artificial intelligence (AI) and internet of things (IoT) for sustainable aquaculture practices, Processes, 13(7): 2204.
https://doi.org/10.3390/pr13072204

Baena-Navarro R., Carriazo-Regino Y., Torres-Hoyos F., and Pinedo-López J., 2025, Intelligent prediction and continuous monitoring of water quality in aquaculture: Integration of machine learning and internet of things for sustainable management, Water, 17(1): 82.
https://doi.org/10.3390/w17010082

Baker L., Knott N., Gorkin R., Aubin S., Brown C., and Peters K., 2025, Fishing for data: AI approaches to advance recreational fisheries monitoring, New Zealand Journal of Marine and Freshwater Research, 59(8): 848-865.
https://doi.org/10.1080/00288330.2024.2438227

Barreiro M., Abad E., Antelo L., Fernández J., Pereira C., Ovalle J., Martín R., and Valeiras J., 2025, Development of smart electronic observation onboard technologies for more sustainable fisheries management, Frontiers in Marine Science, 10: 1545718.
https://doi.org/10.3389/fmars.2025.1545718

Briones S., Briones S., Isorena J., Amata M., and Sabaria J., 2025, The design and development of CATCHFISH system: A collaborative ICT-based tool for an optimize fishing repository and catch efficiency, Journal of Information Systems Engineering and Management, 10(32): 5431.
https://doi.org/10.52783/jisem.v10i32s.5431

Chandravanshi S., Sudan P., Bihari K., Venkat C., Sandeep J., Yadav B., Revathi A., and P P., 2025, Digital innovations in fisheries and aquaculture: A systematic review of technologies, adoption, and socio-economic impacts, International Journal of Advanced Biochemistry Research, 9(9): 5642.
https://doi.org/10.33545/26174693.2025.v9.i9e.5642

Chen L.Q., and Huang W.Z., 2025, Sustainable fisheries management: Balancing resource use and conservation, International Journal of Aquaculture, 15(6): 287-297.

Huang W.Z., and Han Y.P., 2025, Habitat degradation and restoration in aquatic ecosystems: Implications for fish populations, International Journal of Aquaculture, 15(4): 175-183.

Huang Y., and Khabusi S., 2025, Artificial intelligence of things (AIoT) advances in aquaculture: A review, Processes, 13(1): 73.

https://doi.org/10.3390/pr13010073

Hungevu R., Ademola T., Yinusa S., Titiloye T., Lasisi R., and Okunola M., 2025, The impact of low-cost technological innovations on sustainable fisheries for economic development in developing countries, World Journal of Advanced Research and Reviews, 25(2): 0463.
https://doi.org/10.30574/wjarr.2025.25.2.0463

Idoko F., Idoko D., and Idoko F., 2025, Exploring the role of IoT, AI, and remote sensing in precision aquaculture: Monitoring, automation, and data-driven decision-making, Magna Scientia Advanced Biology and Pharmacy, 14(2): 0018.
https://doi.org/10.30574/msabp.2025.14.2.0018

Jang S., Liu Y., Liu J., and Kim H., 2025, The impact of smart aquaculture environmental characteristics and system quality on acceptance intentions through value recognition of the fisheries industry in the era of AI, International Journal of Innovative Research and Scientific Studies, 8(2): 5463.
https://doi.org/10.53894/ijirss.v8i2.5463

Kharabsheh R., and Bdour A., 2025, Predictive modeling coupled with wireless sensor networks for sustainable marine ecosystem management using real-time remote monitoring of water quality, Open Engineering, 15: 0129.
https://doi.org/10.1515/eng-2025-0129

Khiem N., Van Thanh T., Dung N., and Takahashi Y., 2025, A novel approach combining YOLO and DeepSORT for detecting and counting live fish in natural environments through video, PLOS One, 20: 0323547.
https://doi.org/10.1371/journal.pone.0323547

Li L., Jiang S., and Lin Y., 2025, The impact of the digital economy on sustainable fisheries: Insights from green total factor productivity in China's coastal regions, Sustainability, 17(6): 2673.
https://doi.org/10.3390/su17062673

Lina L., and Butt M., 2025, Analysing Pakistan's fisheries legislation and institutional framework: Integrating sustainable development goal 14 within the scope of international fisheries law, Frontiers in Marine Science, 10: 1503748.
https://doi.org/10.3389/fmars.2025.1503748

Lv H., 2025, Underwater vision technologies for smart fisheries: A comprehensive review of OpenCV-based optimization and edge computing applications, Applied and Computational Engineering, 10: 22709.
https://doi.org/10.54254/2755-2721/2025.22709

Masmitja I., Palomeras N., Toma D., Bahamón N., Carandell M., Del Arco J., Chatzievangelou D., Real M., Sánchez-Márquez A., Batet G., Vial P., Bonin-Font F., Muntaner C., Hurtós N., Lopez J., Ripoll A., De Arcas G., Grinyó J., Gomáriz S., Katija K., Aguzzi J., Carreras M., Del-Río J., Navarro J., and Company J., 2025, Interconnected robotic platforms inform deep-sea ecological restoration trends, Marine Pollution Bulletin, 219: 118314.
https://doi.org/10.1016/j.marpolbul.2025.118314

Montana J., 2025, Co-producing fisheries governance with new data technologies: Satellite tracking turtles and fishing vessels for co-management and marine protection, Environment and Planning E: Nature and Space, 8(5): 1212.
https://doi.org/10.1177/25148486251337250

Nandhini P., M H., S H., G G., and K H., 2025, OceanLink: A blockchain-integrated IoT framework for enhancing fishermen safety and livelihood resilience, 2025 Third International Conference on Augmented Intelligence and Sustainable Systems (ICAISS), 1610-1618.
https://doi.org/10.1109/icaiss61471.2025.11042220

Radi D., Lamantia F., and Bischi G., 2025, Benefits and perils of integrated data systems in managing sustainable fishing quotas, Environmental and Resource Economics, 88: 2845-2883.
https://doi.org/10.1007/s10640-025-00979-x

Sharma P., 2025, Fishing forecast guardian: A machine learning-powered platform for illegal fishing detection, International Journal for Research in Applied Science and Engineering Technology, 10: 71936.
https://doi.org/10.22214/ijraset.2025.71936

Suherman A., Hernuryadin Y., Suadela P., Furkon U., and Amboro T., 2025, Transformation of Indonesian capture fisheries governance: Review and prospects, Marine Policy, 10: 106619.
https://doi.org/10.1016/j.marpol.2025.106619

Wang Q., Xu L., and Wu J., 2025, Marine intelligent technology as a strategic tool for sustainable development: A five-year systematic analysis, Journal of Marine Science and Engineering, 13(5): 855.
https://doi.org/10.3390/jmse13050855

Research Article Open Access

The Future of Aquaculture: Sustainable Development, Economic Growth, and Environmental Protection

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Abstract Aquaculture is one of the fastest-growing food production sectors globally, playing a vital role in food security, employment, and economic development. This review synthesizes literature spanning from 1988 to 2024, with a primary focus on contemporary advancements and policy shifts within the last decade, to evaluate the balance between seafood demand and ecosystem integrity. While it supports millions of livelihoods, ensuring sustainability remains a challenge. The study identifies that traditional intensive systems have caused groundwater salinization, mangrove loss, and chemical residue accumulation. Modern aquaculture utilizes diverse species-seaweeds, mollusks, and finfish to promote resource optimization. With the decline in capture fisheries, many nations have shifted toward inland and integrated farming systems. Sustainable development now emphasizes ecosystem-based management, including wetland conservation, effective effluent treatment, and biodiversity protection. Strengthening biosecurity, disease surveillance, and reduced antibiotic use are essential for meeting global hygiene standards. In tropical regions, integrated models like rice-fish culture are evolving into advanced systems such as Integrated Multi-Trophic Aquaculture (IMTA), Recirculating Aquaculture Systems (RAS), and Biofloc Technology (BFT). These innovations aim to minimize footprints while improving resource efficiency and biological balance. Overall, promoting environmentally responsible and socially inclusive aquaculture is crucial for conserving marine ecosystems and safeguarding the future of global seafood security.

Keywords Sustainable aquaculture; Integrated farming; IMTA and livestock farming; Organic aquaculture

1 Introduction

Aquaculture plays a vital role in ensuring global food security and enhancing the livelihoods of small-scale and marginal fish farmers. Currently, the oceans cover approximately 70% of the Earth's surface, hosting biological communities ranging from microscopic prokaryotes to the mammoth blue whale. These marine ecosystems provide essential services and food products; however, they are increasingly threatened by ocean acidification, rising sea surface temperatures, marine litter, and coastal pollution. Furthermore, these ecosystems remain relatively under-explored, offering significant potential for the discovery of novel bioactive molecules and secondary metabolites.

The fisheries sector is multifaceted, encompassing capture, commercial, artisanal, and recreational fishing, alongside freshwater and marine aquaculture. Notably, aquaculture has overtaken capture fisheries as the primary source of seafood for human consumption, serving as a vital alternative to mitigate food security challenges and prevent the depletion of wild fish stocks (White and Lopez, 2017). Global production has escalated from 19 million tons in 1950 to 122 million tons in 2020 (FAO, 2022a). Sustainable management is essential to strengthen the resilience of coastal ecosystems and achieve the United Nations Sustainable Development Goal (SDG-14), which emphasizes the conservation and equitable use of oceanic resources by 2030.

Developing sustainable "incubator systems" in maritime nations can foster environmentally conscious businesses and ensure equitable economic growth (OECD/World Bank, 2016). However, the scientific community recognizes that the intensive use of land and water, chemical eco toxicity, and the introduction of non-native species are major drivers of biodiversity loss (Peay et al., 2019). Historical intensification of shrimp farming, for instance, has been linked to soil salinization, reduced agricultural yields, and the degradation of mangrove wetlands.

Ensuring environmental protection at an acceptable level is mandatory given the rising global food demand. Transitioning toward resource-efficient and technologically advanced systems-such as Recirculating Aquaculture Systems (RAS), Integrated Multi-Trophic Aquaculture (IMTA), and well-managed offshore cage farming-can address the challenges associated with conventional methods (Brugere and Ridler, 2004). Ultimately, the effective protection of the marine environment supports the creation of high-value products, including new pharmaceuticals, renewable energy, and sustainable protein sources.

2 Methods Adopted

This review was conducted using a systematic literature search strategy to ensure rigor, transparency, and relevance. Scientific databases including Scopus, Web of Science, PubMed, Science Direct, and Google Scholar were searched to collect peer-reviewed literature related to sustainable aquaculture practices in India and globally. The time window for literature selection covered publications from 1988 to 2024, with greater emphasis on studies published after 2010 to ensure contemporary relevance.

The primary keywords used for the search included: sustainable aquaculture, biosecurity in aquaculture, integrated multi-trophic aquaculture, recirculatory aquaculture systems, shrimp farming sustainability, climate change and aquaculture, inland fisheries management, and biodiversity conservation in aquaculture. Boolean operators (AND, OR) were applied to refine search combinations and improve specificity.

Inclusion criteria comprised peer-reviewed journal articles, review papers, official reports (e.g., FAO and national fisheries agencies), and research studies directly addressing sustainability, ecological management, disease control, productivity enhancement, and environmental impacts in freshwater, brackishwater, and marine aquaculture systems. Exclusion criteria involved non-scientific opinion articles, duplicated studies, papers lacking methodological clarity, and publications not directly related to aquaculture sustainability.

The selected studies were screened initially based on title and abstract relevance, followed by full-text evaluation for methodological robustness and data reliability. Extracted data were categorized into thematic areas including ecological aspects, natural resource management, biodiversity conservation, biosecurity, climate resilience, and socio-economic sustainability. A qualitative descriptive synthesis approach was adopted to compare findings, identify common trends, highlight gaps, and draw integrative conclusions regarding sustainable aquaculture development. This structured methodology ensures that the review is comprehensive, evidence-based, and aligned with contemporary academic standards for systematic review articles.

3 Sustainable Aquaculture Production

3.1 Overview of sustainable aquaculture

Sustainable aquaculture systems are engineered to maximize socio-economic benefits while mitigating adverse environmental impacts. Despite economic fluctuations, aquaculture remains a cornerstone of rural livelihoods and food security, particularly in Indian states like Andhra Pradesh. In regions such as West Godavari, the sector has transitioned into high-density farming zones. However, the intensification of commercial practices-including integrated rice-fish farming-faces challenges regarding long-term ecological resilience. Transitioning toward moderate stocking densities and optimized feed application is essential to satisfy international market demands while maintaining ecosystem health (Betala and Betala, 2025).

3.2 Traditional aquaculture systems and their challenges

In Southeast Asia, traditional systems like rice-cum-fish and carp polyculture are being refined through Environmental Impact Assessments (EIA) to eliminate the misuse of aqua chemicals and promote natural resource conservation. Sustainability in these systems is achieved by managing biomass and waste through strategic site selection and the determination of carrying capacity (Wurts, 2000). Comprehensive hazard assessments are vital to prevent disease transmission and ensure food safety for human consumption.

3.3 Environmental challenges in aquaculture

A significant environmental challenge is the discharge of aquaculture effluents, which contain dissolved nutrients like nitrogen that contribute to eutrophication, particularly in cage culture systems. High-density culture environments can stress aquatic species, increasing susceptibility to disease and leading to a reliance on antibiotics, which further deteriorates water quality (Noor et al., 2019). Furthermore, the transition from traditional rotational cropping to intensify shrimp culture has occasionally resulted in poor water quality and reduced growth rates. A critical ecological risk is the escape of farmed fish, as interbreeding with wild populations can lead to high mortality rates and reduced genetic fitness in offspring.

3.4 Freshwater aquaculture in India

Freshwater aquaculture development in India continues to expand, though it faces constraints related to input availability and environmental management (Jayasankar, 2018). Cage aquaculture has been introduced as a viable method for ecosystem-based management, showing success with species such as cyprinids, perches, and catfishes (Radhakrishnan et al., 2010). When managed correctly, these systems leverage natural productivity (phytoplankton and zooplankton) to provide economic opportunities for rural communities. Currently, India is the second-largest fish producer globally, contributing approximately 8% of total production. The country continues to leverage its vast inland resources-including rivers, reservoirs, and tanks through strategic development programs aimed at enhancing sustainable productivity (Table 1, Table 2).

Table 1 Marine resources and statistics

Parameter	Value	Unit	Source
Total Coastline Length	8,118	km	Government of India / FAO (2022-2024)
Exclusive Economic Zone (EEZ)	2.02	million km^2	FAO (2022-2024)
Continental Shelf Area	0.42	million km^2	FAO (2022-2024)
Fish Landing Centers	1,376	Number	National Marine Fisheries Census (2005)
Fishing Villages	3,322	Number	National Marine Fisheries Census (2005)
Fishermen Families	764,868	Number	National Marine Fisheries Census (2005)
Total Fisher folk Population	3,574,704	Number	National Marine Fisheries Census (2005)

Table 2 Inland resources

Parameter	Value	Unit
Rivers and Canals	195,210	km
Reservoirs	3.15	million hectares
Tanks and Ponds	2.414	million hectares
Flood Plains / Derelict Water Bodies	0.8-1.2	million hectares
Brackishwater Area	1.24	million hectares
Saline / Alkaline Affected Area	1.20	million hectares

3.5 Brackish water aquaculture in India

India has contributed remarkable aquaculture producer, contributing significantly to both domestic and international markets. The country leverages vast inland resources like ponds and tanks, along with brackish/saline areas, for a variety of fish like carps, catfish, and tilapia, and has expanded into saline water aquaculture using inland saline groundwater. This is exemplified by the commercial farming of the Pacific white leg shrimp (*Litopenaeus vannamei*) in states like Haryana, Punjab, Rajasthan, and Uttar Pradesh. India is the second-largest producer of aquaculture in the world. The emphasis on brackishwater aquaculture invited large number of private companies and multi-nationals in intensive aquaculture resulted detrimental impact and serious environmental and health issues among the coastal community due to large conversion of thousands of hectares of coastal lands for intensive shrimp farming. The mangroves were cleared, wetlands were encroached and drained, and aquaculture tanks were built into freshwater lakes. Apart from saltwater intrusion into freshwater bodies, including aquifers, and aquaculture practices led to the release of contaminants into water sources.

