Pramod Kumar Pandey
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Fisheries and Aquaculture of the Temperate Himalayas

Springer

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This book is dedicated to Dr Padmakar Vishwanath Dehdrai, the First Deputy Director General—Fisheries (DDG-Fisheries) of the Indian Council of Agricultural Research, for his outstanding contributions to the overall development of the fisheries sector in India.

Foreword

The diverse population of indigenous and a few exotic fishes in the Himalayan region water bodies offer an immense support for food security and livelihood to the economically underprivileged population through aquaculture, ornamental fishery, sport fishery and fish-based eco-tourism. An increase in fish production by horizontal expansion, intensification, diversification and sustainable management of natural resources shall prove prime mover in deriving economic benefit leading to the prosperity of the people in the region. It is also imperative to reduce the demand and supply gaps of aquaculture produce and augment the blue economy by rational utilization of available resources in the very fragile ecosystem. Simultaneously, rehabilitation and conservation are the priority for sustainable development of fisheries in the Himalayan region which are confronted with severe anthropogenic stresses, leading to environmental degradation.

The theme of the book has a global perspective. The temperate Himalayas and its ecosystem have similarity in many regions of Europe and Asia and hence the subject of this book is likely to evoke an equal interest in Europe and Asian countries.

I believe that the book *Fisheries and Aquaculture of the Temperate Himalayas* will serve as an important reference and knowledge to planners, academicians, scientists and other stakeholders for fisheries development in the Himalayan region.

I congratulate the editors and authors for their very meaningful and genuine efforts.

Department of Agriculture Research and Education (DARE), Indian Council of Agricultural Research (ICAR), Ministry of Agriculture and Farmers Welfare, Government of India
New Delhi, India
5 September 2022

Himanshu Pathak

Preface

The unique ecosystem and resources of the Himalayas are significant both from biodiversity and economic point of view that play a crucial role in nutritional security. The primary occupation in the mountain regions of the Himalayas is agriculture-based activities, having small land holdings and limited resources. As fisheries play an important role in providing food and income to the people in mountain areas, they must be integrated with rural development for sustainable use of water resources. Fisheries and aquaculture contribute to the livelihood of a large section of the economically underprivileged population of the Himalayas. The emerging production technologies, higher economic growth, population explosion and shifts in the dietary pattern are leading to rapid growth in production as well as demand for food of animal origin. Several constraints, such as low productivity of upland waters, the comparatively slow growth rate in almost all fish species, low fecundity in fishes and poor landing and marketing facilities, have been seen as significant obstacles to the rapid development and expansion of fisheries and aquaculture in the temperate Himalayan region. The fish fauna at higher altitudes is also vulnerable to activities resulting from human pressure on the environment, such as deforestation and water pollution. Hence, water bodies at high altitudes mostly have low fish production and can be easily overfished. There is a need to adopt large-scale farming in the temperate Himalayan region through proper planning, scientific efforts and public participation.

This book *Fisheries and Aquaculture of the Temperate Himalayas* contains specific chapters on capture fisheries, resource mapping, temperate aquaculture, sports fishery and ornamental fishery, highlighting the technological status and possible use of modern science for profitable aquaculture and sustainable management of resources. The objective of publishing the book is to compile a comprehensive account of the status of temperate fisheries and aquaculture, to explore the prospects and opportunities and to give way forward for the fisheries development in the temperate Himalayas.

We would like to thank all the authors for their contribution and support in making this book a complete reference in the historical perspective of the practices and modern immerging techniques to be applied for accelerated growth of the fisheries sector in the Himalayan region. The authors' contribution to different chapters on important topics has given superiority to the book, which would be helpful for researchers, academicians, students, planners and managerial officials.

Bhimtal, Uttarakhand, India
30 August 2022

Pramod Kumar Pandey
Nityanand Pandey
Md. Shahbaz Akhtar

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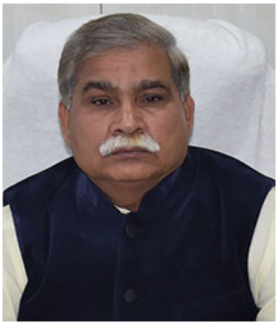

Pramod Kumar Pandey has more than 33 years of experience in the field of Fisheries and Aquaculture in different capacities. He started his professional career at Marine Products Export Development Authority, Kochi, in 1988. He joined the Agricultural Research Service as a Scientist in the year 1993 and worked at different positions in the Indian Council of Agricultural Research, India. He has worked as a Scientist, Sr. Scientist, and Principal Scientist at ICAR-Central Institute of Fisheries Education, Mumbai. After working as Dean, College of Fisheries, Central Agricultural University (Imphal), for more than 5 years, he has joined as Director, ICAR-DCFR, Bhimtal, since May 2021. He has received many national and international awards from different organizations. He has around 150 publications including research papers in national and international journals, 8 books, and many institutional and externally funded research projects to his credit. He has also conducted many training programs, workshops, seminars, and symposia for farmers, students, academicians, researchers, and fisheries officials. His most significant achievement has been the voluntary breeding of magur (*Magur magur*) in captivity. He has guided around 36 students for their PG and PhD programs. He has been involved in developing and preparing several policy papers for the development of fisheries in the country and new course curricula for PG students in the field of Fisheries Science. He has visited countries such as the USA, Mauritius, and Thailand in different capacities.

Nityanand Pandey works as Principal Scientist at the ICAR-Directorate of Coldwater Fisheries Research since 2007. He is a medalist fisheries graduate from the G. B. Pant University of Agriculture & Technology, Pantnagar, India. He obtained his master's degree from ICAR-Central Institute of Fisheries Education (ICAR-CIFE), Mumbai, India, and doctorate from Gurukul Kangri University, Haridwar, India. He was conferred the Young Scientist Award and Gold Plated Medal 2002, Fellow of Natural Science & Culture (FNSC), 2011, by Nature conservators (India), Fellow of Coldwater Society of India, and Distinguished Scientist award, AETDS 2020. He did field level extension work for more than 8 years and taught at UG & PG level for 5 years. He has more than 85 research papers in peer-reviewed journals and guided more than 24 research scholars for their research work. He has expertise in the field of temperate aquaculture, ploidy manipulation in fish, and climate-resilient aquaculture.

Md. Shahbaz Akhtar, PhD, ARS, works as a Senior Scientist at the ICAR-Directorate of Coldwater Fisheries Research since 2010. He graduated from the Kerala Agricultural University, Kerala, India. He obtained his master's (in 2008) and doctorate degrees (in 2012) from ICAR-Central Institute of Fisheries Education (ICAR-CIFE), Mumbai, India. He is awarded the K. C Naik Gold Medal by the Professional Fisheries Graduates Forum (PFGF), Mumbai, for being the Best Fisheries Graduate of India in 2006. He is the recipient of the Hiralal Choudhary Gold Medal and the Sir Dorabji Tata Endowment Award by ICAR-CIFE in 2008. He was conferred the "Dr. M.S. Swaminathan Award for the Best Indian Fisheries Scientist" in 2014 by PFGF and Fellow of Zoological Society of India. His research area includes fish reproductive biology, conservation, thermal eco-physiology, fish physiology and nutrition, and climate-resilient aquaculture. He has developed a climate-resilient indoor technology for captive maturation and year-round multiple breeding of endangered golden mahseer. This technology is truly helping in the conservation and rehabilitation of mighty mahseer in the Himalayan waters. So far (until 2022), Dr. Akhtar has published >80 research papers in peer-reviewed international impact journals and has earned >2200 citations (h-index: 25; i10-index: 42).