3.6 Intensification vs sustainability in aquaculture

In India, over 1.4 billion people are significantly affected by environmental issues arising from agricultural intensification, which impacts both terrestrial and aquatic ecosystems. Inland aquatic resources have declined over recent decades due to landscape destruction, water pollution, and the over-exploitation of fish stocks, leading to a marked depletion in biodiversity. Intensive aquaculture contributes to this lack of sustainability through nutrient enrichment, soil leaching, and groundwater salinization. A critical concern is the widespread use of antibacterial medicines; the discharge of antibiotics into the environment-often via wastewater-facilitates the development of selective drug resistance in bacteria. Exposure to sub-lethal levels of these compounds allows bacteria to evolve resistance, making future infections increasingly difficult to treat with standard clinical medicines (Pillay, 1994).

Marine pollution, driven by eutrophication and the sedimentation of organic matter, acts as a significant pollutant source, causing harmful environmental impacts as large amounts of nutrients sink to the benthos (Dawood and Koshio, 2020). Intensification results in habitat destruction and compromised water quality due to the accumulation of metabolic waste and uneaten feed, which ultimately stresses the cultured organisms. The environmental footprint varies across systems; extensive systems have minimal impact, whereas intensive operations generate substantial waste depending on stocking density, feed inputs, and waste treatment efficiency (Maulu et al., 2021). Common detrimental practices include the release of dissolved nutrients, feces, and carcasses into water bodies containing aquaculture cages. Consequently, pathogens such as *Aeromonas salmonicida*, *Vibrio* sp., and motile aeromonads have developed significant resistance. Furthermore, fish larvae and fingerlings are highly vulnerable to pesticides and heavy metal pollution, which primarily damage the gill, kidney, and liver tissues (De Kinkelin and Michel, 1992).

Globally, sustainable aquaculture has become a revitalizing economic force for rural communities. To achieve long-term viability, there is an increasing emphasis on eco-labeling and the adoption of ecosystem-based approaches (FAO 2009a, b; Davenport et al., 2018). While some chemicals used in aquaculture, such as certain parasiticides, break down quickly, others like organotin and antibiotics-including oxytetracycline and flumequine-can significantly alter bacterial ecology and sedimentation processes (Shah et al., 2018). The residual effects of hormones used for induced spawning and growth stimulation also pose potential health hazards to humans. Ecologically, the most severe impacts include the loss of biodiversity and the destruction of mangroves, which serve as vital breeding grounds. Globally, shrimp pond construction has led to the loss of approximately 3.7 million acres of mangroves; in some Asian nations, this accounts for 27% to 50% of total mangrove area (Pillay, 1994). In contrast, the removal of mangroves for shrimp farming is less common in India, where strategies focus on integrated and responsible farming practices to address sustainability (Ninawe, 1999).

4 Risks/ Hazards in Aquaculture

4.1 Issues and concerns

Aquaculture plays a critical role in global food production, and its sustainable development is a key focus for international bodies like the United Nations (UN) and the Food and Agriculture Organization (FAO). The concept of sustainability, as defined by the World Commission on Environment and Development (WCED), emphasizes meeting current needs without compromising the ability of future generations to meet their own. This necessitates adopting practices that ensure long-term productivity, minimize environmental impacts-such as waste and pollution-and contribute to economic growth across related sectors like agriculture and forestry. Historically, the FAO has recognized that responsible management is essential for securing future food supplies and maintaining healthy ecosystems. FAO declarations provide the foundation for policies aimed at ensuring the long-term viability of aquatic food systems by minimizing waste and pollution in adherence with the broader sectors of agriculture, fisheries, and forestry (FAO, 1988).

Risk analysis in aquaculture involves identifying potential hazards with the capacity to cause economic loss or introduce harmful pathogens into the aquatic environment, which impacts genetic diversity, ecological integrity, and food safety. These hazards can have a broad impact on the environment and human health, often leading to significant, long-lasting damage. Natural disasters-such as tsunamis, floods, and wildfires-can destroy habitats and alter ecosystem functions. Additionally, industrial accidents, oil spills, or chemical leaks introduce toxins into the air, water, and soil, while prolonged droughts deplete water resources, impacting both agriculture and natural water bodies (Hader et al., 2020; Cramer et al., 2018; Harun et al., 2021). Specific aquaculture uncertainties include harmful algal blooms (HABs), which produce toxins that affect aquatic organisms and pose significant public health risks through the food chain. Silt buildup, poor water quality, and fish escapes are also recognized as major challenges (Bondad-Reantaso et al., 2018; Luna et al., 2020). These risks involve genetic issues, climate change, habitat structural changes, and occupational hazards (Yang et al., 2020).

In closed aquaculture technologies, water quality is maintained with minimal exchange with natural waterways, reducing pollution, negative wildlife interactions, and the transfer of parasites or diseases. Improving aquaculture performance is essential to provide safe, nutritious food while minimizing the environmental footprint. This ecologically friendly approach increases production efficiency relative to the land, water, feed, and energy used (Richard Waite, 2014). India promotes carp polyculture as a sustainable production method based on ecological principles that maximize resource utilization. By stocking compatible species-including surface feeders, column feeders, bottom feeders, and plankton feeders-all available ecological niches within the pond are utilized efficiently. This ecological basis for sustainability is further enhanced by waste recycling and resource management through modern engineering approaches (Jana et al., 2000; Jana, 2003). Conversely, the destruction of mangrove swamps-which are ecologically sensitive nurseries-directly impacts coastal estuaries, fish migration, coral reefs, and seagrass beds, ultimately affecting marine biodiversity and the livelihoods of coastal communities.

4.2 Climate change and fisheries

Climate change significantly impacts aquaculture production through fluctuations in water temperature, sea-level rise, and increased disease prevalence. Implementing robust mitigation techniques and adaptation strategies is essential to address extreme climate variance, overcome severe disruptions, and adapt to evolving ecosystem dynamics for sustainable development (Shukla et al., 2019; Galapaththi et al., 2020). Developing climate resilience strategies-such as the adoption of Biofloc Technology (BFT) and Recirculating Aquaculture Systems (RAS) assists farmers and stakeholders in withstanding adverse environmental shifts. Furthermore, Integrated Multi-Trophic Aquaculture (IMTA), cage culture, monosex tilapia farming, and the cultivation of air-breathing fishes serve as critical components of climate-smart aquaculture. These management strategies resist environmental changes by combining mitigation and adaptation to protect threatened marine ecosystems and fisheries.

According to the United Nations Conference on Trade and Development (UNCTAD), global fishing fleets powered by fossil fuels, such as marine diesel, emit between 0.1% and 0.5% of global carbon emissions, totaling up to 159 million tons annually. Consequently, understanding the impact of climate change on fisheries management is vital for developing policies that emphasize practical water quality management. This includes regular monitoring of critical parameters such as pH, ammonia, and dissolved oxygen levels-and the implementation of efficient water circulation systems. Utilizing bio-filters to remove waste products and excess nutrients is essential for maintaining optimal water quality and reducing the overall environmental footprint of aquaculture operations in a changing climate.

4.3 Carrying capacity and production

Carrying capacity refers to the maximum population density of a species that a given environment can support indefinitely without causing irreversible damage to the ecosystem or the health of the cultured stock. This threshold ensures productivity can be sustained without deleterious effects on the surrounding aquatic environment (Chapman and Byron, 2018). Carrying capacity is evaluated throughout the site selection procedure, beginning with initial capability calculations and receiving particular emphasis during the establishment of aquaculture facilities. This process adheres to spatial and temporal dimensions by evaluating the complete range of available space before determining suitable locations (Weitzman and Filgueira, 2020).

Furthermore, carrying capacity encompasses a cultural dimension; it is a dynamic process dependent on evolving standards and innovative concepts designed to avoid ecological overreach. Emphasizing community satisfaction and economic benefits is essential, particularly through the implementation of eco-friendly technologies. Consequently, long-term sustainability is realized when community needs are met through sufficient economic rewards derived from green technologies that provide additional resource benefits (Van Senten, 2018; McQuatters et al., 2019)

4.4 Health and disease management

Vaccination and rigorous biosecurity protocols are fundamental pillars of modern aquaculture, essential for the prevention and mitigation of disease outbreaks. Enhanced health management practices, supported by rapid detection and timely response systems, minimize economic losses and curtail the excessive use of antibiotics, thereby addressing the global challenge of antimicrobial resistance (FAO, 2022b; WOAH, 2023). Intensive aquaculture, particularly shrimp farming, has historically faced environmental degradation and disease crises, necessitating regulatory interventions to ensure long-term viability. In India, the native tiger shrimp (*Penaeus monodon*) industry suffered catastrophic losses due to viral pathogens, notably the White Spot Syndrome Virus (WSSV). In response, the exotic whiteleg shrimp (*Litopenaeus vannamei*) was introduced following comprehensive risk assessments and officially permitted for commercial culture in 2009. This transition significantly bolstered productivity and biosecurity management while enhancing economic returns and addressing socio-economic concerns (FAO, 2022a; Government of India Fisheries Reports, 2023).

Sustainable shrimp aquaculture has increasingly expanded into inland saline environments, such as Haryana, where eco-friendly technologies and community-based models have demonstrated environmental compatibility and improved rural livelihoods (Raghunathan et al., 2024). Achieving ecological sustainability requires scientific site selection, biosecure hatchery designs, effective effluent management, and optimized feed formulations. Furthermore, climate change poses significant risks to both freshwater and coastal systems through thermal stress, extreme weather events, and salinity fluctuations, which exacerbate disease susceptibility (FAO, 2023; IPCC, 2022). Consequently, strengthening policy frameworks and implementing climate-resilient farming strategies are critical for maintaining environmental monitoring and ensuring global seafood security

5 Fishing Regulations in India

In India, fishing is regulated within territorial waters and the Exclusive Economic Zone (EEZ); specifically, the zone within 12 nautical miles of the coast falls under the 'State List' of the Constitution. Coastal states and Union Territories (UTs) manage these activities through the Marine Fishing Regulation Act (MFRA). Modern aquaculture supports these frameworks by implementing rigorous biosecurity and disease control systems, minimizing the use of antibiotics and pharmaceuticals, and ensuring microbial sanitation. These practices maintain global hygiene standards while optimizing transport, traceability, and profitability. Furthermore, established aquaculture zones promote farm well-being by defining clear responsibilities for aquaculturists, fostering community involvement, and ensuring worker safety with equitable compensation.

To address historical ecological drawbacks, the Government of India introduced the National Policy on Marine Fisheries (NPMF) to prioritize the long-term sustainability and conservation of marine fishery resources. Key conservation measures include sea ranching, the installation of artificial reefs, and the farming of mussels, clams, and seaweed, alongside integrated cage farming systems. These efforts are central to the 'Blue Economy Growth Initiative,' which focuses on the sustainable utilization of aquatic wealth to improve the livelihoods of fishermen and their families (NPMF, 2017). By aligning resource management with economic development, the initiative seeks to realize the full potential of marine resources while safeguarding biodiversity for future generations.

6 Coastal Zone Regulations and AAI

The Coastal Regulation Zone (CRZ) Notification of 1991, enacted under the Environment (Protection) Act of 1986, imposes strict prohibitions on the expansion of industrial operations within ecologically sensitive coastal zones. Legal interventions have directed Union and State governments to discontinue intensive prawn farming in fragile areas, instead prioritizing regulated hatcheries and the introduction of *L. vannamei* and Specific Pathogen Free (SPF) *Penaeus monodon* for sustainable production. Shrimp farming in India has experienced cycles of rapid growth followed by setbacks, notably the disease epidemics of the late 1990s. Transitioning from the native black tiger shrimp to the exotic Pacific white shrimp (*L. vannamei*) has since revitalized the sector, contributing significantly to seafood exports and coastal livelihoods. Manoj and Vasudevan (2009) emphasize that robust regulatory mechanisms are essential to address environmental challenges such as nutrient enrichment, salinization, and mangrove destruction. To provide a formal legal framework, the Coastal Aquaculture Authority (CAA) was established in 2005 to ensure that activities are conducted in an eco-friendly manner.

Mandatory CAA guidelines now require Effluent Treatment Systems (ETS) for farms exceeding 5 hectares within the CRZ and 10 hectares outside the CRZ to mitigate adverse ecological impacts on open waters. Historically, the influx of private and multinational companies in the 1990s transformed traditional practices into intensive systems, often at the expense of mangrove ecosystems. Mangroves are vital for coastal food security, providing breeding grounds for crabs, prawns, and finfish, while also protecting groundwater aquifers from saline intrusion and buffering against tsunamis and floods. Globally, the rapid expansion of aquaculture has raised sustainability concerns, as unlimited profit motives and poor pond management have led to litigation and social conflict. In countries like the Philippines, Indonesia, and Thailand, high rates of mangrove depletion are directly attributed to shrimp farming expansion.

India accounts for approximately 3.3% of global mangrove cover, with significant areas located in West Bengal, Gujarat, and the Andaman and Nicobar Islands. Historically, some of these wetlands were drained for aquaculture tanks, leading to salt-water intrusion and the release of contaminants into local aquifers. Globally, such environmental degradation negatively impacts genetic diversity, water quality, and the overall feasibility of culture systems (Nesar Ahmed and Marion Glaser, 2016). To ensure long-term sustainability, integrated models combining agriculture, aquaculture, and salt panning are being promoted to meet the diverse dietary and livelihood requirements of coastal communities (Salin and Ataguba, 2018). These integrated approaches aim to harmonize economic development with the preservation of critical coastal habitats.

7 Promotion of inland aquaculture

In freshwater systems, the sustainability of a species depends on its ability to breed in captivity, optimize nutrient output, and adapt to resource-efficient culture environments. Polyculture is generally preferred over monoculture to meet the rising demand for animal protein by maximizing productivity per unit area. As the world's fastest-growing food-producing sector with an annual growth rate of 8.0%, aquaculture in India relies heavily on bulk production of Indian Major Carps (IMC), namely *C. catla*, *L. rohita*, and *C. mrigala*. Additionally, exotic carps such as *H. molitrix*, *C. idella*, and *C. carpio* constitute the second most significant group of cultured fishes. This six-species combination is a cornerstone of modern polyculture in South Asia, achieving high yields by utilizing all ecological niches: the surface (*C. catla* and *H. molitrix*), column (*L. rohita* and *C. idella*), and bottom (*C. mrigala* and *C. carpio*).

Major carps (IMCs) account for approximately 80% of total production in these systems, while exotic species like silver, grass, and common carp contribute significantly to maximizing spatial and nutritional efficiency (Laxmi Prasad et al., 2020). The adoption of such advanced polyculture systems-including sewage-fed aquaculture-enhances food security, builds resilience against extreme weather, and supports the livelihoods of rural farmers (Ghosh, 2020; Bhattacharya, 2021). Despite this potential, challenges such as low technology adoption, disease prevalence, and the high cost of quality feed must be addressed through scaled-up dissemination and capacity building (Lakra and Gopalakrishnan, 2021). Furthermore, biotechnological advancements, including the use of synthetic hormones for breeding, monosex culture, polyploidy, and transgenesis, are revolutionizing the industry. These modern approaches improve nutrition, health management, and gene banking, ultimately bolstering the global aquaculture sector (Lakra and Ayyappan, 2003).

8 Human Resource Development

Currently, India requires technically skilled fisheries professionals to navigate future industry challenges. Enhanced education is vital for improving fish productivity and generating employment across academic institutions, industrial research facilities, and state government departments (Kamleshbhai et al., 2024). Despite ongoing efforts to strengthen manpower, a significant shortage remains in this rapidly growing sector, which ultimately constrains overall growth. Fisheries education fosters innovation and creates employment by transferring specialized knowledge to farmers and stakeholders. Because the sector is highly skill-based, professional training is essential for equipping the workforce for roles in resource management and industrial operations. While comprehensive data are limited, an increasing number of universities now offer advanced M.Sc. and Ph.D. programs in aquaculture and marine sciences to address these needs.

In many higher education programs, modern communication technologies are being effectively utilized to disseminate technological expertise. Graduates with hands-on field experience are better prepared to manage commercial farms and address the technical challenges facing the aquaculture industry. Extension programs further support sector growth by transferring best practices to practitioners, while specialized training-such as scuba diving for resource assessment-addresses critical human resource gaps in deep-sea fishing and governmental departments. Furthermore, the Central Institute of Fisheries Education (CIFE), through its HRD initiatives, has trained a significant number of extension workers who promote sustainable practices nationwide. These trained professionals find diverse employment in research, academia, and administration, where their expertise helps build robust cold chains and marketing networks to reduce spoilage and waste.

9 Sustainable Ecofriendly Aqua Farming Technologies

The integrated fish farming (IFF) is an optional solution refers to the production and integrated management of comprehensive use of aquaculture, agriculture and livestock giving emphasis on a sustainable farming system. It is efficiency better in resources utilization in enhanced income and higher food fish production. IFF is simple, cost-effective technology to ensure employment, food and nutritional security for marginal and small hill farmers suitable to use resources sustainably to achieve the productivity as economic viable systems. It enhances the net return, generates employment, conserves natural resources, reduces the cost of production and increases the income by minimizing risk enable farmers producing diverse food by conserving resources well. IFF practices are highly eco-friendly and ensures higher returns as well as suitable for sustained production of fish and other components (Deepa Bisht, and Harshit Pant Jungran, 2023). The practice of carp polyculture introduced in China and India, as a traditional aquaculture production technique and in many Asian nations with integration of conventional management practices of animal husbandry. The farming supports aquaculture as ecologically healthy ecosystem with culture of native carp species, freshwater prawns with appropriate stocking of different fishes having different feeding habits. The wastage generated from agriculture also utilizes as fertilizer or feed in fish culture. Thus fishery sector plays a vital role in the socio- economic development of the state and is recognized to stimulate the growth of several subsidiary industries and is a cheap nutritious food besides being a foreign exchange earner.

10 Integrated Multi Trophic Aquaculture (IMTA)

Integrated Multi-Trophic Aquaculture (IMTA) is a sustainable and innovative approach that cultivates multiple species from different trophic levels within the same aquatic system. By utilizing the waste products of one species as nutritional inputs for another, IMTA creates a closed-loop system that reduces environmental impact and maximizes resource efficiency. In a typical IMTA configuration, three distinct groups are cultured: primary high-value finfish (e.g., salmon or trout), secondary filter-feeders or detritivores (e.g., shellfish or sea cucumbers), and tertiary extractive species (e.g., seaweeds or algae). The primary species produces waste in the form of uneaten feed and fecal matter, which microorganisms convert into dissolved nutrients. These are then sequestered by the secondary and tertiary species, transforming potential pollutants into valuable biomass while significantly improving water quality.

IMTA offers significant advantages, including enhanced biodiversity and improved economic resilience through crop diversification. By recycling nutrients and reducing reliance on external inputs, this model aligns with "Blue Transformation" programs, integrating seaweed and bivalve farming with finfish cages (FAO, 2022b). Globally, aquaculture has grown at an average annual rate of 5.3% from 2001 to 2018, with IMTA gaining recognition for its role in enhancing food security (Barange et al., 2014). Despite its promise, the approach requires optimized system design to manage disease risks and ensure species compatibility. As seafood demand rises, IMTA provides a framework for climate-resilient practices by utilizing climate-tolerant native species and promoting water conservation (Goh et al., 2023).

Effective waste management in IMTA mitigates the negative impacts of intensification-such as soil and water degradation, fish stress, and reduced profitability (Asgard et al., 1998). By operating across different trophic levels, these systems function as complementary ecosystems where by-products are converted into fertilizer and energy for other crops (Jana et al., 2000). Utilizing acclimatized native species further ensures efficient bio-mitigation and sustained biomass growth. Ultimately, diversifying the production system keeps water quality parameters within balanced levels, achieving long-term sustainability in global food security (Kibria and Haque, 2018).

11 Biofloc Technology

Biofloc Technology (BFT) in aquaculture and the animal food industry represents a shift toward increasing biomass by maintaining a higher carbon-to-nitrogen (C:N) ratio. This ratio is essential to stimulate the establishment of a microbial community, primarily consisting of heterotrophic bacteria, which aggregate into significant clusters or "flocs" (Emerenciano et al., 2013). This technology has gained global popularity in countries such as South Korea, Brazil, China, Italy, Indonesia, Australia, and India. The microbial community plays a crucial role in managing water quality and providing a sustained supply of supplemental nutrition for the cultivated species. Recent investigations in rapidly urbanizing areas have further interpreted the relationship between efficient resource utilization in BFT and the reduction of carbon emissions (Yao et al., 2023). BFT systems are most effective with species such as tilapia and prawns that can directly consume the floc, leading to significantly increased production output while minimizing negative environmental impacts.

In the late 1980s and 1990s, research in Israel and the USA specifically at the Waddell Mariculture Centre-initiated studies on biofloc technology across multiple species, including *Penaeus monodon*, *Fenneropenaeus merguiensis*, *Litopenaeus vannamei*, and *L. stylirostris*. Their primary focus remained on tilapia and *L. vannamei* prawns. Commercial implementation of BFT first occurred at a farm in Tahiti (French Polynesia) in 1988, demonstrating beneficial features ranging from water quality control to in situ feed production. Currently, carp, catfish, tilapia, and shrimp are the species most commonly cultivated in biofloc systems (Alam and Khan, 2024; Raza et al., 2024). Further refinements in these systems were implemented following subsequent studies (Crab et al., 2012). For instance, the performance of freshwater prawns (*M. rosenbergii*) in low-density biofloc systems showed optimal growth and survival rates when managing stocking densities to maximize productivity.

Research in Bangladesh regarding the giant freshwater prawn, *M. rosenbergii*, demonstrated that biofloc helps reduce dietary protein requirements from 42% to 35% without compromising yield, allowing farmers to adopt more sustainable and cost-effective farming practices (Alam and Khan, 2024). Additionally, a 165-day study at Mindanao State University in the Philippines evaluated the effects of BFT on the water quality and growth performance of *M. rosenbergii*. The postlarvae of *M. rosenbergii* thrived as water parameters remained within the optimum range; interestingly, the technology did not significantly influence the dissolved oxygen, temperature, or pH values of the water and sediment samples (Camarin et al., 2023). These findings highlight the robustness of biofloc technology in maintaining stable aquatic environments for freshwater prawns while improving overall biological efficiency and resource management.

12 Recirculatory Aquaculture System

In recirculatory aquaculture system (RAS) water is recycled and reused after removal of suspended matter and metabolites and is used for high- density culture of various species of fish, utilizing minimum land area and water. It is suitable intensive high density fish culture unlike other aquaculture production systems instead of the traditional method of growing fish outdoors in open ponds and raceways in a controlled environment. Recirculating systems filter and clean the water by recycling it back to fish culture tanks. The technology is based on the use of mechanical and biological filters is used for species grown in aquaculture (Jham et al., 2024). The reconditioned water circulates through the system and less than 10% of the total water volume of the system is replaced daily in recirculation system. The management of recirculating systems relies heavily on the quantity and quality of feed and f filtration system used to remove metabolic wastes, excess nutrients, and solids from the water and provide good water quality. It encourages farmers and entrepreneurs and to facilitate fish production in urban and semi-urban areas where land and water resources are limited. In backyard Recirculation Aquaculture Systems is promoted RAS minimizes the risk of disease and promotes a healthier and more resilient aquaculture system keeping environmental conditions stable with increased production yields. The challenges reflects a significant challenge in agriculture, where high initial investment acts as a major barrier to economic viability and accessibility for small-scale farmers (Sedyaaw et al., 2025). RAS systems have been successfully implemented to produce various fish species, including Atlantic salmon, Arctic charr, rainbow trout, yellowtail king fish, the European seabass, and gilthead seabream (Supra Subhadarsani, 2024). H_2S-poisoning as a health hazard. RAS system can lead to both fish and other culture species. The RAS can assess adverse weather, unfavorable temperature conditions, external pollution and predation that can help achieve aquaculture production from limited waterbody (Shruti Gupta et al., 2024).

13 Introduction of Livestock and Organic Aquaculture

Here is the corrected portion of your manuscript. I have addressed the reviewer's comments by refining the academic language, improving the technical flow, and ensuring the distinction between integrated and organic systems is clear, while maintaining your original references, species names, and paragraph length. Livestock-fish farming is an integrated system that combines fish cultivation with livestock and poultry, allowing wastes from one component to serve as inputs for another. This synergistic approach is widely practiced across Indian states, including Tamil Nadu, Assam, Bihar, Andhra Pradesh, Tripura, Orissa, Karnataka, Kerala, and Uttar Pradesh. Currently, India supports approximately 17% of the global livestock population on only 2% of the world's geographical area, creating immense pressure on land resources and necessitating the integration of crops and livestock. This integration is mutually beneficial; animal manure serves as a potent natural fertilizer that enhances aquatic productivity while maintaining soil fertility. The diversity of species produced in these systems includes finfish, shellfish, mollusks, and aquatic plants.

While some species and production systems are difficult to adapt to strictly traditional "organic" frameworks, integrated farming shares a close relationship with organic aquaculture principles. This synergy is highly popular in Europe, where certified organic salmon, carp, and trout are cultivated and marketed. Similarly, mussels, tiger shrimp, white shrimp, and tilapia are cultured in diverse regions such as Vietnam, Peru, Ecuador, Chile, New Zealand, and Israel. These certified organic products have gained universal acceptance by addressing consumer health concerns (Dube and Chanu, 2012). Integrated crop-livestock-fish farming systems promote agricultural growth and environmental equilibrium by optimizing resource utilization and improving ecosystem services (Regar et al., 2022).

Poultry-fish farming is increasingly accepted and popular among farmers within integrated models. This practice involves raising birds such as chicken, ducks, and geese simultaneously with fish. The system significantly benefits aquaculture by utilizing poultry waste as a direct or indirect nutrient source, which reduces the dependency and cost associated with conventional fish meals. Consequently, this resource efficiency enhances the profit margins for small-scale and commercial producers (Gabriel et al., 2007). By recycling on-farm nutrients, these integrated models represent a sustainable pathway toward increasing food production while maintaining the ecological integrity of the farming environment.

14 Strategy for Higher Growth Rate

The development of coldwater fishery resources holds immense potential for generating rural income and providing food security to economically underprivileged populations in Indian upland regions. This is achieved through targeted aquaculture practices, ornamental fisheries, and sport fishery-based ecotourism. India has projected a sustained annual growth rate in its inland sector, characterized by an impressive Compound Annual Growth Rate (CAGR) of 8.58% from 2013-14 to 2023-24. While this growth aligns with national projections, the freshwater aquaculture sector faces specific constraints that require urgent attention for both horizontal and vertical expansion. The Himalayan region is blessed with an abundance of rivers, streams, and lakes across Jammu and Kashmir, Himachal Pradesh, Uttarakhand, West Bengal, Sikkim, Arunachal Pradesh, Nagaland, and Meghalaya. Similarly, the Western Ghats in Kerala, Tamil Nadu, Karnataka, and Maharashtra offer enormous resources for coldwater farming.

The lower temperature regimes in these regions support the farming of selected fast-growing species, including rainbow trout (*Oncorhynchus mykiss*), and exotic carps such as grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*), and common carp (*Cyprinus carpio*), alongside various exotic ornamental and minor carps. However, climate change, biodiversity loss, and over-exploitation remain significant challenges. ICAR-DCFR is actively promoting sustainable and responsible practices to improve infrastructure and reduce production waste (Sarma and Chandra, 2020). In the North Eastern region, particularly in Assam, Manipur, and Tripura, the exploitation of high-value indigenous fishes has gained priority due to high local consumption. Over 95% of the population in these states is involved in fish consumption, and meeting this demand requires intensive farming supported by appropriate technological interventions and infrastructure (Barman, 2012). While rural and tribal communities currently utilize small to medium-sized ponds, there remains tremendous scope for introducing fast-growing species tailored to the North East (Das, 2018).

Ornamental fish, abundantly distributed across freshwater, brackish, and inshore marine ecosystems, are gaining significant attention due to rising global and local demand. India possesses a high potential for the culture and export of ornamental varieties, many of which are easily accessible from wild resources for aquarium rearing. This sector fosters entrepreneurship, offering opportunities for individuals and women’s groups through small-scale backyard units or larger enterprises. By advancing breeding and farming techniques, there is a clear opportunity to boost production and increase foreign exchange (Raja et al., 2014). Government departments are now emphasizing modern fishing practices, the expansion of aquaculture, and effective technology transfer. Well-managed aquatic food systems, integrated with efficient value chains, are essential for ensuring food security and improving livelihoods (Sarkar et al., 2020; Prado-Carpio et al., 2021). Furthermore, adherence to certifications regarding food safety and animal welfare ensures that consumers receive healthier, safer products, thereby boosting the overall credibility of the industry (Amundsen and Osmundsen, 2020).

15 R & D Support Towards Blue Economy

To achieve a sustainable economy, India leverages various sectors-including fisheries, tourism, shipping, offshore energy, and biotechnology-as primary drivers for growth, livelihood improvement, and job creation for coastal and inland communities. India's ocean economy is expanding at an annual rate of 15%, with projections to exceed USD 120 billion by 2025. The nation is committed to socioeconomic prosperity by transforming the fisheries sector, promoting food security, and ensuring the judicious utilization of resources on a sustainable basis. Furthermore, India’s Integrated Coastal Zone Management (ICZM) program facilitates the sustainable management of coastal resources by balancing economic objectives with social and environmental considerations.