Fish and Fisheries of the Temperate Himalayas: An Overview and Way Forward

1

Pramod Kumar Pandey and Nityanand Pandey

Abstract

Fish is an important source of food and income and also provides the opportunity for trade and export as blue economy. Considering the vast resources available, there is immense potential to draw economic benefit for the prosperity of the people residing in temperate zone of the Himalayan region through multifold increase in fish production by horizontal expansion, intensification, diversification, and sustainable management of existing natural resources. This would be helpful to reduce the gap between demand and supply. Though the present aquaculture in the Himalayan region is a traditional and rural practice, reforming has been done for fisheries sector in temperate zone through awareness and technological advancement which may also require the vertical and horizontal expansion of this sector toward the commercial practice and export avenues. Sport fishery and ecotourism in hill region is a potential component, and reorientation is required for this purpose with private–public partnership mode. Research and development support would be a key factor to accelerate the development of fisheries and aquaculture practices in hill region. Ornamental fish culture has been adopted as small-scale enterprises which provide an alternative source of employment and also require an intensive approach in potential areas. The Himalayan region is bestowed with diverse natural resources such as rivers, streams, lakes, and reservoirs. Fish occurrence and wild population in these water bodies are badly affected with overfishing, siltation, damming, pollution, and poor management. Hence, the fisheries in these water bodies are either unexploited or unmanaged. Use of modern techniques and implementation of scientific management would be fruitful to bring this sector more realistic and economic to support the

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livelihood and nutrition security. The fragile nature of fish occurrence, environmental threats, and anthropogenic activities indicated the need of conservation and management of existing resources on sustainable basis. Overall review of the temperate fisheries and aquaculture reflects the potential and prospects of livelihood support and nutritional security.

Keywords

The Himalayan fisheries · Ecotourism · Trout culture · Fish diversity · Exotic species · Policy issues

1.1 Introduction

The largest mountain range in Asia is the Himalayas which demarcates the plains of the Indian subcontinent and area of Tibetan Plateau. Sivalik Hills, the Great Himalayas, and the Tibetan Himalayas are the major ranges of this mountain range. The Gangotri, Yamunotri, and Zemu in India; Khumbu in Nepal; and Langtang glacier in Langtang region are the major glaciers along with other numerous small glaciers which store about 12,000 km^3 freshwater. Geographically, this mountain covers the hilly areas of Pakistan, India, China, Nepal, and Bhutan. The entire range of the Himalayas is bordered with Karakoram and Hindu Kush ranges in northwest, Tibetan Plateau in north, and Indo-Gangetic Plain in south with a large drainage area. The Ganges, the Indus, and the Tsangpo-Brahmaputra are the major river systems of the Himalayas with large drainage basin, which provides shelter to about 600 million people of different countries. The Himalayas is also an emblematic of the cultures of South Asia and Tibet. The entire Himalayan range has been categorized into four major agroclimatic zones including the low hills and valleys near the plain areas, the middle hills and valleys, high mountains and valleys, and cold dry desert zone. Each zone is characterized with variations in altitudes and climatic conditions such as rainfall, temperature, and humidity. The third zone of the Himalaya is characterized with temperate climatic conditions, having physiographically a large mountainous tract (1800–2000 m above msl). This temperate zone of the Himalayas has the winter during the month of October and February, the summer during the month of March and June, and monsoon season during the month of July to September with a brief spring period during mid-February to March and autumn during late September to October in the annual calendar. The thermal regime of 5–20 °C is reported with minimum temperature in the winter and maximum in the summer during the month of April to June. The temperate zone of the Himalayas reflects variable climatic conditions, having resourcefulness and rich biodiversity. Presently, this zone has been affected with anthropogenic activities and possesses the challenges of habitat destruction and aquatic pollution. The Indian part of the Himalayan region has varied geographical and topographical climatic conditions with diverse natural water resources. The total geographical area of the Indian Himalayan region is about 533,604 km^2 which is about 16.2% of the total geographical area of the country, being inhabited by 39,628,311 people (3.86% of total population). This geographical unit is a fragile zone having richness in water resources and biodiversity. Biodiversity of any ecosystem provides stabilization, protection of overall environmental quality, and understanding of the intrinsic worth of all species. The hydrological parameters along with flora and fauna perform a critical balance for sustainability and susceptibility for larger implications due to climate change and various water-induced hazards. The temperate zone of the Himalayas comprises water bodies in the form of streams and rivers and natural lakes including brackish water lakes at high altitude. Existence of fish in any aquatic system may be used as indicator of habitat suitability and health of the system. This is fact that if the fish stocks dwindle in any aquatic ecosystem, there would be a grave threat to ecosystem and food security which affects inhabitants by virtue of their habitation. Hence, rational utilization of aquatic resources is directly linked with the benefit of the contemporary society, and it is more ethical and wise to think for the future.

Fisheries and aquaculture play vital role in food, nutrition, income, and livelihood to the rural populations and blue economy of the nation, having commercial earnings and foreign trade. India is the second largest fish producer in the world with the fish production registering an average annual growth rate of more than 7% in the recent years. Fish contributes to 10% of total exports from India and almost 20% of agricultural exports. This rapid growth in fish production and increasing demand for food of animal origin are mainly due to better management practices, accelerated economic growth, population explosion, and change in dietary pattern. Fish not only is an important source of food and income but also supports the foreign earning. Considering the vast resources available in the temperate region, there is immense potential to draw economic benefit for the prosperity of the people residing in the hill states. Due to the limited resources to support the livelihood, the people of temperate region have to depend on the natural resources and subsistence farming. The available fishery resources are significant for ecosystem and economic point of view that play a crucial role in the nutritional security of the people dwelling in temperate regions. This geographical area has paradoxical situation for short supply of animal origin food which require to cop the low temperature as well as the limited resources to support the livelihood. Though there are certain limitations for the development of fisheries such as inaccessibility, difficult terrain, limited candidate fish species for culture, difficult transportation, slow growth of fish in aquaculture due to low thermal regime, and lack of marketing channel, recent success of developing temperate aquaculture shows that people in the rural areas are direct beneficiaries as it provides employment opportunities and protein-rich food. The integrated farming practice provides opportunities for the rural development as well as resources utilization. However, there is scope for scaling up temperate fisheries and aquaculture with improved management practices and technological advancement, having opportunities for entrepreneurship development with sport fishery and ornamental fish farming.

1.2 Fishery Resources in Temperate Region

The Himalayan region is characterized with occurrence of diversified fish fauna. The temperate region of India accounts about 17% fishes of the total ichthyofaunal diversity of the country, which is a center of origin and evolution of this biotic form. The Indian part of the Himalayas has fishery resources having 8243-km-long streams and rivers, 50,000 ha of natural and manmade reservoirs, and 20,500 ha of natural lakes including 2500 ha of brackish water lakes at the high altitudes (Mahanta and Sarma 2010). In Bhutan, the total length of streams and rivers is estimated to be about 7200 km having Amo, Chang, Wang, Tongsa, and Manas as major rivers in the country. Bhutan also has over 590 natural lakes with 4250 ha area at altitude of 2200 m and only one reservoir having area of 150 ha. Nepal has numerous rivers, streams, and lakes in the hill region. About 36 species of freshwater fishes are endemic to the Himalayan region. Cool and cold-water resources of the Himalayas support predominantly the subsistence fisheries, sport/recreational fisheries, and low-scale commercial fisheries in lakes and reservoirs. Capture fishery in stream and rivers is not managed; however, considerable efforts have been given for fisheries in lakes and reservoirs in India, Nepal, and Pakistan. Introduced trout and indigenous mahseer support the sport fishing in India, Nepal, and Bhutan. Schizothoracinae contributes the major share in the wild catch of fish from streams and rivers. However, natural occurrence of this fish in wild waters is highly fragmented, suffering from overfishing. The water quality is also deteriorating in some streams, rivers, and lakes due to the deterioration of soils and pollution which affects the wild fish stock. Lakes of the Kashmir are getting reduced in size due to the eutrophication and explosive growth of aquatic plants. Hence, the capture fisheries in temperate region are at lower pace without any commercial practice in existence. The fragmented wild population of fishes of small size is restricted in certain pools where fish have some shelter and resting places. Thermal variation and variable microclimatic conditions are the limiting factors influencing geographical distribution and local occurrence in the natural water bodies. Enhancement of wild fish stocks through regular ranching of indigenous fish species in the natural water bodies of the Himalayas is priority for further development of capture fisheries in temperate region.