Central to these efforts is the Pradhan Mantri Matsya Sampada Yojana (PMMSY), which promotes fisheries development through infrastructure enhancement, robust marketing, and social security for fishers. Complementing this, the Integrated National Fisheries Action Plan (NFAP) is instrumental in achieving the goals of the Blue Revolution by addressing critical sustainability issues in aquaculture and ensuring long-term livelihood security. These strategic frameworks align modern production techniques with conservation goals, fostering a resilient aquatic economy that supports millions. By integrating technological innovation with policy reform, India continues to strengthen its position as a global leader in sustainable aquaculture and marine resource management.

16 Summary

Aquaculture faces significant environmental challenges, particularly regarding nutrient pollution and disease outbreaks. Consequently, understanding the causal relationships between production intensity, species diversification, and environmental impact is essential for developing effective strategies that support long-term sustainability and resilience. Current expansions in aquaculture and allied activities are strategically planned to address complex socio-economic and environmental constraints. India, in particular, emphasizes the balanced utilization of oceanic, coastal, and freshwater resources while prioritizing the preservation of ecosystem biodiversity. Sustainable technologies are being adapted to diverse agro-climatic conditions, integrating advanced diagnostics, aquatic pollution monitoring, and specialized therapeutics alongside the adoption of best management practices (BMPs).

The focus has shifted toward achieving sustainability by prioritizing the cultivation of native species within both open-water and improved closed-culture systems. A precautionary approach is applied to the use of genetically modified organisms, feed additives, and organochemicals, ensuring they undergo rigorous validation before implementation. To mitigate the risk of disease transmission, stocking densities are optimized to prevent physiological stress. Furthermore, coastal zones are protected through strict regulations on effluent discharge, ensuring that intensive operations do not compromise the surrounding environment or human health. The integration of innovative, eco-friendly technologies-such as Integrated Multi-Trophic Aquaculture (IMTA), Recirculating Aquaculture Systems (RAS), and Biofloc Technology (BFT)-represents a transformative approach to organic and integrated farming, significantly enhancing both productivity and ecological integrity.

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References

Alam M.A., and Khan M.A., 2024, Evaluation of the yield performance of freshwater prawns (*Macrobrachium rosenbergii*) cultured in a biofloc system at various densities, Journal of Aquatic Research and Sustainability, 1(1): 15-22.

Amundsen V.S., and Osmundsen T.C., 2020, Becoming certified, becoming sustainable? Improvements from aquaculture certification schemes as experienced by those certified, Marine Policy, 119: 104097.

Asgard T., Hillestad M., Austreng E., and Holmefjord I., 1998, Can Intensive Aquaculture Be Eco-Friendly? Akvaforsk and Biomar, Aas, Norway.

Barange M., Merino G., Blanchard J.L., Scholtens J., Harle J., Allison E.H., et al., 2014, Impacts of climate change on marine ecosystem production in fisheries-dependent societies, Nature Climate Change, 4(4): 211-216.

Barman D., Kumar V., and Mandal S.C., 2012, Epizootic ulcerative syndrome (EUS): A great concern in modern aquaculture, World Aquaculture, 63-65.

Betala A.B., and Betala A., 2025, Sustainable Aquaculture in India: Environmental and Economic Assessment in West Godavari, Andhra Pradesh, American Journal of Business Science Philosophy (AJBSP), 2(2): 285-297.

Bondad-Reantaso M.G., Garrido-Gamarro E., and McGladdery S.E., 2018, Climate Change-Driven Hazards on Food Safety and Aquatic Animal Health, in Impacts of Climate Change on Fisheries and Aquaculture, FAO, Rome, p. 517.

Brugere C., and Ridler N., 2004, Global Aquaculture Outlook in the Next Decades: An Analysis of National Aquaculture Production Forecasts to 2030, FAO Fisheries Circular No. 1001, FAO, Rome.

Camarin M.A., Gonzaga A., Jamis J., and Calpe A., 2023, Effects of biofloc technology on water quality and growth performance of Macrobrachium rosenbergii, Israeli Journal of Aquaculture - Bamidgeh, 75(2).

Chapman E.J., and Byron C.J., 2018, The flexible application of carrying capacity in ecology, Global Ecology and Conservation, 13: e00365.

Crab R., Defoirdt T., Bossier P., and Verstraete W., 2012, Biofloc technology in aquaculture: Beneficial effects and future challenges, Aquaculture, 356-357: 351-356.

Cramer W., Guiot J., Fader M., Garrabou J., Gattuso J.P., Iglesias A., and Xoplaki E., 2018, Climate change and interconnected risks to sustainable development in the Mediterranean, Nature Climate Change, 8: 972-980.

Das S.K., 2018, Mid hill aquaculture: Strategies for enhancing production in Northeast hill region of India, Journal of Coldwater Fisheries, 1(1): 42-47.

Davenport M., Delport M., Blignaut J.N., Hichert T., and van der Burgh G., 2018, Combining theory and wisdom in pragmatic, scenario-based decision support for sustainable development, Journal of Environmental Planning and Management, 62(4): 692-716.

Dawood M.A., and Koshio S., 2020, Application of fermentation strategy in aqua feed for sustainable aquaculture, Reviews in Aquaculture, 12(2): 987-1002.

De Kinkelin P., and Michel C., 1992, The use of drugs in aquaculture, Infofish International, 11(4): 45.

Deepa Bisht and Harshit Pant Jugran, 2023, Integrated Fish Farming: A simple, cost-effective technology to ensure employment, food and nutritional security for marginal and small hill farmers, International Journal of Scientific Development and Research, 8(12): 845-855.

Dube K., and Thongam I.C., 2012, Organic aquaculture way to sustainable production, in U.C. Goswami (Ed.), Advances in Fish Research, Narendra Publishing House, p. 219-229.

Emerenciano M., Gaxiola G., and Cuzon G., 2013, Biofloc Technology (BFT): A Review for Aquaculture Application and Animal Food Industry, in M.D. Matovic (Ed.), Biomass Now - Cultivation and Utilization, p. 462.

FAO, 1988, Aspects of FAO's Policies, Programmes, Budget and Activities Aimed at Contributing to Sustainable Development, Document to the 94th session of FAO Council, FAO, Rome.

FAO, 2009a, Guidelines for the ecolabelling of fish and fishery products from marine and capture fisheries (Revision 1), Rome.

FAO, 2009b, Fisheries management. 2. The ecosystem approach to fisheries. 2.2 Human dimensions of the ecosystem approach to fisheries, FAO Technical Guidelines for Responsible Fisheries No.4, Suppl., Rome.

FAO, 2022a, The State of World Fisheries and Aquaculture 2022, Rome.

FAO, 2022b, The State of World Fisheries and Aquaculture 2022: Towards Blue Transformation, Rome.

FAO, 2023, The State of World Fisheries and Aquaculture 2023: Towards Blue Transformation, Rome.

Gabriel U., Akinrotimi O., Bekibele D., Anyanwu P., and Onunkwo D., 2007, Economic benefit and ecological efficiency of integrated fish farming in Nigeria, Scientific Research and Essays, 2(8): 302-308.

Galappaththi E.K., Ichien S.T., Hyman A.A., Aubrac C.J., and Ford J.D., 2020, Climate change adaptation in aquaculture, Reviews in Aquaculture, 12(4): 2160-2176.

Ghosh S., 2020, Accumulation of Heavy Metals in Sewage Fed Aquaculture of India: A Review, Environment and Ecology, 38(1): 56-61.

Goh P.S., Lau W.J., Ismail A.F., Samawat Z., Liang Y.Y., and Kanakaraju D., 2023, Microalgae-Enabled Wastewater Treatment: A Sustainable Strategy for Bioremediation of Pesticides, Water, 15(1): 70.

Government of India, Department of Fisheries, 2023, Annual Fisheries Statistics and Production Report.

Hader D.P., Banaszak A.T., Villafañe V.E., Narvarte M.A., González R.A., and Helbling E.W., 2020, Anthropogenic pollution of aquatic ecosystems: Emerging problems with global implications, Science of The Total Environment, 713: 136586.

Harun S.N., Hanafiah M.M., and Aziz N.I.H.A., 2021, An LCA-based environmental performance of rice production for developing a sustainable agri-food system in Malaysia, Environmental Management, 67: 146-161.

IPCC, 2022, Climate Change 2022: Impacts, Adaptation and Vulnerability, Cambridge University Press.

Jana B.B., and Jana S., 2003, The Potential and Sustainability of Aquaculture in India, Journal of Applied Aquaculture, 13(3-4): 283-316.

Jana B.B., Banerjee R.D., Guterstam B., and Heeb J., 2000, The ecological basis of carp polyculture towards sustainable fish farming, in Waste Recycling and Resource Management in the Developing World: Ecological Engineering Approach, p. 169.

Jayasankar P., 2018, Present status of freshwater aquaculture in India - A review, Indian Journal of Fisheries, 65(4): 157-165.

Jham Lal, Vaishnav A., Deb S., Kashyap S., Debbarma Devati P., Gautam P., Pavankalyan M., Kumari K., and Verma D.K., 2024, Re-Circulatory Aquaculture Systems: A Pathway to Sustainable Fish Farming, Archives of Current Research International, 24(5): 799-810.

Kamleshbhai B.P., Riya Tandel, and H.V. Parmar, 2024, Fisheries Education and its new branch, in Frontiers in Animal Science: Research and Development, Vol. I, p. 30-39.

Kibria A.S.M., and Haque M.M., 2018, Potentials of integrated multi-trophic aquaculture (IMTA) in freshwater ponds in Bangladesh, Aquaculture Reports, 11: 8-16.

Lakra W.S., and Ayyappan S., 2003, Recent advances in biotechnology applications to aquaculture, Asian-Australasian Journal of Animal Sciences, 16(3): 455-462.

Lakra W.S., and Gopalakrishnan A., 2021, Blue revolution in India: Status and future perspectives, Indian Journal of Fisheries, 68(1): 137-150.

Laxmi Prasad, Kumar R., Singh S., Kumar D., Maurya A., Pal J., Verma S.K., and Kumar S., 2020, Adoption of carps based polyculture system and status of fish productivity in eastern Uttar Pradesh, India, Journal of Entomology and Zoology Studies, 8(3): 157-161.

Luna M., Llorente I., and Cobo A., 2020, Aquaculture production optimisation in multi-cage farms subject to commercial and operational constraints, Biosystems Engineering, 196: 29-45.

Manoj V.R., and Vasudevan N., 2009, Functional options for sustainable shrimp aquaculture in India, Reviews in Fisheries Science, 17(3): 336-347.

Maulu S., Hasimuna O.J., Haambiya L.H., Monde C., Musuka C.G., Makorwa T.H., and Nsekanabo J.D., 2021, Climate change effects on aquaculture production: Sustainability implications, mitigation, and adaptations, Frontiers in Sustainable Food Systems, 5: 609097.

McQuatters G.A., Mitchell I., Vina-Herbon C., Bedford J., Addison P.F., Lynam C.P., and Otto S.A., 2019, From science to evidence-how biodiversity indicators can be used for effective marine conservation policy and management, Frontiers in Marine Science, 6: 109.

Ministry of Fisheries, Animal Husbandry & Dairying, 2017, National Policy on Marine Fisheries (NPMF), Government of India.

Nesar Ahmed and Marion Glaser, 2016, Coastal Aquaculture, Mangrove Deforestation and Blue Carbon Emissions: Is REDD+ a Solution?, Marine Policy, 66: 58-66.

Ninawe A.S., 1999, Coastal aquaculture versus environment: Pros and cons, Infofish International, 18(2): 43-47.

Noor N.M., and Das S.K., 2019, Effects of elevated carbon dioxide on marine ecosystem and associated fishes, Thalassas: An International Journal of Marine Sciences, 35: 421-429.

OECD/The World Bank, 2016, Climate and Disaster Resilience Financing in Small Island Developing States, OECD Publishing.

Peay S., Johnsen S.I., Bean C.W., Dunn A.M., Sandodden R., and Edsman L., 2019, Biocide treatment of invasive signal crayfish: Successes, failures and lessons learned, Diversity, 11: 29.

Pillay T.V.R., 1994, Aquaculture Development: Progress and Prospects, Fishing News Books, Blackwell Publications Ltd.

Planning Commission, 2011, Report of the Working Group on Development and Management of Fisheries and Aquaculture for the XII Five Year Plan: 2012-17, Government of India.

Pradhan Mantri Matsya Sampada Yojana, 2020, Guidelines and Framework, Department of Fisheries, Government of India.

Prado-Carpio E., Olivo-Garrido M.L., Quiñonez-Cabeza M., Beitl C.M., Martínez-Soto M., and PradoRodríguez-Monroy C., 2021, Performance and Challenges in the Value Chain of the Anadara tuberculosa Bivalve Mollusk in Ecuador, Sustainability, 13(5): 2951.

Radhakrishnan K., Samraj Aanand P., Padmavathy, and Biswas I., 2010, Current status of freshwater cage aquaculture in India: Towards blue revolution, Aquaculture, 23(1): 1-9.

Raghunathan C., Singh R., and Kumar P., 2024, Sustainable shrimp aquaculture in inland saline waters: community outcomes and eco-technology adoption, Journal of Sustainable Aquaculture, 12(1): 45-58.

Raja S., Babub T.D., Nammalwar P., Jacob C.T., and Dinesh K.P.B., 2014, Potential of ornamental fish culture and marketing for future prospects of India, International Journal of Biosciences and Nano Sciences, 1(5): 119-125.

Raza B., Zheng Z., and Yang W., 2024, A Review on Biofloc System Technology, History, Types, and Future Economical Perceptions in Aquaculture, Animals, 14(10): 1489.

Regar J.K., Misra A.K., Rana J.S., Ponnusamy K., and Dixit A.K., 2022, Dairy based integrated farming system model for income enhancement of small farmers, The Pharma Innovation Journal, 11(2): 782-786.

Richard Waite, Beveridge M., Brummet R., and Castine S., 2014, Improving Productivity and Environmental Performance of Aquaculture, Technical Report, World Resources Institute.

Salin K.R., and Ataguba G.A., 2018, Aquaculture and the Environment: Towards Sustainability, in Sustainable Aquaculture, p. 1-62.

Sarkar U.K., Mishal P., Borah S., Karnatak G., Chandra G., Kumari S., and Das B.K., 2020, Status, Potential, Prospects, and Issues of Floodplain Wetland Fisheries in India: Synthesis and Review for Sustainable Management, Reviews in Fisheries Science & Aquaculture, 29(1): 1-32.

Sarma D., and Chandra S., 2020, Coldwater fish farming in Indian Himalayan region: Challenges and opportunities, Indian Farming, 70(11): 49-53.

Sedyaaw P., Wasave S., and Pandey A., 2025, Recirculatory Aquaculture System (RAS) and its Challenges to Fish Farmers, in Aquaculture Technological Advancements, p. 197-217.

Shah M.R., Lutzu G.A., Alam A., Sarker P., Kabir Chowdhury M.A., Parsaeimehr A., and Daroch M., 2018, Microalgae in aquafeeds for a sustainable aquaculture industry, Journal of Applied Phycology, 30: 197-213.

Shruti Shukla, P. R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H. O., Roberts, D. C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., and Malley, J. (Eds.). (2019). Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. IPCC.

Shukla P.R.,Shukla, P. R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H. O., Roberts, D. C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick K., Belkacemi M., and Malley J., eds., 2019, Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

Supra Subhadarsani, Padhi J., and Behuria M.R.L., 2024, Exploring India's Blue Economy: Opportunities and Challenges for a Sustainable and Resilient Future, Bio. Res. Today, 6(2): 63-66.