1.3 Fish Fauna and Fish Production Trend in Temperate Region

The Himalayan region is rich in ichthyofaunal diversity with diverse kinds of fish fauna comprising of 258 fish species in India, 25 species in Pakistan, 41 species in Bhutan, and 179 species in Nepal including indigenous and exotic fishes. The major groups of fish in the existence are cyprinids (*Labeo* and *Tor* spp.), lesser barils (*Barilius* spp.), schizothorax group (*Schizothorax* and *Schizothoraichthys* spp.), garrids (*Garra* spp.), and sisoridae family (*Glyptothorax* and *Glyptosternum* spp.). The volume of other genera is less having low economic value. Rheophilic species such as *Nemacheilus gracilis*, *N. stoliczkae*, and *Glyptosternum reticulatum* are found in headwater zone of the torrential streams, while *Diptychus maculatus* and *Nemacheilus* spp. remain prevalent in large stream zone. *Schizothorax longipinnis*, *S. planifrons*, and *S. micropogon* can be found in intermediate reaches of the large stream zone, and *Garra gotyla*, *Crossocheilus diplochilus*, *Labeo dero*, and *L. dyocheilus* always prefer the least rapid reaches of large stream zone. Species such as *Barilius* spp., *Tor* spp., catfishes, homalopterid fish (*Homaloptera* spp.), and snakeheads (*Channa* spp.) inhabited mainly in slow-moving meandering zone of the torrential streams.

The exotic brown trout (*Salmo trutta fario*), rainbow trout (*Oncorhynchus mykiss*), and common carp (*Cyprinus carpio*) have also established itself in some natural waters of the Himalayas (Sehgal 1999). Among the indigenous fishes, Golden mahseer (*Tor putitora*) is one of the largest species having sports and angling value (Bhatt et al. 2004). In present contest, decline in the mahseer fishery has been experienced due to the indiscriminate fishing and growing number of hydroelectric and irrigation projects in Himalayan streams and rivers (Bhatt et al. 2004). The Indian snow trout falls under seven genera, majority of which constitute an important part of cold-water fishery in the Himalayan region (Tilak 1987). The second most important group among the indigenous fishes is Schizothoracinae having 17 species including *Schizothorax richardsonii*, *S. plagiostomus*, *Schizothoraichthys niger*, *S. esocinus*, *S. longipinnis*, *S. planifrons*, *S. micropogon*, *S. curvifrons*, *S. nasus*, *S. huegelii*, *S. labiatus*, *S. progastus, Diptychus maculates*, *Ptychobarbus conirostris*, *Schizopygosis stoliczkae*, *Gymnocypris biswasi*, and *Lepidopygopsis typus*. Wild population of the fishes of this group is fragmented and badly affected by indiscriminate fishing and growing number of hydroelectric and irrigation projects on the rivers. There are some indigenous fascinating fish species in the rivers and their tributaries having ornamental value and demand in international market. The Northeast Himalayan region is rich in such type of indigenous ornamental fish species.

The present fish production of temperate Himalayan region is mainly contributed by capture fisheries and some part from temperate aquaculture practices. The temperate region of India contributes to about 3% of total inland fish production which is a very small contribution to the total share in national fish production. As far as fishery development is concerned for temperate region in India, Nepal, and Bhutan, maximum area is still poorly developed or underexploited.

1.4 Potential of Temperate Fisheries and Aquaculture to Support Livelihood

Fisheries is a potential enterprise in the hills, having opportunities for providing animal protein to the dwellers and also supporting other agriculture activities under integrated farming practice for improving socioeconomic life. Though the capture fishery resources are under the environmental threats, however, capture fishery supports employment and income to the inhabitants and traditional food to the rural people and fish eaters. Lakes and reservoirs are also vital sources for wild catch, and different areas of the reservoirs have been earmarked for commercial fishing and fish marketing activities.

Trout farming is the major aquaculture practice in the Himalayan region, where sufficient quantity of cool, clean, and oxygen-rich water is available. In India and Nepal, the rainbow trout farming has accelerated significantly with quantum jump in the production. However, the potential of the trout farming in Himalayan region is yet to be exploited fully with improved genetic material and culture system. Chinese carp farming under monoculture and polyculture system is a common aquaculture practice in mid-altitudes, having the features of easy and simple farming techniques with low input requirements and possibilities of integration of available resources. Traditional carp culture in small-sized ponds (0.01–0.03 ha) is popular as rural aquaculture in most of the temperate areas. The carp culture has also been integrated with dairy, horticulture, agriculture, and paddy cultivation. However, the productivity in this culture practice is not so encouraging and needs technological advancement, better management, and improved strains for aquaculture. Many suitable sites are available in different parts of the Himalayan region, which could be utilized for fish production through carp culture or trout farming.

The Himalayas is an abode for sport fishing and angling or recreational fishing as most popular outdoor activities in hill. Himalayas have diversified indigenous fish species of sport value and suitable water resources for sport fishing. In India, about 4000 km stretches of rivers and streams are the sites of attraction for local and foreigner anglers to hook the sizeable mahseer and trout. Fish watching also has scope for fish-based ecotourism and has the potential of employment generation for the local inhabitants. People like to watch the different moving fishes of different sizes, shapes, and colors, which attract the visitors of all age groups. In India, many of the religiously protected streams and lakes in different hill states are fish watching spots to attract the tourists. Fish-based ecotourism has prospects for further development in all Himalayan countries including India, Nepal, and Bhutan.

1.5 Subtle Issues and Hazards in Temperate Fisheries

1.5.1 Infrastructure and Policy-Related Issues

The aquatic resources in the Himalayan region provide opportunities for food and sport, but scientific management of these resources is necessary to translate the opportunities into achievements. Sustainable management and balanced use of these resources are imperative for the development of fisheries sector in temperate region of the Himalayas. However, the Himalayan region is in progressive phase for capture fisheries and aquaculture including sport fishery, intensive trout farming, welfare of the fishermen, and other support services. However, the production and productivity in fisheries sector of the Himalayan region is below the optimum as compared to the other plain areas. Some part of the hills is still undeveloped due to the lack of adequate attention and infrastructure. The primary reason for this situation is lack of proper planning and poor research and development support for the fisheries activities. But, now it has been realized that fisheries in the Himalayan region can contribute significantly for livelihood as well as for nutritional security. Therefore, fisheries sector needs to be given due importance in terms of financial, infrastructure, and modem institutional backup facilities in the planning process. In hills, the fishery development should be promoted in order to introduce diversification and hi-tech culture system and sustainable management of natural resources. This will result in profitable utilization of available resources for livelihood and high valued food protein production in the form of fish.

1.5.2 Conservation-Related Issues

There was a rich population of indigenous fishes such as mahseer, snow trout, and minor carps in the Himalayan streams and rivers, and introduced exotic fishes were very limited. Mahseer-based angling and sport fishing are well known, but due to the rapid overall development increasing demand of fish as food, the aquatic ecosystem of Himalayan region is threatened with man-induced stress which is detrimental to the fish fauna. Presently, some of the indigenous fish species have been declared as threatened/vulnerable and endangered and are subject of rehabilitation and conservation. This declining trend in species composition and catch volume of individual fish is very often related to so many factors such as habitat, destruction, indiscriminate fishing, and anthropogenic activities especially the power generation projects in cascading manner on the streams and rivers. Hence, rehabilitation and conservation is the priority for the planning of the sustainable development of fisheries in the Himalayan region.

1.5.3 Habitat Destruction

Construction of dams across the river results in changing the ecology mainly due to siltation from the catchment areas and is subject to the destruction of the spawning and feeding grounds of many fishes (Sehgal 1994). There is a dramatic change in fish habitats and local fish communities due to the creation of power dams and reservoirs on the Himalayan rivers which also have blocked the migration routes of important native fishes like mahseer (*T putitora* and *T. tor*) and snow trout (*Schizothorax richardsonii*, *S. plagiostomus*) (Sehgal 1994). Habitat alteration is a causative factor for fragmented distribution and abundance of native fishes in hill streams of the Himalayan waters (Sehgal 1994; Raina and Petr 1999). The excessive withdraw of water from the river courses for agriculture and domestic and industrial uses left inadequate water flow to support the life existence of the fishes and are major factors responsible for the depletion of fisheries resources in the Himalayan region. Wanton killing by the use of dynamites, electric shocks, and poisoning to kill the brood fishes during their spawning season and juveniles during the post-monsoon periods is prevalent in the Himalayan region which affects the existence of various commercial fishes, especially in the rivers and streams of India, Nepal, Bhutan, and Pakistan. Activities such as increased water abstractions, pollution, and wanton methods of fishing create anthropogenic pressure on aquatic ecosystem.