Van Senten J., Engle C.R., Hartman K., Johnson K.K., and Gustafson L.L., 2018, Is there an economic incentive for farmer participation in a uniform health standard for aquaculture farms? An empirical case study, Preventive Veterinary Medicine, 156: 58-67.

Weitzman J., and Filgueira R., 2020, The evolution and application of carrying capacity in aquaculture: Towards a research agenda, Reviews in Aquaculture, 12: 1297-1322.

White P., and Lopez N., 2017, Mariculture Parks in the Philippines, in Aquaculture Zoning, Site Selection and Area Management under the Ecosystem Approach to Aquaculture: A Handbook, FAO and World Bank.

World Organization for Animal Health (WOAH), 2023, Aquatic Animal Health Code, WOAH.

Wurts W.A., 2000, Sustainable aquaculture in the twenty-first century, Reviews in Fisheries Science, 8(2): 141-150.

Yang X., Utne I.B., and Holmen I.M., 2020, Methodology for hazard identification in aquaculture operations (MHIAO), Safety Science, 121: 430-450.

Yao Y., Shen Y., and Liu K., 2023, Investigation of resource utilization in urbanization development: An analysis based on the current situation of carbon emissions in China, Resources Policy, 82(1): 103442.

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Review Article Open Access

Management and Mitigation Strategies for Harmful Algal Blooms: Current Approaches and Future Prospects

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Abstract This study explores the management and mitigation strategies for harmful algal blooms (HABs), with a focus on analyzing their formation mechanisms, monitoring and early warning technologies, the effectiveness and limitations of various control methods, and the practical application of integrated management measures. It also discusses the current challenges in governance and future development directions. The occurrence of harmful algal blooms is the result of multiple interacting factors, including excessive nutrient inputs, climate change, altered hydrological conditions, and ecosystem imbalance, posing serious threats to aquatic ecosystems, human health, and socioeconomic development. Current response measures primarily fall into three categories: proactive source prevention, direct in-water intervention, and impact mitigation based on monitoring and early warning, encompassing various physical, chemical, and biological methods. Advanced technologies such as satellite remote sensing, unmanned aerial vehicles, and artificial intelligence models have become important tools for monitoring and early warning. In terms of integrated management, watershed-scale nutrient control, ecological restoration measures such as constructed wetlands and ecological floating islands, combined with best management practices (BMPs), have shown promising results. Typical regional cases further validate the importance of cross-sectoral collaboration and comprehensive policies. However, current governance still faces challenges such as high costs, limited technology application, unstable long-term control effects, and increased difficulty due to climate change. Research indicates that a single governance method is insufficient to achieve long-term effective control of harmful algal blooms, highlighting the need for more integrated, adaptive, and ecosystem-based management strategies in the future.
Keywords Harmful algal blooms; Management strategies; Formation mechanism; Monitoring and early warning Comprehensive Management

1 Introduction

Harmful algal blooms (HABs) refer to the phenomenon where tiny algae and cyanobacteria rapidly and massively multiply within a short period of time. These types of algae produce toxins, consume oxygen in the water, and form large amounts of algae bodies, thereby damaging the water environment. Such phenomena not only occur in freshwater areas such as lakes and rivers, but are also common in estuaries and oceans. It has now become a key issue in global water quality and ecological environment (Anabtawi et al., 2024; Brenckman et al., 2025;). Originally, this phenomenon was very rare, but in recent years, with the increase in nutrients such as nitrogen and phosphorus in the water, combined with the effects of climate warming, hydrological changes, and human activities, harmful algal blooms have become more frequent, longer-lasting, and have a wider impact (Chang, 2025). Global studies have shown that since the end of the last century, the frequency and impact of harmful algal blooms have significantly increased, especially in coastal and inland lakes in Asia, Africa, Europe, and North America (Feng et al., 2024).

The greater the quantity of harmful algal blooms, the greater the impact on the ecology, resources, and human health. From an ecological perspective, a large number of algae will block sunlight, affecting the growth of aquatic plants and altering the entire food chain. When the algae die and decompose, they consume a large amount of oxygen, causing water to become oxygen-deficient and leading to the mass death of fish and shrimp, making the living environment in the water worse and worse (Anabtawi et al., 2024; Liu et al., 2025). Many harmful algal blooms contain algae that produce highly toxic biological toxins (such as microcystin, saxitoxin, and short-brown algal toxin, etc.). These toxins accumulate continuously through the food chain, polluting drinking water and seafood, poisoning humans, livestock, pets, and wild animals, and some can cause rapid onset while others accumulate slowly to affect health (Brenckman et al., 2025; Chang, 2025). In terms of economy, harmful algal blooms affect fishing, aquaculture, tourism, and recreational activities, causing annual losses of hundreds of millions of dollars and posing difficulties for the development of "blue economy" in many areas. In terms of water resources, harmful algal blooms make daily water quality testing and risk assessment more difficult, and some lakes and reservoirs cannot be used as drinking water sources normally, increasing the cost of water purification and treatment in water plants (Igwaran et al., 2024).

To address this issue, various management approaches have been adopted, mainly divided into three categories. The first is proactive prevention, such as reducing the inflow of nutrients into water bodies, managing water resources properly, and utilizing land rationally; the second is direct control within the water body, using methods from physics, chemistry, and biology; the third is relying on monitoring and early warning to reduce the harm caused by the rampant growth of algae (Igwaran et al., 2024). Remote sensing, molecular detection, and various sensors are increasingly used in monitoring, and new biological management ideas are gradually being implemented. However, the large-scale promotion of these technologies still faces obstacles and is restricted by policies, management, and social factors; in addition, the impact of climate change makes it even more difficult to predict the governance effects (Lan et al., 2024; Liu et al., 2025; Zahir et al., 2024).

This study will focuses on the control issues of harmful algal blooms in freshwater and marine environments, analyzing the advantages, disadvantages and applicable scenarios of various governance methods. This article integrates the latest global research, sorts out various measures such as source control, water treatment, and hazard mitigation, as well as ongoing research technologies. At the same time, it focuses on the comprehensive governance approach that integrates multiple disciplines and technologies, discusses future development directions, and explores how to establish a more complete monitoring, analysis and policy system to reduce the environmental and social losses caused by algal blooms.

2 Formation Mechanisms of Harmful Algal Blooms

2.1 Excessive nutrients lead to rampant growth of algae

Human activities have led to an increasing accumulation of nutrients in water bodies, which is a significant factor contributing to the rapid proliferation of harmful algae. Especially when the levels of nitrogen and phosphorus are too high, algae will grow in large quantities in various water bodies such as freshwater and estuaries. Nutrients from agricultural fertilization, discharged domestic sewage, surface runoff formed by urban rainfall, and airborne sediment, all of which may cause the continuous accumulation of nutrient salts in water, providing sufficient growth conditions for algae and eliminating the limitation of insufficient nutrients. Such environmental conditions are more favorable for fast-growing algae, such as cyanobacteria and some diatoms (Figure 1) (Brenckman et al., 2025). In studies conducted in many regions around the world, it has been found that the more nutrients there are in water bodies, the more frequently and on a larger scale harmful algae outbreaks occur, and the more significant the impact is. After the large-scale proliferation of algae, it often leads to oxygen deficiency in water bodies, produces odors and releases toxins, thereby damaging water quality and affecting the entire ecosystem. Studies on lakes, rivers, estuaries, and coastal waters have also shown that when the nutrient salt levels in water bodies increase, the number of planktonic organisms usually increases significantly. This further indicates that excessive nutrients are an important cause of algae outbreaks, and therefore, from the perspective of controlling nutrient input, this issue can theoretically be managed and alleviated.

In addition to excessive nutrients, the types and proportions of nutrients, as well as when they enter the water, are also crucial for the outbreak of algae. Many harmful cyanobacteria and flagellate algae have special abilities, such as being able to fix nitrogen from the air, storing excess nutrients, or efficiently utilizing certain forms of nitrogen. These abilities allow them to survive even in cases of nitrogen and phosphorus imbalance and unstable nutrient supply, and sometimes their toxicity becomes stronger. Intermittent nutrient input brought by heavy rain or changes in water flow can cause an algal bloom to occur suddenly if the timing is right (Huang and Liang, 2025). Moreover, phosphorus and other substances released from sediments and dead algae, even if the external nutrient sources are controlled, can allow the algal bloom to persist. This shows that algal blooms caused by eutrophication of water bodies are the result of the combined effect of nutrients introduced from outside and those circulating within the water body. That is to say, to control them, both these types of nutrients need to be controlled, and the long-term nutrient balance between land and water also needs to be managed.

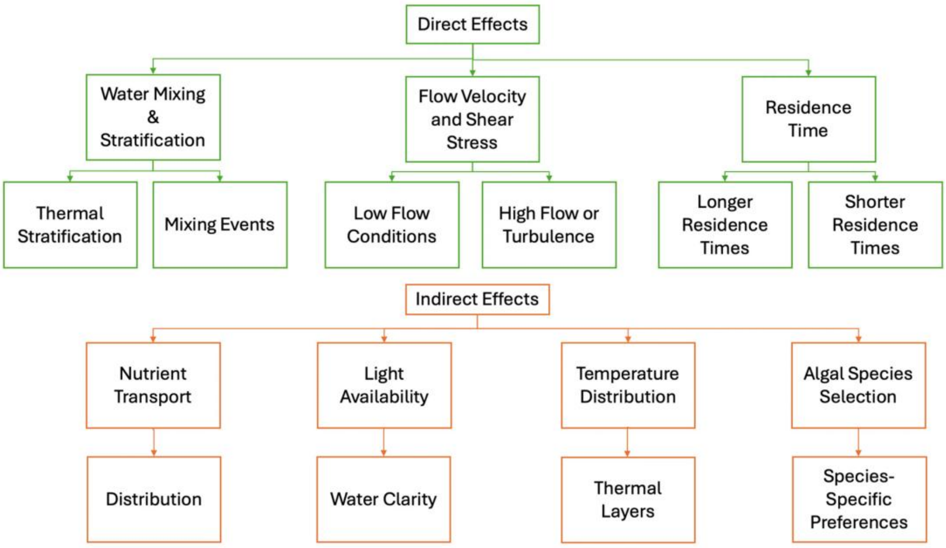

Figure 1 Flow diagram summarizing the mechanisms by which hydrodynamic conditions affect algal blooms in reservoirs, focusing on both direct and indirect effects (Adopted from Brenckman et al., 2025)

2.2 Climate change makes algal blooms more likely to occur

Climate change will cause the water temperature to rise, making the stratification of water layers more stable. At the same time, the flow conditions and the chemical environment of the water body will also change. These changes will provide more favorable conditions for harmful algae to grow, thereby increasing the possibility of algae outbreaks (Feng et al., 2024). When the water surface temperature rises, many cyanobacteria and some toxic marine plankton grow faster, having an easier advantage in competition, and their growth season will also be prolonged. Some species can even expand to regions that were previously colder and difficult to survive, such as higher latitudes or higher altitudes of water bodies. Long-term monitoring data and model studies have shown that in the case of continuous temperature rise and an increase in marine and freshwater heat waves, the range of algae outbreaks in lakes and coastal waters may expand, the duration will be longer, and the toxic risk may also increase (Lan et al., 2024; Wang et al., 2025a). In some bodies of water, the massive proliferation of algae sometimes creates a cycle: when the water surface is covered by a thick layer of algae, it actually absorbs more heat, causing the water temperature to rise even higher. As a result, the algae grow faster (Kuijpers et al., 2025).

Changes in rainfall volume, unstable water salinity, and an increase in extreme weather events all make it easier for algae to undergo large-scale outbreaks. For instance, during heavy rain or storms, more nutrients from the land are washed into lakes or estuaries; while in cases of prolonged drought or slow water flow, the water in lakes and reservoirs cannot flow freely and stays longer. Both of these situations make the already nutrient-rich water bodies more conducive to the rampant growth of algae (Feng et al., 2024; Brenckman et al., 2025). In coastal areas, the increase or decrease of incoming freshwater can affect the salinity of the sea water, and a change in salinity, in turn, can affect the growth of some harmful algae. According to some climate change research predictions, in those areas with relatively low salinity, these algae may grow even more vigorously (Shi et al., 2024). Additionally, ocean acidification, reduced oxygen levels in water, and continuous warming of water temperatures, these factors may also interact with each other to affect the growth of harmful algae, and even cause them to produce more toxins. However, the exact way these factors interact is not yet fully understood. Overall, climate change, the increasing amount of nutrients in water, combined with various human activities, have made the phenomenon of large-scale algae outbreaks increasingly common and severe in many places (Wang et al., 2025).

2.3 The flow conditions have changed, and so has the ecological structure

Fluid dynamic conditions, including water flow velocity, turbulence, water stratification and residence time, have a significant impact on the occurrence and development of red tides by influencing the physical environment for the survival of phytoplankton. Long water residence time and weak scouring effect can lead to continuous accumulation of algae, which is very common in nutrient-rich rivers, reservoirs and large lakes; while strong convection and mixing often dilute or destroy red tides. In artificially controlled rivers and reservoirs, sluices, dams and selective water intake can change water depth, water stratification and hydraulic residence time. Under nutrient-rich conditions, a slow water flow and stratified water body usually form, which is conducive to the dominance of cyanobacteria and increases the risk of red tides. On the contrary, management methods such as enhancing water mixing, increasing scouring or reducing water thermal stability can limit the development of red tides, which also indicates that fluid dynamics is crucial in the formation of red tides.

Changes in the ecological structure and food chains are also intertwined with these flow conditions and further affect whether algal blooms will occur. Changes in water body fertility, artificial alteration of water flow, and excessive fishing can all change the number and species of phytoplankton-eating zooplankton, weakening their ability to control algae. In many water bodies that are rich and stratified, these changes will cause algae to gradually shift from being dominated by diatoms to being dominated by cyanobacteria or flagellates. The latter have advantages in terms of taste, toxicity, or ability to adapt to weak water flow and long-term stillness (Brenckman et al., 2025). Once algal blooms occur, they will in turn change the ecological structure, making the water quality worse, the distribution of light and nutrients changing, and biodiversity decreasing. This, in turn, makes algal blooms more likely to occur again, forming a vicious cycle, and keeping harmful algae in the dominant position. Therefore, the formation of harmful algal blooms is the result of changes in the interaction between the physical environment and the ecosystem. Changes in flow conditions, combined with the reorganization of the biological community in the water body, jointly lead to water bodies becoming more prone to frequent and persistent algal blooms.

3 Monitoring and Early Warning of Harmful Algal Blooms

3.1 Traditional water quality and algal monitoring methods

Conventional HAB monitoring relies on in situ sampling combined with physical, chemical, and biological analyses to quantify algal biomass, species composition, and toxin levels. Routine programs typically measure temperature, nutrients, chlorophyll-a, and other water-quality parameters alongside microscopic identification of phytoplankton and cyanobacteria, often supported by spectrophotometry, chromatography, and biochemical or immunological toxin assays. These approaches remain the regulatory backbone because they provide species-level resolution and direct toxin measurements necessary for public-health decisions and seafood or drinking-water safety compliance. Standardized protocols, such as stepwise workflows integrating physical, chemical, and biological sampling with metabarcoding, improve data comparability across stations and over long time series, supporting robust risk assessment and model calibration (Saleem et al., 2023).

However, traditional monitoring is labor-intensive, costly, and limited in spatial and temporal coverage. Ground sampling and laboratory analyses require skilled personnel and specialized facilities, leading to low sampling frequency relative to the rapid dynamics of blooms (Saleem et al., 2023). These constraints can hinder timely detection of bloom onset or rapid intensification, particularly in large or remote water bodies (Byrd et al., 2025). To address these gaps, newer technologies such as biosensors, automated in situ instruments, and molecular tools (PCR/qPCR, metabarcoding) have been developed to shorten assay times, enable near-real-time detection of target taxa or toxins, and complement classical microscopy-based approaches (Zahir et al., 2024). The future of traditional monitoring lies in its integration with automated, molecular, and observational platforms within multi-scale observing systems.

3.2 Remote sensing and drone-based monitoring technologies

Satellite and airborne remote sensing have transformed HAB monitoring by providing synoptic, repeated observations of bloom extent and intensity over large spatial scales. Optical remote sensing, including multispectral, hyperspectral, and emerging high-performance sensors, retrieves proxies such as chlorophyll-a, phycocyanin, and water color, enabling the detection and mapping of surface blooms in both inland and coastal waters (Figure 2) (Zahir et al., 2024). Meta-analyses of hundreds of studies show rapid growth in remote-sensing-based HAB monitoring, while also highlighting needs for standardized methods, improved atmospheric correction (especially in turbid waters), and harmonized multi-sensor constellations to increase spatial–temporal resolution (Wang et al., 2025). Hyperspectral imaging in particular can discriminate algal groups with high classification accuracy and support robust early-warning applications when coupled with suitable algorithms (Arias et al., 2025; Wang and Qin, 2025).

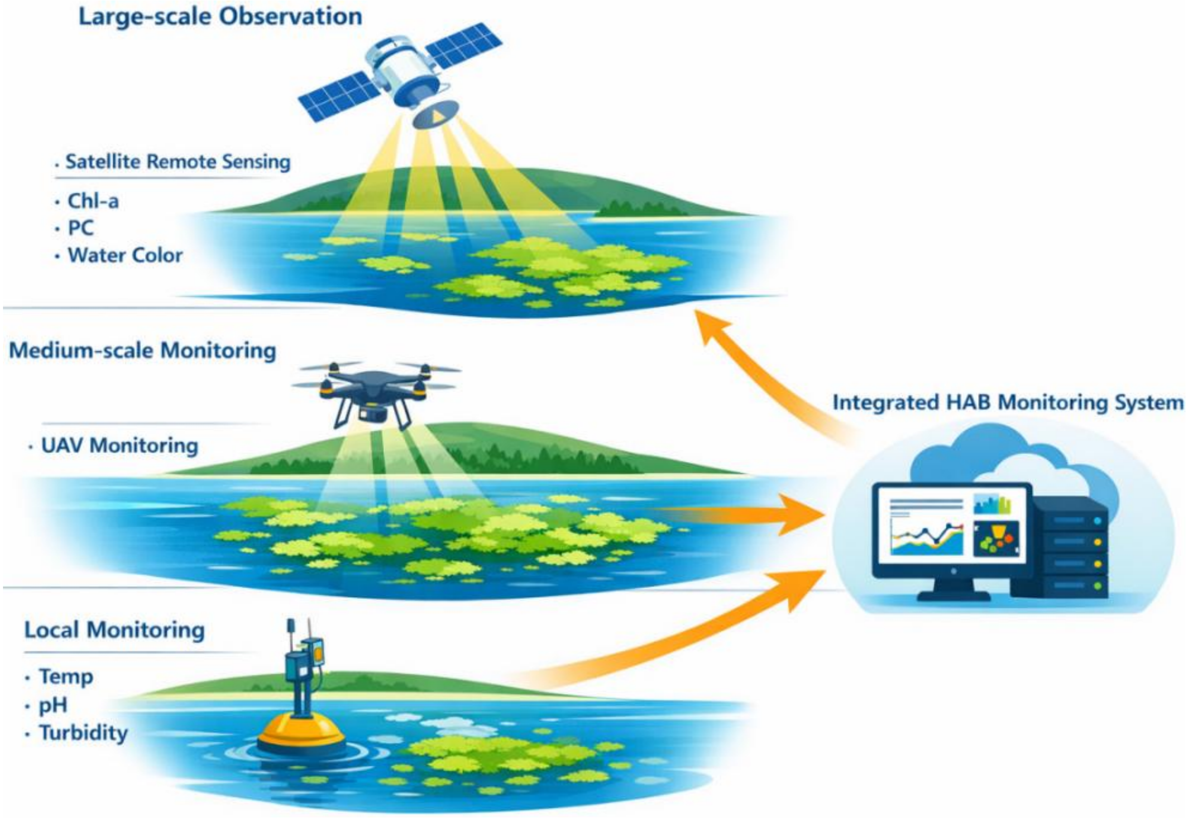

Figure 2 Conceptual framework for harmful algal bloom monitoring (Adopted from Zahir et al., 2024)

Unmanned aerial vehicles (UAVs) provide flexible, high-resolution coverage that bridges scales between in situ sampling and satellites. UAV platforms equipped with RGB, multispectral, hyperspectral, or thermal sensors can rapidly map fine-scale bloom patches, validate satellite products, and guide targeted sampling or public-health interventions (Arias et al., 2025; Wang and Qin, 2025). Recent systems integrate onboard water-quality sensors (e.g., temperature, pH, turbidity) and real-time communications (e.g., LoRaWAN) to deliver immediate data streams for operational decision-making (Hagh et al., 2024). Nonetheless, UAV-based monitoring faces challenges including regulatory constraints, the need for robust calibration and validation, and integration with risk frameworks and other observing platforms (Byrd et al., 2025). The emerging direction is coordinated, multi-platform observation networks that combine satellite, UAV, and in situ data for comprehensive HAB surveillance.

3.3 Prediction and early warning based on models and artificial intelligence

Forecasting and early-warning systems have evolved from empirical statistical models toward sophisticated process-based, data-driven, and hybrid approaches that exploit growing environmental and monitoring datasets.

Numerical and process-based models simulate physical-biogeochemical drivers such as stratification, nutrient dynamics, and algal growth to provide mechanistic insight and scenario testing, whereas data-driven models correlate historical environmental variables and remote-sensing products with bloom metrics for short-term prediction (Lan et al., 2024; Campbell and Vinebrooke, 2025). Ensemble frameworks that stack multiple model types (e.g., tree-based methods, neural networks, Bayesian regression) improve skill in predicting exceedance probabilities of algal densities and toxins, offering probabilistic risk forecasts for management programs (Szewczyk et al., 2025).

Machine-learning and deep-learning techniques, including random forests, gradient boosting (XGBoost, LightGBM), artificial neural networks, CNN-LSTM architectures, Transformers, and other hybrid models, now play a central role in HAB prediction (Szewczyk et al., 2025; Wang et al., 2025). These models effectively capture nonlinear relationships among meteorological, hydrodynamic, nutrient, and remote-sensing inputs, achieving high accuracy for short-term HAB detection and multi-day forecasts and demonstrating operational potential for early-warning systems in both coastal and freshwater systems (Park et al., 2024). Integration of explainable AI (e.g., SHAP values) helps identify key drivers and improve interpretability, while coupling ML with real-time monitoring (sensors, satellites, UAVs) is highlighted as critical for sustained performance and generalizability across diverse bloom scenarios (Zahir et al., 2024).

4 Control and Mitigation Methods for Harmful Algal Blooms

4.1 Physical methods: aeration, mixing, and mechanical removal

These physical methods do not add chemical substances to the water body. Instead, they work by altering the water environment or directly removing algae. For instance, by artificially stirring the water or supplementing oxygen at the bottom, the original stratification structure of the water body can be disrupted, reducing the accumulation of algae on the water surface, while increasing the dissolved oxygen in the water and reducing the possibility of nutrient release from the bottom sediment into the water. In this case, the growth conditions of algae will be restricted, and those algae that do not form algal blooms may have more space to grow. If the oxygenation technology is designed reasonably based on the morphological characteristics of the lake or reservoir and the pollution status, it can increase the oxygen content of the water body within a certain period and reduce the release of phosphorus from the bottom sediment, thereby reducing the number of algae to a certain extent (Brenckman et al., 2025). However, this method requires high costs in construction and operation, and the effects vary greatly in different water bodies. If external inputs of large amounts of nutrients continue, the governance effect is often weakened. Therefore, it is still difficult to promote this method in large lakes or sea areas (Lan et al., 2024).

These physical methods include using dredging tools, filtration equipment, or throw in substances that cause algae to sink to the bottom. These are commonly used in small ponds and aquaculture areas and can quickly reduce the excessive algae in the water (Lan et al., 2024). For example, when dealing with marine red tides, clay or modified clay is often used to cause the algae to aggregate and sink to the bottom. However, it is currently uncertain whether this method will harm underwater organisms (Anderson et al., 2025). There is also a method of thoroughly cleaning the bottom sediment, which can remove nutrient-rich sediment and dormant blue-green algae spores. However, this method is costly and environmentally damaging and cannot be frequently used. In general, physical methods are more suitable for emergency handling in areas with high economic value.

4.2 Chemical methods: using algaecides and oxidants

Chemical methods, especially the use of algicides and oxidants, remain common measures for dealing with excessive algal growth. The main reason is that these methods are more effective and can significantly reduce the algal population within a short period of time, as well as lower the toxins produced by the algae. Through a comprehensive analysis of multiple field test results, it was found that among various chemical agents, only a few, such as copper sulfate, hydrogen peroxide, peroxyl acetate, and carbendazim, can improve water quality by reducing the pigment content of the algae, decreasing the cell count, and removing microcystin toxins. Some oxidants, such as hydrogen peroxide and potassium persulfate, have a good inhibitory or killing effect on blue-green algae like Microcystis in a wide range of pH conditions. If used properly, they have a relatively small impact on the water's acidity and alkalinity, produce little dissolved organic carbon, and can decompose microcystin-LR and chlorophyll a. Moreover, these oxidants also have a strong killing effect on marine flagellates that are harmful to fish, making them a potential alternative to chlorine in ship ballast water treatment and coastal water management.

However, although chemical treatment can take effect quickly, it also brings some environmental and management issues. For instance, copper preparations and some synthetic herbicides may gradually accumulate in sediments or aquatic organisms, thereby posing long-term ecological risks. At the same time, when herbicides or oxidants cause a sudden death of a large number of algae, toxins and organic substances in the cells will rapidly be released into the water, which may increase toxicity in a short period and lead to oxygen deficiency in the water body. Some recent review studies have also pointed out that in practical applications, most chemical treatment measures are difficult to improve water quality in the long term, indicating that relying solely on chemical agents is insufficient to solve the problem of excessive nutrients at the watershed level (Table 1) (Lan et al., 2024). Some recently emerged nano-material oxidants and photocatalysts can improve treatment efficiency and selectivity, but they also raise new issues, such as the fate of nanoparticles in the environment and whether they will be toxic to the ecosystem. The current situation is unclear. Therefore, in practical management, chemical methods are more often used as emergency or short-term control measures. When using these agents, strict control of dosage, enhanced monitoring, and their integration into a prevention-oriented comprehensive management strategy are necessary.

Table 1 Innovative fertilizer technologies for reducing eutrophication (Adopted from Lan et al., 2024)

Fertilizer Technology	Nutrients Provided	Mechanism	Suitable Crops
Slow-Release Fertilizers (SRFs)	Nitrogen, Phosphorus, Potassium	Gradual nutrient release aligned with crop uptake	Cereals, horticultural crops, turfgrass
Controlled-Release Fertilizers (CRFs)	Nitrogen, Phosphorus, Potassium	Coating controls nutrient release over time	Vegetables, fruits, ornamental plants
Nitrification Inhibitors	Nitrogen	Inhibits nitrification, reducing nitrate leaching	Maize, wheat, rice
Urease Inhibitors	Nitrogen (Urea-based)	Prevents rapid urea conversion, reducing ammonia loss	Rice, cereals, pasture
Enhanced Efficiency Fertilizers (EEFs)	Nitrogen, Phosphorus	Combines slow and controlled release with inhibitors	Various crops including cereals, fruits, vegetables
Polymer-Coated Fertilizers	Nitrogen, Potassium	Encapsulated nutrients in a polymer for controlled release	High-value crops like fruits, vegetables, ornamentals
Biochar-Enhanced Fertilizers	Nitrogen, Phosphorus, Potassium, micronutrients	Uses biochar to retain nutrients and reduce leaching	Cereals, legumes, vegetables
Struvite Fertilizers	Phosphorus, Nitrogen, Magnesium	Mineral compound with slow nutrient release	Horticultural crops, cereals

4.3 Biological methods: using microorganisms, filter-feeding organisms and aquatic plants

Biological control methods involve using predator relationships, species competition, or microbial actions to inhibit the growth of harmful algae. This approach is generally considered more environmentally friendly and more in line with natural ecological laws. Microbial control mainly includes the use of bacteria, fungi, or actinomycetes that can kill algae, or the use of some microbial groups to cause the cell lysis of algae, inhibit their growth, or cause the aggregation, sedimentation, and gradual decomposition of algae cells, thus forming a process of "aggregation-lysis-degradation-nutrient regulation". Relevant research and reviews indicate that some strains with algicidal effects, such as certain streptomyces, vibrio, and the algicidal fungus known as D7, not only can reduce the number of algae in water bodies, but can also, to a certain extent, lower the nutrient salt levels in water, thereby simultaneously alleviating the problems of algal blooms and excessive nitrogen and phosphorus (Anabtawi et al., 2024; Pan et al., 2025). Most related studies are still at the stage of laboratory or medium-scale simulation tests, and there is not sufficient evidence to prove that they can improve the long-term water quality of natural bodies. These methods are unstable in natural environments and some microorganisms may even affect non-target organisms. Moreover, due to regulatory requirements and limitations on public acceptance, it is fundamentally difficult to directly introduce foreign microorganisms into natural water bodies (Abate et al., 2024).

Large aquatic plants, as well as filter-feeding organisms (such as mussels, shellfish, zooplankton and certain fish), and some allelochemicals secreted by plants, can also play a role in assisting in the control of algal blooms by altering the food chain, competing for nutrients and sunlight, and releasing inhibitory substances. Through management, by strengthening the population of filter-feeding organisms, the number of cyanobacteria can be reduced, and the algal community can shift towards a less harmful direction; in freshwater environments, restoring seagrass beds, algal fields and emergent plants can provide habitats for natural algal-killing bacteria, making the ecosystem more stable and preventing harmful algae from dominating. Based on plant management strategies, such as adding straw and reed to the water or using purified allelochemicals, they have shown inhibitory effects on algal growth in experimental conditions and small ponds. However, as these methods are used more frequently in practice, their effectiveness becomes less reliable, and they usually cannot be relied upon alone to control algae (Anabtawi et al., 2024). In summary, relying solely on these biological means often does not significantly improve water quality. In other words, biological control should be regarded as part of a long-term comprehensive management approach. At the same time, it is necessary to reduce nutrient input, restore the ecosystem, and carefully consider its benefits and potential problems (Abate et al., 2024).