1.5.4 Introduction of Exotic Species

The two salmonids, rainbow trout (*Oncorhynchus mykiss*) and Brown trout (*Salmo trutta fario*), were introduced in the streams, lakes, and reservoirs in the Himalayan region primarily for recreational purpose and now established as natural stock and are subject of invasion for native biodiversity. Two phenotypes of common carp, viz., scale carp, *Cyprinus carpio* (*communis*), and mirror carp, *Cyprinus carpio* (*specularis*), are used as commercial fishery in certain lakes and reservoirs of the Himalayan region. Presently, these exotic rainbow trout and common carp are the major candidate fish species for temperate aquaculture, and escaped fishes create environmental risk. However, the aquaculture of these exotic fishes increased the aquaculture productivity but has resulted in sharp decline of the indigenous fishery. This situation has created the conflict between increased fish productivity and existence of the native indigenous fishes, but both the issues are equally important for the fishery development in the temperate region.

1.5.5 Impact of Climate Change

This is fact that the mountains are early indicators of changing climate due to the direct effects of increasing CO_2 concentration and the increasing water temperature in the Himalayan waters and indirect effects on hydrology caused by the melting of glaciers and the erratic precipitation pattern. These changes are subject to affect the resources of the Himalayan region and their fisheries negatively impacting on breeding behavior and culture potential of fish species. In order to mitigate the impact of climate change, there is need to develop climate-resilient fish farming protocols including more resilient indigenous species in culture practices in the hill region, and it needs further refinement and validation of smart fish farming through adequate strategy involving thermally adopted more resilient fish species and availability of efficient system such as re-circulatory aquaculture system (RAS) for reuse of water.

1.6 Consideration Required for Further Development

Location-, situation-, and system-specific culture practices coupled with scientific management approach are the priority for the further development of temperate fisheries in the Himalayan region. At present, attention is required toward the standardization of suitable technologies for hilly areas of the region depending on available resources and environmental concerns. A species-based system in accordance to fish biodiversity in geographical location is also important for the sustainability of the system. The following steps are important in order to improve fisheries and aquaculture in Himalayan region:

- Specific aquaculture system suitable for higher production and prevailing climatic conditions of the Himalayan region.
- Remedial measures for depleting population of economically important native fish species and regular monitoring of their breeding performance and reproductive behavior.
- Rational exploitation and conservation of resources to support the optimum stock at sustainable basis particularly for high altitudes.
- Research and development support for intensification and diversification of temperate aquaculture in accordance to geomorphological feature of the Himalayan region.
- Regular monitoring to assess threat perspectives in relation to ichthyofaunal diversity in aquatic resources.
- Intensive culture system and smart fish farming in context to water scarcity and climate resilience.
- Scientific management of natural lakes and natural and manmade reservoirs of the Himalayan region to bridge the gap between yield and carrying capacity.
- Decision support system for aquaculture site suitability and resource mapping by using geoinformatics.
- Active involvement of women in fisheries and aquaculture activities for management and utilization of natural resources.
- Promotion of ornamental fishery and diversion of exotic to indigenous species.
- Proper disaster management protocols for the protection of habitat and biodiversity.
- Use of gene manipulation techniques to counter slow growth and low fecundity and to increase environmental plasticity.
- Prevention of postharvest losses and value addition for fishes.
- Intelligence for marketing and supply chain for profitability and mobilization of system.

1.7 Conclusion

The immense ecosystem of unique Himalayas has provided opportunities for getting goods and services which may be continued in the future with proper planning and management. However, we should realize that the entire Himalaya is facing anthropogenic pressure, leading to environmental degradation. Fish is the best food item to supplement the protein requirement of the poor people located in the remote Himalayan region and to provide source of income to a section of people who are resource poor in terms of cultivable lands in hills and overexploited natural resources. At high altitudes, trout farming is in vogue and has potential of multifold increase. Mid-altitudinal areas are also potential sites for the carp culture. Fish-based ecotourism and ornamental fishery have the potential for entrepreneurship development. Temperate fisheries and aquaculture have promising future and are indeed valuable and important not only because of unique diversity of species but also for nutritional security and livelihood support.

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2 Fishery Resources and Ichthyofaunal Diversity in the Temperate Himalayas

Kishor Kunal, Garima, and P. A. Ganie

Abstract

According to some reports, water resources in the Himalayas harbor 268 fish species distributed to 76 genera and 21 families. An updated study by the Zoological Society of India has reported nearly 316 fish species from the Indian Himalayan landscape. Besides, 13 invasive species have been identified, which have been introduced in the Himalayan waters. Ninety-seven of the 316 species found in this area are native to the Indian Himalayan freshwater systems. The fish variety known from the region accounts for roughly 30.8% of India's total freshwater fish species (1027), 62.8% of total genera (188), and 18.6% of the total endemic species (522). The major fishery in the Himalayas mainly comprises of the rainbow trout, snow trouts, mahseers, loaches, garrids, barils, catfishes, and carps.

Keywords

Indian Himalaya · Ichthyodiversity · Fishery resources · Snow trouts · Fish aggregating devices

2.1 Introduction

The literal meaning of Himalaya is "abode of snow." The Himalayas are geologically young and structurally folded mountains that stretch over 4000 km from the east (Myanmar and China) to the west (Afghanistan), with all 14 of the world's

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highest mountains looming over 8000 m. The Himalayas is a beacon for clouds of moisture that generously bestow its slope with precipitation and, through rapidly growing mountains, create the great rivers of Asia (Zurick and Pacheco 2006). Variation in Himalayan altitudes is greater in the eastern half than in the western half. Rivers are linear systems that show a gradient of characters along their length. The Himalayas has a larger number of rivers that originate from it and possesses a perennial supply of liquescent snows and a substantial number of lakes and reservoirs which have been constructed for different purposes harboring the numerous cold-water fish stock. These mighty rivers are fed by copious rainfall, large glaciers, and extensive snow fields. Streams, originating from the Himalayas, are very peculiar in their characteristics by virtue of their fast-flowing waters, high altitude, low water temperatures, and heterogeneous substrates due to snowmelt or glacier-fed water (Rajput et al. 2013).

"Rhithron" is the steep and turbulent upper course, and "potamon" is the wide, flat, lower course with less water flow rate. Rhithron course of rivers falls in the Himalayan region. River streams of the Himalayas can generally be categorized under three subsystems: collecting system, transporting system, and dispersing system. Stream order depends on the drainage density of the region. Drainage channels of similar flow inputs are identified with the same stream order. Streams of the same order join together and form a higher-order stream. The stream order varies from first order onward, based on their connection with tributaries. Higher stream order or stream with high flow concentration results in lesser fluctuations in physicochemical parameters and supports higher diversity/population (Whiteside and McNatt 1972). The rivers and streams of the Himalayas flow through deep valleys and gorges until they exit the mountains. Enormous power potential of the Himalayan reservoirs is still underutilized. Several sites in the Himalayan region can house hydroelectric plants, either by utilizing waterfalls at many places or by constructing dams at other places. Most of the lakes found in the Himalayan region are of glacial origin. Glacial lakes are widespread in glacierized basins at high elevations. When glacial ice, moraines, or natural depressions impound water, they form glacial lakes. There are many different types of such lakes, ranging from meltwater ponds on glacier surfaces to enormous lakes inside valleys dammed by a glacier in the main valley. They are formed when glaciers dug out a basin, which was later filled with snowmelt. Fishery resources of the Himalayas comprised of both endemic and exotic fishery resources.

2.2 Ichthyodiversity

The altitudinal regime mainly influences the weather condition in this region. The low temperature is a major factor determining the profile of organisms dwelling in the drainage. Fish are important sources of protein for people residing in hills and mountains and provide them livelihood by making income through it. The cold-water rivers and hill streams are renowned for their waterfalls, torrential stream flow, substratum comprising with bedrock boulder sand, rapids, cascades and deep pools. The distribution of fishes is greatly affected by the slope, flow rate, types of substrata, and availability of food. According to some old reports, these water resources harbor 268 fish species belonging to 76 genera and 21 families in the country of which 203 are recorded from the Himalayas and 91 from the Deccan Plateau (Sehgal 1999).

Variation in Himalayan altitudes is greater in the eastern than in the western part. Such variations might have established greater ichthyodiversity toward the east than the west (Menon 1962). According to an updated study of fish diversity and distribution in the Indian Himalayan landscape, roughly 316 fish species with valid names are found in the Indian Himalayan freshwater ecosystems/ habitats (Chandra et al. 2018). Thirteen invasive species have been identified in the Himalayan landscape waters, some of which have become established. There are 118 recognized genera and 38 families in the fish fauna, which are divided into 13 orders (Gopi et al. 2018). Ninety-seven of the 316 species found in this area are native to the Indian Himalayan freshwater systems. The fish variety known from the region accounts for roughly 30.8% of India's total freshwater fish species (1027), 62.8% of total genera (188), and 18.6% of the total endemic species (522) (Gopi et al. 2017).

The headwater zone is dwelled by species of loaches (e.g., *Nemacheilus stolickai* and *N. gracilis*) and catfishes (e.g., *Glyptosternum reticulatum*, which are rheophilic in nature). Further, where the headwater streams join, the large stream zones are formed which are inhabited by species like *Nemacheilus* spp. and *Diptychus maculatus*. The upper and intermediate stretches of this zone are inhabited by different rheophilic species of snow trouts. The slow-moving meandering zone is inhabited by fish species like snakeheads, homalopterid fishes (*Homaloptera* spp.), catfishes, mahseers, and *Barilius* spp. (Petr and Swar 2002).

The order "Cypriniformes" makes up the major ichthyodiversity in the Himalayan waters, accounting for around 54.7% of all species (173 species). There are 92 species of catfish (Siluriformes) identified from this region (29.1%). Cyprinidae, with 111 species, is the most species-rich family, followed by Nemacheilidae (42 species), which together account for 35.1% and 13.3% of the ichthyodiversity recorded from the Indian Himalayan region (Gopi et al. 2018). Snow trouts belong to family Cyprinidae, subfamily Schizothoracine. Seven genera and 15 species of snow trout are found in the sub-Himalayan regions of India. Two major genera of snow trout are *Schizothorax* and *Schizothoraichthys*. Due to declining catch of snow trout in different rivers and streams, IUCN has listed them as vulnerable species. Most common species found in India are *Schizothorax richardsonii*, *S. kumaonensis*, *S. niger*, *S. esocinus*, *S. progastus*, *Shizopyge curvifrons* and *Diptychus maculatus*. In Ladakh streams, five species of snow trout, *D. maculatus*, *Schizopygopsis stolickai*, *Schizothorax labiatus*, *Schizothorax richardsonii*, and *Ptychobarbus conirostris*, are found (Gopi et al. 2018). In Himachal Pradesh, the most dominant species is *S. richardsonii*. In northeast, the Himalayan streams are dominated by snow trouts, such as *S. richardsonii*, *S. esocinus*, and *S. progastus*. *S. richardsonii* and *S. plagiostomus* were found to be the dominant species in the Kameng drainage, whereas *S. progastus* and *S. richardsonii* dominated in the Siang drainage of Arunachal Pradesh. Maximum species of *Schizothorax* spp. and *Schizothoraichthys* are endemic to Kashmir and Ladakh. *Schizothorax progastus* is mainly found in the eastern part of the Himalayas. *Schizothorax richardsonii* is the most dominant species and found almost all along the Himalayas. Maximum species of snow trout prefers lacustrine habitat.

The family Sisoridae is the most diverse among catfishes, with 41 species accounting for 13.0% of the region's total fish diversity, followed by Bagridae and Erethistidae (15 species each). The family Cyprinidae (Cypriniformes) has the highest generic abundance (40) in the Himalayan freshwater systems, accounting for 33.9% of all fish genera. Twelve genera (10.2%) of the fish genera recorded in the region belong to the Sisoridae (Siluriformes) family.

Only seven families out of 38 exhibit a species diversity of ten species or more in family-specific dominance. They are classified into the following orders: Cyprinidae (111 species), Nemacheilidae (42 species), Sisoridae (41 species), Bagridae (15 species), Erethistidae (15 species), Cobitidae (13 species), and Channidae (10 species); and they account for approximately 78.2% of the total fish species. Four families have 2 species in 1 or 2 genera, whereas 15 families have 1 genus with 1 species each. There are 46 species in 21 families with only 1 genus each, among which the Channidae family has the most species (10 species), followed by Badidae (7 species), and Psilorhynchidae (5 species). Each family has an average of >8 species diversity of fishes known from the Indian Himalaya (Gopi et al. 2018).

Comparing all the genera, the genus *Glyptothorax* of family sisoridae is the most diverse genera with 20 species, followed by genus *Garra* of family cyprinidae also with 20 species. The genus *Schizothorax* (12 species), genus *Barilius* (8 species), genus *Psilorynchus* (5 species) of cyprinidae family, and genus *Triplophysa* (10 species), genus *Aborichthys* (7 species) of Nemacheilidae family are the other genera with diverse species. The genera *Pseudolaguvia* (7 species) (Erethistidae family), *Mystus* (5 species) (Bagridae family) in order Siluriformes, and the *Badis* (7 species) (Badidae family) and *Channa* (6 species) (Channidae family) in order Perciformes are also species-rich groupings in India's Himalayan freshwater systems. There are more than two species under each genus on an average. In comparison with the west, the Indian Himalayan fishes have a greater diversity in the east. Fishes of the genus *Aborichthys*, *Erethistoides*, *Olyra*, and others can be found in the Brahmaputra drainage system and are not found elsewhere in the Himalayas.

The genera *Semiplotus* and *Balitora* are found up to the Gandak drainage system, whereas *Pseudecheneis* and *Neolissochilus* are found up to the Kosi drainage system. The genus *Psilorhynchus* is widely distributed, extending all the way to the Jumna. *Schizothorax*, *Schistura*, *Paracanthocobitis*, *Indotriplophysa*, *Glyptothorax*, *Garra*, *Gagata*, *Botia*, *Bagarius*, *Amblyceps*, and other genera are found throughout the Himalayan region. Even beyond the Himalayas, genera like *Silurus*, *Schizothorax*, *Schizopygopsis*, *Schizopyge*, *Triplophysa*, *Indotriplophysa*, *Glyptothorax*, and *Garra* can be found. The western Himalayas lack certain fish species found in the Assam hill streams and the Brahmaputra drainage. In Myanmar, Southern China, and Southeast Asia, the same genera or closely related forms are found at the same time (Malay Peninsula).

2.3 Major Fisheries in the Himalayas

Fishes are not only source of high-quality protein, but they are also used for recreational purposes or sport fisheries. The beauty of fish makes them attractive and provides the ornamental value to it. The different fishes of Himalayas fall in two main categories: (1) subsistence fishery and (2) recreational fishery. The exotic species which were introduced in water bodies were mainly for the recreational purpose. The overall fish production in Himalayan streams remains low due to particular environmental condition, so commercial fishery is very limited. Low temperature causes low metabolic activities which result in low biological productivity and small size, while in few lentic waters bodies, large sizes also exist. There are few fishing methods which are commonly used in mountain streams such as cast net, drag net, stake net, bag net, noose trap, and harpoons. Tough terrain of the Himalayas and absence of standardized fishing crafts and gears to operate in cold-water streams are mainly responsible for the same.

The upstream part of the reservoir mainly comes under cold-water, while near the dam, comparatively higher temperatures exist due to stagnant water. To allow the smooth passage of fishes across the dam or avoid hindrance in the migration of fishes, installation of fish passes facilitates this migration.

The fishes which inhabit the Himalayan rivers are rheophilic in nature which prefer and thrive well in the fast-flowing water. Menon (1954) reported that the different morphological characteristics of fishes enable them to inhabit the torrential streams. Water temperature plays significant role in distribution of fishes, such as exotic trout and the endemic Schizothoracines. These fishes can only tolerate temperature below 20°C and fall in the category of cold stenothermic species. In order to cope up with the change in temperature, fishes migrate across upstream and downstream. The cylindrical body shape of fishes enhances the swimming capacity as in snow trout. Loaches possess adhesive organs on the ventral surfaces for attaching themselves to the rock. Adhesive organs also vary among the different species based on requirement. *Schizothorax* spp. which belong to the subfamily Schizothoracine under family Cyprinidae is prime/predominant group of fishes, followed by mahseer which is one of the important sport fishes. Major fisheries of the Himalayas are comprised of (1) snow trout (*Schizothorax* and S*chizothoraichthys*), (2) mahseer (*Tor* and *Neolissochilus*), (3) loaches (*Nemacheilus*), (4) garrids (*Garra*), (5) barils (*Barilius*), (6) carps, and (7) exotic species (*Oncorhynchus* sp.). Other fish species, such as *Bagarius bagarius*, *Chagunius chagunio*, *Clupisoma garua*, and *Puntius* (*Barbus*) *chilinoides*, also have a promising future from a fisheries perspective in addition to the ones mentioned above.