5 Integrated Management and Practical Applications

5.1 Water pollution control and nutrient management

When dealing with harmful algal blooms, people are increasingly focusing on controlling the nutrient flow throughout the entire river basin. These nutrients come from various sources, such as farmlands, livestock farms, and centralized discharge sources like urban domestic sewage and rainwater (Feng et al., 2024). Global studies have found that nitrogen and phosphorus in rivers flowing into the ocean must be controlled simultaneously; controlling only one of them will still lead to excessive algal growth. The research suggests that nitrogen and phosphorus reduction targets should be set based on the actual conditions of each river basin, while also considering the impact of climate change on water volume, temperature, and extreme weather. This is the fundamental approach for long-term control of algal blooms.

The combination of catchment analysis models and ecological risk assessment tools has now been able to assist in designing and optimizing the best management methods (referred to as BMP). In the Taihu Lake Basin of China, a SWAT–Bayesian Network model shows that reducing fertilizer usage by 40% can maximize the reduction in the probability of harmful algal blooms in the model; at the same time, extensive planting of vegetation filter strips can also bring additional governance effects. Combining these two measures can significantly reduce the risk of harmful algal blooms, even maintaining stability under extreme climates (Liu et al., 2024; Lin et al., 2025). In the Malmaino sea area of Spain, a similar SWAT+-Lagoon modeling study found that the comprehensive application of BMP measures (reducing fertilizer use, planting vegetation filter strips, crop rotation, etc.), can reduce the number of days with harmful algal blooms by 81%, and the chlorophyll a content during the algal bloom period by 50%, with much better effects than single measures (Pacheco et al., 2025). Interviews with water management personnel in the United States also indicate that measures for nutrient management, especially BMP measures in the agricultural sector and urban fertilizer control measures, are the main methods for preventing harmful algal blooms. However, relevant personnel also admit that "under the influence of climate change, harmful algal blooms will not disappear in the short term" (Goodrich et al., 2024).

5.2 Ecological restoration: artificial wetlands and ecological floating islands

Combining ecological restoration projects with the best management methods for river basins can intercept nutrients and rebuild the local food web. Around eutrophic lakes (such as the wetlands along Lake Erie), restoring wetlands can enhance the natural ability to intercept nutrients, buffering the entry of phosphorus and nitrogen before they reach the open waters prone to cyanobacteria blooms. Research summaries on eutrophication and harmful algal blooms indicate that well-planned wetlands, riparian buffer zones, and reconnecting floodplains can reduce the episodic nutrient load brought by heavy rain, which is a key factor in triggering the "extreme situation" of cyanobacteria blooms (Figure 3) (Huang and Han, 2025).

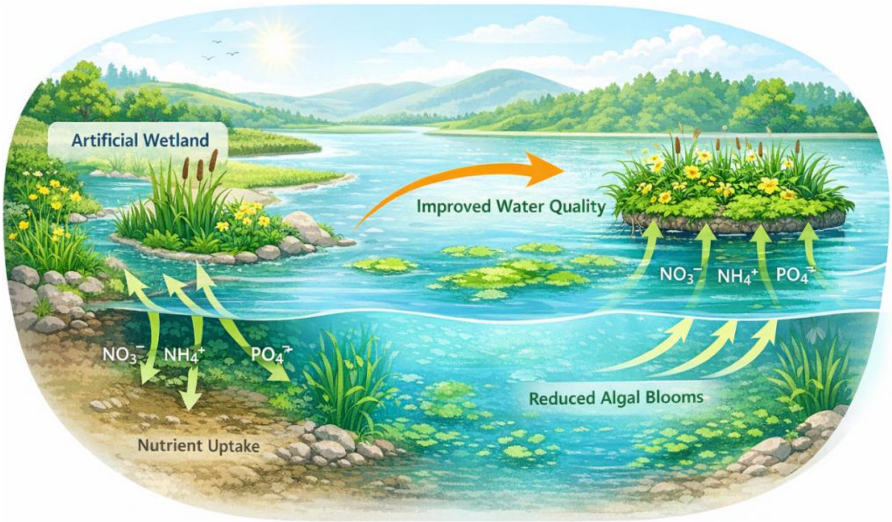

Figure 3 Schematic diagram of ecological restoration mechanism (Adopted from Huang and Han, 2025)

Artificial floating treatment wetlands and ecological floating islands are a type of biological treatment method that can be widely used. They are particularly suitable for application in lakes, especially in small water bodies in cities. In cities such as Baltimore, Boston and Chicago in the United States, the results of long-term pilot projects show that by harvesting the wetland plants grown on these floating islands, approximately 2 grams of phosphorus can be removed per square meter per year. At the same time, the ecological environment around these facilities has also changed, the number and species of large invertebrates, plankton, cyanobacteria and fish in the water have all changed. This indicates that the water quality and ecological environment have indeed improved (Nayak et al., 2025). Although the total amount of nutrients taken away by these floating islands from urban water bodies is not large, they can not only purify the water quality, but also provide habitats for aquatic animals, become an open ecological landscape for the public, and can be used as a test platform to help scientists determine how large the facilities should be built and how they should be designed. It can be said that it brings multiple benefits.

5.3 Typical management cases and regional experience

By comparing cases from different regions, it can be observed that the methods for dealing with algal blooms vary significantly in different areas, but some governance measures are applicable in multiple locations. Researchers analyzed 12 large and medium-sized eutrophic water bodies worldwide and found that most regions would formulate basin management plans based on local water quality standards and carry out governance through means such as regulation, economic measures, risk prevention, and public awareness campaigns. Even if these measures are implemented, algal blooms are difficult to be completely eradicated; they can only reduce the scale of the outbreak but cannot solve the problem at its root. For example, in North America and Europe, early measures relied on controlling nutrient levels to slow down algal blooms, but after the 1990s, due to climate warming and residual nutrients, toxic algal blooms reappeared. This indicates that merely reducing emissions is not sufficient; climate adaptation measures must also be combined (Qiu et al., 2024).

Various on-the-ground projects have also accumulated rich experience. The Domal acid incident caused by the pseudo-Nichols algae in the western United States in 2015 provided an important warning. Washington State, by establishing an early cross-departmental cooperation mechanism, had a higher acceptance rate among the public for fishing bans and risk information. After the Toledo drinking water crisis in Lake Erie in 2014, several international seminars reaffirmed the necessity of reducing emissions, restoring wetlands, and optimizing monitoring systems. The practices in coastal and inland areas have demonstrated that continuously advancing comprehensive projects such as long-term monitoring, model analysis, and watershed governance can more effectively reduce the risk of harmful algal blooms (Figure 4) (Feng et al., 2024).

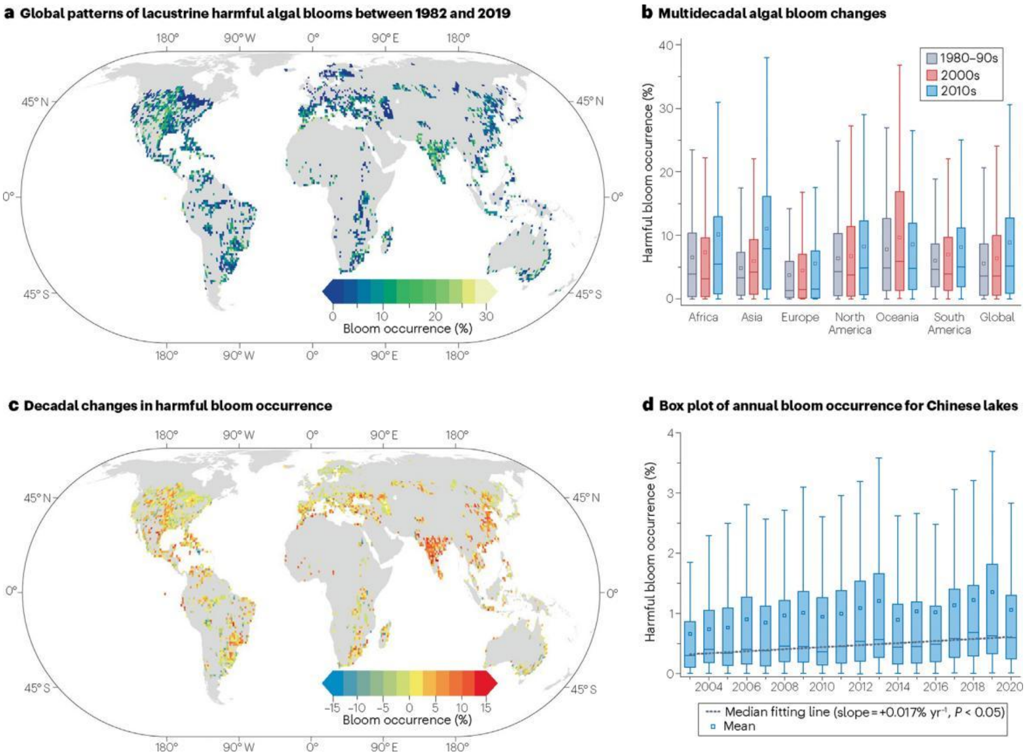

Figure 4 Global patterns and trends in harmful bloom occurrences in lakes (Adopted from Feng et al., 2024)

Image caption: a, Global occurrence patterns of harmful lacustrine algal blooms between 1982 and 2019 aggregated into 1° ×1° grid cells and expressed as a percentage of total observational bloom number over the time period. b, Box plots of harmful algal bloom (HAB) occurrence (%) separated by continent and time period; the bottom and top of the boxes are the first and third quartiles, respectively, the bar in the middle shows the median, and the whiskers show the minimum and maximum values. c, Change in harmful bloom occurrence from the 1980-90s to the 2010s expressed as the percentage change in annual bloom frequency in each location. d, Annual HAB occurrence for large, bloom-affected lakes in China, expressed as a percentage of the total number of bloom-containing pixels over the total number of cloud-free MODIS pixels within a year. The data in panels a – c were extracted from Landsat images1, and the data in panel d are from the Moderate-resolution Imaging Spectroradiometer (MODIS)20. Although most global studies show a general increase in HABs in recent decades, the trends vary by region and time period (Adopted from Feng et al., 2024)

6 Key Challenges in the Management of Harmful Algal Blooms

6.1 High management costs and technical limitations

For a long time, controlling the rampant growth of algae has been a challenging issue. It requires significant investment and often yields unsatisfactory results. Many treatment technologies have limited applicability and are difficult to be widely adopted in large lakes and oceans. For instance, physical methods such as manual water mixing and oxygen enhancement can reduce the amount of algae in certain scenarios, but they consume a lot of electricity and have cumbersome equipment, making them unsuitable for long-term use in large water bodies (Lan et al., 2024). Additionally, new technologies like nanomaterials, ultraviolet treatment, etc., can quickly kill algae, but they are costly, subject to policy and safety regulations, and have ecological risks. Therefore, they have not been widely adopted (Wang et al., 2025c).

On the other hand, advanced early warning technologies such as satellite monitoring, automatic sensors, molecular detection, and machine learning are crucial for detecting and resolving algae problems in advance. However, these systems require continuous capital investment and professional maintenance, and they need to be customized based on different water body conditions (Zahir et al., 2024). In practical applications, these technologies face problems such as insufficient funds and decentralized management responsibilities. Currently, they are only widely used in regions with sufficient funds. In areas with high algae risks but scarce resources, the monitoring capabilities are weak, and they are often not detected until the algae outbreak occurs (Feng et al., 2024).

6.2 Instability of long-term control effects

Even if governance measures are implemented, long-term control effects are often unstable. A comprehensive analysis of global on-site governance measures shows that most physical, microbial, and plant-based control methods, when used alone, do not significantly improve water quality; the observed governance benefits mainly come from a few chemical control methods, and their effects usually only last for a short period. The summary of governance strategies for operating reservoirs also indicates that water flow regulation and internal nutrient control can temporarily suppress algal blooms, but as climate and nutrient load conditions change, or residual nutrients in sediments and algae propagules are not treated, the control effects will fail.

The most fundamental way to control the rampant growth of algae is to reduce the nutrients in the water. However, for severely eutrophic water bodies, it takes a long time to restore and the process is unstable, prone to recurrence. Currently, there is no universal method that can completely solve the problem of large-scale and long-term algal blooms. Therefore, the monitoring plan needs to be continuously optimized, and various comprehensive control measures need to be repeatedly evaluated for their effectiveness. For most water body management, the goal is generally to reduce the frequency of algal blooms and mitigate the damage, rather than completely eradicating algae (Anabtawi et al., 2024; Liu et al., 2025).

6.3 Management challenges exacerbated by climate change

Climate change makes the management of algal blooms increasingly challenging, as it turns the management goal into a "moving target", making the already difficult task of reducing emissions even more complicated. The rise in temperature makes water more prone to stratification, and the duration of stratification becomes longer; coupled with changes in hydrological conditions, as well as the increasing occurrence of extreme weather such as ocean heat waves, heavy rains, and droughts, all these create a more favorable environment for harmful algae to grow, prolonging the season and expanding the range of algal blooms. Long-term data shows that although some lakes in North America and Europe have been managed for several decades and have been controlling the input of nutrients, toxic algal blooms have reappeared (Feng et al., 2024), which is the result of the combined effect of climate warming and residual pollution.

Extreme weather events such as ocean heat waves and El Niño have triggered rare large-scale algal blooms, with toxic algae proliferating in the Pacific Ocean and waters in the Southern Hemisphere. This has also sounded the alarm for subsequent algal bloom control efforts. Climate change has significantly reduced the effectiveness of the original emission reduction targets and control methods. Pet et al. pointed out that whether it is nutrient control or water diversion and dilution, all types of control strategies must be re-planned in light of the new water temperature and volume. Emission reduction targets need to be adjusted promptly, and the algal bloom warning line should also take climate factors into account. The combination of climate change and human activities has made the timing and location of algal blooms more difficult to predict, which not only increases the difficulty of prediction but also makes the governance work more cumbersome (Feng et al., 2024; Hwang et al., 2024). If the monitoring network and engineering measures cannot keep up with the pace of climate change, the existing governance methods will soon become ineffective.

7 Future Directions

7.1 Integrated management combining multiple technologies

Future HAB mitigation is expected to rely on integrated, multi-technology portfolios rather than single interventions. Recent reviews stress that physical, chemical, and biological methods each have characteristic limitations, and that combining them can compensate for weaknesses in efficacy, cost, and environmental side-effects (Anabtawi et al., 2024; Lan et al., 2024). Integrated strategies include pairing watershed nutrient controls with in-reservoir hydrodynamic manipulation, selective chemical treatments, and biological controls to deliver both rapid risk reduction and long-term ecosystem recovery. Studies also highlight the potential to couple treatment with biomass harvesting and valorization, turning blooms into resources (e.g., bio-products, materials) and aligning mitigation with circular and low-carbon development goals (Hwang et al., 2024; Liu et al., 2025).

Scaling such integrated approaches requires frameworks that match tool combinations to bloom type, system characteristics, and management objectives. Inland and coastal reviews propose decision schemes in which preventive nutrient and hydrologic measures form the backbone, while more intensive physical, chemical, and biological tools are deployed tactically during high-risk periods (Feng et al., 2024). Future research priorities include rigorous field-scale testing of multi-method packages, better understanding of cumulative ecological impacts, and design of operational guidelines for “integrated management interventions” that explicitly coordinate watershed, in-water, and downstream coastal actions across the aquatic continuum (Anabtawi et al., 2024).