2.3.1 Snow Trout Fisheries

The capture fisheries in cold-water is mainly based on schizothoracines. Two major genera of snow trouts are *Schizothorax* and *Schizothoraichthys*. Due to declining catch of snow trout in different rivers and streams, the IUCN has listed them in Vulnerable species. Most common species found in India are *S. richardsonii*, *S. kumaonensis*, *S. niger*, *S. esocinus*, *S. progastus*, *Shizopyge curvifrons* and *Diptychus maculatus.* Twenty-eight species of snow trouts have been recorded in the Himalayan region of which 15 have been reported from Indian sub-Himalayan region. It is considered a delicacy among the various local populace. Only subsistence or artisanal methods of fishing are used for capturing these fishes. Snow trouts are commercially important food species found in upland area. Snow trout is mainly found in numerous snow-fed and glacier-fed streams, lakes, and spring. Most cold-water lakes are perennial which contain water throughout the year, and some are seasonal which contain water only during the rainy season or particular months. Snow trouts live in just a discrete way on stretch of stream of hilly regions. They require low temperature, clear water, ample of food, places to hide from predators, and clean pebbles to lay their eggs. Snow trouts cannot survive in polluted water as their physiology gets affected. Increased tourism in hilly region has affected the population of snow trout and more or less exotic carp has replaced this native fish Region spreading between 21°57′–37°5′ N latitudes and 72°40′–97°25′ E covering 250–300 km on stretches over 2500 km from Jammu and Kashmir to Arunachal Pradesh. Snow trout is found in almost 12 states of India, including Arunachal Pradesh, Himachal Pradesh, Jammu and Kashmir, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura, Uttarakhand, and hills of Assam and West Bengal in mountain regions. It does not form the fisheries of commercial importance but is caught by local fishermen mainly in rivers. Presently, farming of native species of snow trout is not very successful in hilly regions, but cultivable traits have been identified in few species.

The following is a list of 15 snow trout species recorded from Indian Himalayan region:

Genus *Diptychus* Steindachner, 1866
- *D. maculatus* Steindachner, 1866

Genus *Schizopyge* Heckel, 1847
- *S. curvifrons* Heckel, 1838

Genus *Schizopygopsis* Steindachner, 1866
- *S. stolickai* Steindachner, 1866

Genus *Schizothorax* Heckel, 1838
- *S. niger* Heckel, 1838
- *S. esocinus* Heckel, 1838
- *S. huegelii* Heckel, 1838
- *S. intermedius* McClelland and Griffith, 1842
- *S. kumaonensis* Menon, 1971
- *S. labiatus* McClelland, 1842
- *S. microcephalus* Day, 1877
- *S. molesworthi* Chaudhuri, 1913
- *S. nasus* Heckel, 1838
- *S. plagiostomus* Heckel, 1838

S. progastus McClelland, 1839
S. richardsonii Gray, 1832

2.3.2 Mahseer Fisheries

Mahseer is a large-bodied potamodromous freshwater fish with substantial economic and recreational value. It is considered indigenous to Asian rivers. As it is the most tenacious combatant among freshwater sport fish and is consequently regarded as the indisputable king of Indian freshwaters, the mahseer is the most sought-after game fish among anglers in India. The existence of such a mighty game fish in Indian water is depicted in the writings of King Someswara (1127 AD) in Vedic times in his Matsya Vinoda on account of the angling of mahseer with rod and line. As per different resources presently, there are 47 valid species of mahseer around the world belonging to the genera *Tor*, *Naziritor*, and *Neolissochilus* (Nautiyal et al. 2013). In India, 14 valid species of mahseer have been recorded among which *T. putitora* (Hamilton, 1822) (golden mahseer), *T. tor* (Hamilton, 1822) (tor barb), *T. khudree* (Sykes, 1839) (the Deccan or Yellow mahseer), *N. hexagonolepis* (McClelland, 1839) (the Copper mahseer), and *N. chelynoides* (McClelland, 1839) (Black mahseer) are the most common species. *T. putitora*, known as golden mahseer in India, is a significant sport fish. When the southwest monsoon precipitation causes streams to swell, that is when it migrates from the lower reaches of the river to the middle ones to spawn. This species has suffered significant poaching, and dams and weirs that have prevented fish movement have caused more harm. Deforestation of mountains has increased soil erosion, which has resulted in high siltation of streams and rivers, compromising the fundamental biological requirements of this species. The copper mahseer, *N. hexagonolepis*, is a valuable food and sport fish.

If the tourism industry is developed to the expected level, starting with identifying the potential areas, followed by the formulation of effective policies and guidelines for entrepreneurship development, and supported by ancillary services, India has tremendous potential for mahseer recreational fisheries in many states. The country's ecotourism industry focused on fishing, and fish watching has both beneficial indirect and direct effects on mahseer conservation. Mahseer, in this sense, has been designated as the "state fish" in many (7) states of India and possesses all the necessary characteristics to be designated as the "national freshwater fish" for its spectacular color, fighting prowess, and size.

The following are valid *Tor* species found in India (Nautiyal et al. 2013):

1. *Tor putitora* (Hamilton, 1822)
2. *Tor tor* (Hamilton, 1822) Tor barb
3. *Tor khudree* (Sykes, 1839) The Deccan or yellow mahseer
4. *Tor progenius* (McClelland, 1839) The Jungha mahseer
5. *Tor kulkarnii* (Menon, 1992)

6. *Tor barakae* (Arunkumar and Basudha, 2003)
7. *Tor macrolepis* (Heckel, 1838)
8. *Tor remadevii* (Madhusoodana Kurup and Radhakrishnan, 2011)
9. *Neolissochilus hexagonolepis* (McClelland, 1839) The copper mahseer
10. *Naziritor chelynoides* (McClelland, 1839)
11. *Neolissochilus hexastichus* (McClelland, 1839)
12. *Neolissochilus dukai* (Day, 1878)
13. *Neolissochilus spinulosus* (McClelland, 1845)
14. *Neolissochilus wynaadensis* (Barbados) (Day, 1873)

2.3.3 Loach Fisheries

The fish superfamily Cobitoidea includes loaches. They are freshwater fish that live in rivers and creeks all over Eurasia and northern Africa. They are benthic (bottom-dwelling) (Kottelat 2012). Loaches are one of the most varied groups of fish, and the 1249 species of Cobitoidea that are now recognized belong to around 107 genera and nine families (Fricke et al. 2022; Nelson et al. 2016). Some loaches are important food fish, especially in East and Southeast Asia, where they are a common sight in markets.

In the aquarium industry, loaches are very common. The clown loach (*Chromobotia macracanthus*), the kuhli loach (*Pangio kuhlii*), and the dwarf chain loach are a few of the more well-known types (*Ambastaia sidthimunki*). Additionally, gastromyzontid and botiid loaches occasionally enter the market (Ng and Tan 1997). Only the Cobitidae family of loaches had been described at the start of the twentieth century, and it was largely acknowledged by taxonomists. The early 1900s saw the discovery of the Balitoridae and Gastromyzontidae by the American ichthyologist Fowler and the Indian ichthyologist Hora. Up until 2002, Nemacheilidae and later Botiidae were classified as subfamilies of the Cobitidae family (Fowler 1905; Hora 1932). Recent reports suggest a record of at least 57 species of loaches, belonging to 14 genera and 3 families (Cobitidae, Balitoridae, Nemacheilidae) from the Indian Himalayan region. Out of 57 species, 24 are endemic to India (Gopi et al. 2018).

2.3.4 Garrid Fisheries

Garra is a genus of fish in the family Cyprinidae. These fishes are inhabitants of rivers, lakes, small ponds, and small muddy streams in hilly or mountainous regions. The fishes are example of the sucker-mouthed barbs, log suckers, and other cyprinids, commonly kept in aquaria to control algae. Cylindrical body; slightly depressed head; heavily tuberculated or tubercleless blunt snout; inferior mouth; semicircular, thick, and fleshy lips; fimbriated upper lip; lower jaw covered by thick labial fold; and lower lip with a mental adhesive disc consisting of semicartilaginous pad are some of the important characteristics of these fishes. The garrids hide under and among stones and vegetation and are bottom dwellers, feeding on aufwuchs. The garrids are widely distributed from sub-Saharan Africa to Borneo through the Arabian Peninsula, Southern Asia, and Southern China (Zhang and Chen 2002). More than 200 species of this group have been reported worldwide (Yu et al. 2016), and more than 31 species have been recognized from NE India (Roni and Vishwanath 2018).

2.3.5 Baril Fisheries

Indian hill trout, also known as *Barilius bendelisis* (Hamilton), is an important fish under the genus *Barilius*. It is a member of the family Cyprinidae, subfamily Danioninae, and it lives in shallow, chilly, and clear water (Gurung et al. 2005). Its pointed head, compressed body, blue/black vertical bands on the side of the body, and origin of the dorsal fin inserted behind the midsection of the body are distinguishing features (Talwar and Jhingran 1991). This fish is an upland water fish that can be found in a number of Southeast Asian nations, including India, Bangladesh, Nepal, Myanmar, Pakistan, Thailand, and Sri Lanka (Talwar and Jhingran 1991; Fricke et al. 2022). This species is widely found in India throughout the Himalayan foothills in the Ganga and Brahmaputra drainages. *Barilius bendelisis* inhabits both lentic and lotic water bodies which are not quite suitable for subsistence of other carp species, playing a significant role in the capture fisheries of the Himalayan regions of Arunachal Pradesh (Sahoo et al. 2009).

2.3.6 Carp Fisheries

Indian major carps and exotic carps make up the majority of the carp species, caught in the Himalayas. However, from an Indian perspective, the fishery also includes species of the subfamily Cyprininae that live in streams, lakes, and rivers that get snowfall water.

Rohu (*Labeo rohita*) is the most well-known main carp in the highlands in India. Common carps, silver carps, and grass carps are examples of exotic carps. The primary source of these carps is cultured fisheries. The rohu is a sizable, silvery fish with a prominently arched head and a classic cyprinid form. A large portion of northern, central, and eastern India's rivers contain rohu. The species is omnivorous and exhibits distinct feeding preferences at various life stages. It consumes mostly zooplankton in the beginning of its life cycle, but as it grows, it consumes an increasing amount of phytoplankton. As an adult or juvenile, it is an herbivorous column feeder that consumes primarily phytoplankton and submerged vegetation. It appears to feed by sieving the water based on the modification of its thin, hairlike gill rakers. *Cyprinus carpio*, the common carp, is a native of Asia and Eastern Europe. To increase the fish supply, common carp were introduced to Kashmir in 1959. Since that time, this fish has gained significant commercial importance in Kashmir Valley. Additionally, it dominates wetlands found on the Jhelum River floodplain. *C. carpio* *var. specularis*, *C. carpio var. communis*, and *C. carpio var. nudus* are the three different types of common carp. They are frequently regarded as invasive species since they have entered aquatic environments legally or occasionally illegally all over the world. Although common carps like huge quantities of sluggish or standing water and soft, vegetative sediments, they are exceedingly resilient and can easily adapt to most environments. Though larger carp may live alone, they are typically found in small schools. Their natural habitat consists of fresh or brackish water with a pH range of 7.0–9.0 and a temperature range of 5.0–35.0 °C. The common carp is a fish that may be eaten and is very well-liked by anglers. *Hypophthalmichthys molitrix*, commonly known as silver carp, was introduced into Indian waters from China. Among both native and foreign fish, it grows the quickest. It is a plankton-eating fish that is not predatory. The grass carp (*Ctenopharyngodon idella*) is a native resident of Chinese waters. This fish was brought to India from Hong Kong for the first time in 1959 and is now widely distributed throughout the nation. It grows well and is a nice fish that Indians enjoy. They consume up to three times as much food as they do every day. Small lakes and backwaters with an abundance of freshwater flora are ideal for them. Aquatic vegetation are the main source of food for the species' adults. They consume higher aquatic plants and submerged terrestrial flora as well as debris, insects, and other small invertebrates.

In the mid-hill region, there is a lot of room for exploiting local fish species for aquaculture. The following species could be candidates for mid-hill aquaculture in India: *Chagunius* spp., *Cirrhinus reba*, *Labeo pangusia*, *L. dyocheilus*, and *L. dero*, including endemic minor carp, pengba, and *Osteobrama belangeri*.

2.3.7 Exotic Species

Mitchell introduced the first species of exotic trout into the waterways of the Indian Himalayan region in 1900. The western Himalayas were introduced to common carps in 1959. Silver carps were unintentionally introduced in this area in 1971. Biologically, silver carps appear to have an edge over Indian major carp. Approximately 14 foreign fish species have been introduced, according to some fringe literature, into the IHR. The important exotic fish species of the region are *Carassius auratus*, *C. carassius*, *Ctenopharyngodon idella*, *Cyprinus carpio communis*, *C. carpio nudus*, *C. carpio specularis*, *Gambusia holbrooki*, *G. affinis*, *Hypophthalmichthys molitrix*, *H. nobilis*, *Oncorhynchus mykiss*, *Osphronemus goramy*, *Salmo trutta fario*.

Brown trout (*Salmo trutta fario*) and rainbow trout (*Oncorhynchus mykiss*) were introduced to the Indian subcontinent from Europe largely to promote sport fishing or leisure angling. It is necessary to create and scale up brown trout breeding and culture technology for the ecological conditions of the Himalayas. It is a viable ecotourism candidate species.

In the Indian Himalayan regions, rainbow trout, *O. mykiss*, has established itself as a top cultivable cold-water species and is currently raised commercially. There have been independent attempts to introduce rainbow trout to India's northwestern and peninsular regions. The largest trout farming operation in Asia was started in 1984 with the help of the EEC (European Economic Council) at Kokernag, in the Indian state of J&K. In Himachal, trout farming began in 1991 with help from Norway (Indo-Norwegian project). Rainbow trout farming on a commercial scale began in the early 1990s on various fish farms in India's Himalayan area. Presently, there is a well-established farm with modern RAS (Recirculatory Aquaculture System) facility and state of the art hatchery facility at ICAR-Directorate of Coldwater Fisheries Research, Champawat, which maintains quality brooders and produces quality seeds of Rainbow trout to cater to the needs of the sector. Indian trout production continues to be centered in the Northwestern Himalayan region (Jammu and Kashmir and Himachal Pradesh). Majority of India's trout output comes from the northwest (81.2%), with very modest amounts coming from the northeastern, central, and southern highland regions. India now produces 602.0 tons of rainbow trout annually, up from just 147.0 tons in 2004 (309% increase). During this time, the growth rate of trout output maintained 31.0% annually. Over the same time frame, the total number of ova produced increased from 1.8 to 10.17 million (450% increase) (Pandey and Ali 2015).

2.4 Concerns

Overfishing of stock has resulted in overexploitation of different stocks and is posing threat of extinction of few species. There are mainly two types of overfishing: (1) growth overfishing and (2) recruitment overfishing. Destructive fishing methods which most likely include the usage of poison and explosives to stun the fishes are practiced in few Himalayan rivers especially in higher altitude. Usage of destructive fishing methods results in indiscriminate killing of different species and different sizes of fish, have also harmed the fishery resources significantly. Catchment area management is very important for maintaining the quality of water in resources like rivers, reservoirs and lakes. Agricultural practices in the catchment cause the entry of different inorganic and organic compound which consequently deteriorates the environmental condition for fishes. Fish stocks have been impacted by the increasing use of river water for a variety of purposes, including irrigation, hydropower generation, urban and industrial uses, and the input of pollutants (Petr and Swar 2002). The fast-flowing water of Himalayan rivers (lotic) does not allow the aquatic vegetation and bloom to cause a problem, such as in lentic water bodies like lake, in which the macro- and microscopic plant grows immensely and decreases the depth on deposition at bottom. The size of Wular Lake and Dal Lake of Jammu and Kashmir has been reduced significantly due to eutrophication. The nutrient requirement responsible for proliferation of plant is fulfilled by the runoff from agricultural land and other anthropogenic activities. Hailstorm and sediment load also result in fish kill in the rivers. Heavy tourism exists on the few lakes and reservoir which also causes the introduction of pollutants in the water bodies. Dams block rivers, preventing fish and other aquatic animals from migrating. This isolation of ecosystems has an impact on the genetic makeup of populations. Additionally, it causes a patchy area and poor conditions for the mahseer or other fishes downstream of the dam due to the low water level that develops. The runoff of hot water from the dam helps in providing the favorable condition for fish growth, or sometimes increased temperature of water put detrimental effects on fishes by putting impact on their physiology. Species like *Schizothorax*, *Ptychobarbus* and *Gymnocypris* are unusual and more prone to extinction. It is also evident that indigenous species like *Schizothorax* and mahseer may suffer if common carp is introduced in pristine streams or water sources.