7.2 Intelligent monitoring and precision management

Rapid advances in observation and computation are driving a transition toward intelligent, precision HAB management. Integrated monitoring concepts emphasize combining satellite and drone remote sensing, automated buoys, in situ biosensors, molecular diagnostics, and toxin assays to provide multi-scale, high- frequency data for early warning (Lan et al., 2024; Brenckman et al., 2025). Numerical models and Earth-system frameworks are increasingly merged with machine-learning methods such as random forests, support vector machines, and LSTM networks to improve detection, short-term forecasts, and scenario analysis for management decisions (Esposito et al., 2025; Rathore et al., 2025).

Next-generation systems seek to directly couple these data streams to real-time decision support. AI-assisted integrated governance frameworks link multi-modal monitoring with treatment modules and microalgal resource recovery, aiming to move from “passive emergency response” to active prevention and control (Lin et al., 2025). Digital-twin lake architectures and automated buoy-ML platforms demonstrate how continuous, high-resolution data can drive dynamic, site-specific interventions and automated alerts that signal bloom thresholds relevant for public health and operations (Zahir et al., 2024; Rathore et al., 2025). At larger scales, efforts to build regional and ultimately global HAB observing systems envision standardized, interoperable networks that feed into precision management at local and national levels.

7.3 Ecologically prioritized and sustainable governance approaches

There is a growing emphasis on ecologically prioritized, sustainable governance that addresses root drivers while minimizing collateral damage. Multiple syntheses stress that long- term control must be grounded in nutrient-enrichment management-especially dual nitrogen and phosphorus reductions, improved wastewater and agricultural practices, and hydrologic restoration-integrated with climate-adaptation strategies to confront the “moving targets” created by warming and altered hydrology (Feng et al., 2024; Brenckman et al., 2025). Ecological and nature-based solutions, including wetland nutrient capture, biomanipulation, restoration of macrophytes and seagrasses, and promotion of algicidal and growth-inhibiting bacterial communities, are highlighted as core elements of sustainable HAB prevention (Liu et al., 2025; Hwang et al., 2024).

Governance frameworks are evolving toward cross-sectoral, multi-level arrangements that link water quality, fisheries, public health, and climate objectives. Reviews call for integrated observing networks, open data, and participatory approaches that incorporate local stakeholders, indigenous concepts such as “Sato-Umi,” and community co-management to maintain social license for interventions (Hwang et al., 2024). Future directions emphasize embedding HAB policy within broader ecosystem-based and SDG-aligned agendas, strengthening institutional capacity for adaptive management, and ensuring that technological innovation is consistently evaluated against ecological integrity and long-term sustainability criteria (Feng et al., 2024; Brenckman et al., 2025).

8 Concluding Remarks

The research on harmful algal blooms has evolved from focusing only on individual cases in the early stage to a comprehensive research system that includes cause analysis, monitoring, and various governance methods. The technical means involved have also increased. The existing research review summarizes various governance methods such as physical, chemical, and biological ones, and also introduces some emerging technologies, such as nanotechnology, electrocoagulation technology, and ultrasonic technology. The focus of the research is mainly on finding a reasonable balance among the governance effect, economic cost, and environmental impact. The related review also points out that there is currently no single method that can solve all problems or achieve long-term and thorough control of algal blooms. In recent years, with the development of satellite remote sensing, underwater automatic sensors, molecular detection technology, and data models, people's ability to monitor and warn of algal blooms has significantly improved, enabling earlier detection and response to algal blooms in marine and freshwater environments. At the same time, the issue of algal bloom governance has gradually been linked to broader issues such as social development, ecological protection, and policy management. By integrating the results of various studies, it can be seen that although significant progress has been made in scientific understanding and technical reserves, there are still certain deficiencies in long-term governance effects, governance capabilities, and cross-departmental cooperation.

In recent comprehensive studies, "prevention first and comprehensive management" has been regarded as an important approach for controlling algal blooms in the future. For instance, measures such as reducing the discharge of nutrients like nitrogen and phosphorus, improving wastewater treatment and agricultural management methods, and restoring natural water flow have always been considered as important foundations for solving algal bloom problems and key means to reduce the risk of large-scale and long-term algal blooms. However, single governance methods are often limited by factors such as water body size, cost, or ecological impact. Therefore, some studies suggest combining physical, chemical and biological methods, such as using algivorous microorganisms, regulating the food chain structure, or promoting flocculation through nanomaterials, to form more targeted comprehensive management plans. Such plans can not only reduce the risk of algal blooms in the short term but also contribute to the long-term restoration of the water body ecosystem. Moreover, effective prevention also requires the establishment of a complete monitoring network, the formation of unified and standardized monitoring methods, and the establishment of a risk communication mechanism that can promptly convey scientific information to managers and the public, thereby increasing public participation. These practices also indicate that algal bloom control requires interdisciplinary and holistic management from the watershed to the estuary.

In the future, the management of cyanobacterial blooms will rely more on technological upgrades and the optimization of management methods. The new generation of control systems will closely integrate monitoring and management work, integrate various observational data, model algorithms and intelligent tools, build an intelligent monitoring and governance network, and make management more predictive. The current key technical directions are to develop environmental-friendly nanomaterials, promote microbial and ecological restoration methods, and use underwater and hyperspectral observation equipment. Various regions are also improving their management systems, integrating the management of cyanobacterial blooms with major policies such as climate change and public health, and enhancing the adaptability and sustainability of aquatic ecosystems.

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References
Abate R., Oon Y., Oon Y., Bi Y., Mi W., Song G., and Gao Y., 2024, Diverse interactions between bacteria and microalgae: A review for enhancing harmful algal bloom mitigation and biomass processing efficiency, Heliyon, 10(7): e36503. https://doi.org/10.1016/j.heliyon.2024.e36503

Anabtawi H.M., Lee W.H., Al-Anazi A., Mohamed M.M., and Aly Hassan A., 2024, Advancements in biological strategies for controlling harmful algal blooms (HABs), Water, 16(2): 224.
https://doi.org/10.3390/w16020224

Anderson D., Wells M., Trainer V., Suddleson M., Claridge K., Coyne K., Dortch Q., Gobler C., Heil C., Inaba N., Laughinghouse H., Mardones J., Nakayama N., Park T., Peacock M., Pokrzywinski K., Raymond H., Toyoda J., Trethewey D., Visser P., Wang Y., and Yuan Y., 2025, Controlling harmful algal blooms (HABs) in marine waters: Review of current status and future prospects, Harmful Algae, 150: 102989.
https://doi.org/10.1016/j.hal.2025.102989

Arias F., Zambrano M., Galagarza E., and Broce K., 2025, Mapping harmful algae blooms: The potential of hyperspectral imaging technologies, Remote Sensing, 17(4): 608.
https://doi.org/10.3390/rs17040608

Brenckman C.M., Parameswarappa Jayalakshmamma M., Pennock W.H., Ashraf F., and Borgaonkar A.D., 2025, A review of harmful algal blooms: causes, effects, monitoring, and prevention methods, Water, 17(13): 1980.
https://doi.org/10.3390/w17131980

Byrd K., Wu J., and Lee J., 2025, Harmful algal bloom monitoring with unmanned aerial vehicles: Tools, challenges, and public health implications, Toxins, 17(10): 475.
https://doi.org/10.3390/toxins17100475

Campbell K.G., and Vinebrooke R.D., 2025, Advances in forecasting of harmful algal blooms in freshwater ecosystems, Environmental Reviews, 33: 1-18.
https://doi.org/10.1139/er-2025-0136

Chang S., 2025, Distribution and impact of harmful algae blooms (HABs) in background of global climate change, Theoretical and Natural Science, 112: 7-12.
https://doi.org/10.54254/2753-8818/2025.au23559

Esposito G., De Rosa T., Di Matteo V., Ciccarelli C., Ajaoud M., Teta R., Lega M., and Costantino V., 2025, Bio-tracking, bio-monitoring and bio-magnification interdisciplinary studies to assess cyanobacterial harmful algal blooms (cyanoHABs)' impact in complex coastal systems, Science of the Total Environment, 978: 179480.
https://doi.org/10.1016/j.scitotenv.2025.179480

Feng L., Wang Y., Hou X., Qin B., Kutser T., Qu F., Chen N., Paerl H., and Zheng C., 2024, Harmful algal blooms in inland waters, Nature Reviews Earth & Environment, 5(9): 631-644.
https://doi.org/10.1038/s43017-024-00578-2

Goodrich S., Canfield K.N., and Mulvaney K., 2024, Expert insights on managing harmful algal blooms, Frontiers in Freshwater Science, 2: 1452344.
https://doi.org/10.3389/ffwsc.2024.1452344

Hagh S.F., Amngostar P., Zylka A., Zimmerman M., Cresanti L., Karins S., O'Neil-Dunne J., Ritz K., Williams C., Morales-Williams A., Huston D., and Xia T., 2024, Autonomous UAV-mounted LoRaWAN system for real-time monitoring of harmful algal blooms (HABs) and water quality, IEEE Sensors Journal, 24(7): 11414-11424.
https://doi.org/10.1109/JSEN.2024.3364142

Hwang S.O., Cho I.H., Kim H.K., Hwang E.A., Han B.H., and Kim B.H., 2024, Toward a brighter future: Enhanced sustainable methods for preventing algal blooms and improving water quality, Hydrobiology, 3(2): 100-118.
https://doi.org/10.3390/hydrobiology3020008

Huang W.Z., and Liang K.W., 2025, Health management techniques for sustainable marine aquaculture, International Journal of Marine Science, 15(6): 303-312.
https://doi.org/10.5376/ijms.2025.15.0028

Huang W.Z., and Han Y.P., 2025, Habitat degradation and restoration in aquatic ecosystems: implications for fish populations, International Journal of Aquaculture, 15(4): 175-183.
https://doi.org/10.5376/ija.2025.15.0017

Igwaran A., Kayode A.J., Moloantoa K.M., Khetsha Z.P., and Unuofin J.O., 2024, Cyanobacteria harmful algae blooms: causes, impacts, and risk management, Water, Air, & Soil Pollution, 235(1): 71.
https://doi.org/10.1007/s11270-023-06782-y

Kuijpers M., Quigley C., Bray N., Ding W., White J., and Jackrel S., 2025, Intraspecific divergence within Microcystis aeruginosa mediates the dynamics of freshwater harmful algal blooms under climate warming scenarios, Proceedings of the Royal Society B: Biological Sciences, 292: 20242520.
https://doi.org/10.1098/rspb.2024.2520

Lan J., Liu P., Hu X., and Zhu S., 2024, Harmful algal blooms in eutrophic marine environments: Causes, monitoring, and treatment, Water, 16(17): 2525.
https://doi.org/10.3390/w16172525

Lin M., Xu Y., Peng J., Chen Y., Zhu Y., Fu X., Zhu Y., and Lin L., 2025, From passive prevention to proactive intervention: An AI-assisted integrated governance system for algal bloom monitoring and control, Environmental Research, 123379.
https://doi.org/10.1016/j.envres.2025.123379

Liu D., Huang L., Jia L., Li S., and Wang P., 2024, Evaluation of best management practices for mitigating harmful algal blooms risk in an agricultural lake basin using a watershed model integrated with Bayesian Network approach, Journal of Environmental Management, 364: 121433.
https://doi.org/10.1016/j.jenvman.2024.121433

Liu J.M., Zhao H.Y., Emmanuel C., Fan T.H., Deng W., and Zhang Y.F., 2025, Interdisciplinary strategies for the management of harmful algal blooms: Prospects and comprehensive review, Discover Environment, 3(1): 93.
https://doi.org/10.1007/s44274-025-00304-9

Nayak A.R., Kolluru S., Kumar A., and Bhadury P., 2025, Revisiting harmful algal blooms in India through a global lens: An integrated framework for enhanced research and monitoring, iScience, 28(2): 111916.
https://doi.org/10.1016/j.isci.2025.111916

Pacheco J., López-Ballesteros A., Mesman J., Aznarez C., Pierson D., Trolle D., Nielsen A., and Senent-Aparicio J., 2025, Coupling SWAT+ and GOTM-WET models to assess agricultural management practices for mitigating harmful algal blooms in Mar Menor, Spain, Journal of Environmental Management, 380: 125033.
https://doi.org/10.1016/j.jenvman.2025.125033

Pan S., Zhang X., Liu X., Liu H., Li A., Liu X., Chen S., and Zhang H., 2025, Bifunctional fungi trade off denitrification and algicidal performance to inhibit algal growth and control algal bloom: Denitrification-algicidal interactions, organic matter dynamics, and raw water treatment, Water Research, 288(Pt A): 124590.
https://doi.org/10.1016/j.watres.2025.124590

Park J., Patel K., and Lee W.H., 2024, Recent advances in algal bloom detection and prediction technology using machine learning, Science of the Total Environment, 938: 173546.
https://doi.org/10.1016/j.scitotenv.2024.173546

Qiu Y., Huang J., Luo J., Xiao Q., Shen M., Xiao P., and Duan H., 2025, Monitoring, simulation and early warning of cyanobacterial harmful algal blooms: An upgraded framework for eutrophic lakes, Environmental Research, 264: 120296.
https://doi.org/10.1016/j.envres.2024.120296

Rathore W.U.A., Ni J., Ke C., and Xie Y., 2025, Bloomsense: integrating automated buoy systems and AI to monitor and predict harmful algal blooms, Water, 17(11): 1691.
https://doi.org/10.3390/w17111691

Saleem F., Jiang J., Atrache R., Paschos A., Edge T., and Schellhorn H., 2023, Cyanobacterial algal bloom monitoring: Molecular methods and technologies for freshwater ecosystems, Microorganisms, 11(4): 851.
https://doi.org/10.3390/microorganisms11040851

Shi X., Zou Y., Zhang Y., Ding G., Xiao Y., Lin S., and Chen J., 2024, Salinity decline promotes growth and harmful blooms of a toxic alga by diverting carbon flow, Global Change Biology, 30(6): e17348.
https://doi.org/10.1111/gcb.17348

Szewczyk T., Aleynik D., and Davidson K., 2025, Ensemble models improve near-term forecasts of harmful algal bloom and biotoxin risk, Harmful Algae, 142: 102781.
https://doi.org/10.1016/j.hal.2024.102781

Wang S., and Qin B., 2025, Application of optical remote sensing in harmful algal blooms in lakes: a review, Remote Sensing, 17(8): 1381.
https://doi.org/10.3390/rs17081381

Wang S., Qin B., Wen B., and Huang C., 2025a, Climate change influences on algal bloom intensity in lakes in the Yangtze River Basin, China from 1985 to 2022, Journal of Hazardous Materials, 495: 139027.
https://doi.org/10.1016/j.jhazmat.2025.139027

Wang W., Wang G., Li J., Chen J., Gao Z., Fang L., Ren S., and Wang Q., 2025b, Remote sensing identification and model-based prediction of harmful algal blooms in inland waters: current insights and future perspectives, Water Research X, 28: 100369.
https://doi.org/10.1016/j.wroa.2025.100369

Wang Z., Xiong J., Zhou J., and Han Z., 2025c, Algae removal and degradation of microcystins by UV-C system: A review, Water Environment Research, 97: e70049.
https://doi.org/10.1002/wer.70049

Zahir M., Su Y., Shahzad M., Ayub G., Rehman S., and Ijaz J., 2024, A review on monitoring, forecasting, and early warning of harmful algal bloom, Aquaculture, 593: 741351.
https://doi.org/10.1016/j.aquaculture.2024.741351