2.5 Management

If fisheries are to become a more dynamic source of food in the area and fully contribute to the reduction of poverty in mountain nations, there must be a better integration of fisheries development within the overall ecosystem and rural development approach, taking into full consideration the ecological, social, and economic values of fisheries in relation to biodiversity conservation, agriculture, and hydroelectric power generation. Traditional fishing methods which do not harm the ecosystem and are selective in nature should be encouraged. Noose and line is one such gear used for capturing snow trout. Fish aggregating devices (FAD) is a man-made object used to attract fish. FADs attract fish for numerous reasons that vary by specie and help in making the harvest of fish more efficient and responsible. Ranching by which artificial recruitment of different fish species into their natural habitat has helped in improvement and enhancement of production as well as in conservation of stock. The waste produced by anthropogenic activities should be managed properly to avoid its detrimental effects on water resources and its biodiversity.

2.6 Conclusion

The Himalayas has a larger number of rivers, streams, and lakes fed by copious rainfall, large glaciers, and extensive snow fields. The variation in Himalayan altitudes is greater in the eastern half than in the western half. Such variations might have established greater ichthyodiversity toward the east than the west. The rich diversity of the Himalayas is facing threat for their existence due to various concerns, such as overfishing, illegal trades, anthropogenic activities, and competition from introduced exotic species. Species diversification for aquaculture and proper conservation measures for vulnerable and threatened species are of prime concern today.

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3

Mapping of the Himalayan Surface Waters Using Remote Sensing and Geographic Information System Tools: An Overview of Single Band-Based Techniques

Parvaiz Ahmad Ganie, Ravindra Posti, and Kishor Kunal

Abstract

Remote sensing satellite or airborne sensor-captured multispectral and hyperspectral images offer a wealth of data that can be used to examine and evaluate items of interest on the surface of the Earth and their attributes. Researchers have been looking into the possibility of remotely sensed photographs for examining natural resources like water for a long time. The scientific community has shown great interest in these studies because water is a precious natural resource that needs to be conserved. An efficient system can be developed to study the quantitative and qualitative changes, occurring to surface water bodies over a period of time, by using appropriate digital image processing techniques on images taken from remote sensing satellites or airborne sensors. A crucial and necessary step in these studies is the detection and mapping of surface water, and various automated and semiautomated techniques have been developed over time for mapping water in remotely sensed images. In this chapter, single band-based methods employed for surface water extraction from remotely sensed images have been discussed, along with a few case studies.

Keywords

Remote sensing · Multispectral image · Hyperspectral image · Surface water delineation · Geographical data processing · Geographic information system · Resource mapping

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3.1 Introduction

Rapid advancements in computing, information systems, and the digital world have made it possible to collect and utilize data about the physical and cultural worlds for investigation and problem-solving. In many aspects of geographical data processing, modern technology has improved the use of computers and information technology in place of human approaches. These information systems store data about real-world events in analog or digital form, and they can create, change, store, and use geographical data much faster and more efficiently than previous systems. Data becomes increasingly important and valuable as we progress from data to information to knowledge. Geographic information systems (GIS) may store several types of data in digital format. This can speed up the process and make it easier to change the analytical strategy. It can be described as a tool that assists in decision-making. Although creating maps and conducting geographic studies is not new, a GIS accomplishes it more efficiently and quickly than earlier manual methods.

Water resources are essential to humans, the environment, ecology, and climate. The shrinking number of freshwater resources, which account for only around 3% of the total water on the Earth, is the main concern today. A significant group of freshwater resources, such as lakes, canals, streams, ponds, and reservoirs, are surface water resources (Sekertekin et al. 2018a, b). Changes in temperature, land use/land cover (LULC), and other biological factors cause surface waters to fluctuate through time and space in various parts of the world (Palmer et al. 2015). As a result, studying surface waters has piqued interest around the world. Furthermore, changes in these resources throughout time significantly impact the quality of life. If variations in surface water supplies reach large levels, environmental problems such as flooding and droughts might often occur in specific climatological locales. As a result, reliable and timely information on surface water supplies is crucial for environmental and ecological sustainability (Zhang et al. 2018). Thanks to advancements in remote sensing technologies, variations in Earth resources can be successfully monitored and regulated (Sekertekin et al. 2018a, b). Remotely sensed images are frequently used in oceanic, terrestrial, and atmospheric applications for environmental modeling and monitoring, LULC analysis, information extraction, and updating geographical databases (Tso and Mather 2009).

Traditional surveying and mapping methods can provide exact surface water resources, but they have downsides, such as being expensive, time-consuming, and difficult to repeat. Remote sensing technologies are now being employed to give precise and consistent observations for mapping surface water bodies, making the work of mapping surface water bodies easier and faster than before (Huang et al. 2018). Since digital image processing techniques provide access, analysis, and evaluation of the wealth of information, contained in images received from remote sensing satellites or airborne sensors, numerous straightforward and efficient water mapping methods have been presented and refined throughout time (Zhang et al. 2018). Multispectral and hyperspectral images are two forms of remote sensing photographs that are extensively used in mapping geographical features (Harsanyi and Chang 1994; Frazier and Page 2000; Yao et al. 2015; Sun et al. 2012; Feyisa et al. 2014; Olthof 2017). The image is obtained as a function of wavelength in multispectral imaging, which combines digital imaging with spectroscopy. This can be used to find and analyze minerals, oil, and water by revealing their spectra at each pixel. The spectrum information of a scene can be analyzed and understood with the help of multispectral imaging (Sun et al. 2012). Images like this can reveal details about a scenario that aren't immediately obvious to the naked eye. Spectral images of most objects can be used to identify and analyze the object in question since they leave a unique fingerprint. One other name for these identifiers is spectral signatures. This is because each of these atoms or compounds leaves a distinctive fingerprint on the electromagnetic spectrum, making detection and analysis straightforward. For the most part, multispectral images are stored as three-dimensional data cubes with the coordinates (x, y, z), where the first two coordinates refer to the physical position of the image and the third to its spectral composition (Chakrabarti and Zickler 2011; Hagen and Kudenov 2013). High-tech spectrometers typically take such pictures in the air or satellites equipped with such equipment. Because water has its unique spectral signature in the electromagnetic spectrum, multispectral images can be used to learn more about bodies of water.

Pure water and turbid water have quite different spectral signatures; thus, we may use this to determine whether or not a body of water consists of clean water. Recent operational satellites have the spectral range, required for water mapping, including the visible, near-infrared, and shortwave infrared (Doxaran et al. 2002). Different types of remotely sensed data, and multispectral or hyperspectral imaging, can be used to map water (Hess et al. 1990; Townsend 2002; Brisco et al. 2008; White et al. 2011, 2014). One sort of data that has been widely used in water mapping studies is digital elevation models (DEMs) (Jung et al. 2010; Zhu et al. 2019; Chymyrov 2021). DEMs have been found to be particularly helpful in locating bodies of surface water because of the elevation data they offer. Combining data from several sensors has led to the development of systems that take advantage of both sensors' benefits. Water on the surface is a valuable resource that must be maintained for future generations. New algorithms are developed every year when new remote sensing satellites are launched. The advanced and recently developed remote sensing and GIS approaches for mapping water bodies using satellite imagery are discussed in this chapter.

3.2 Techniques for Extraction of Surface Waters Using Satellite Images

In recent years, researchers have been able to unearth data hidden in remote sensing images because too many of advancements in digital image processing techniques. For the detection and mapping of surface water with low cost, less time, and less effort, many approaches and algorithms centered on digital image processing on remote sensing data have been developed in recent years (Bijeesh and Narasimhamurthy 2020). As no approach or methodology is discovered to be suitable for all datasets and all conditions, surface water mapping is still a subject of active research. The majority of the created procedures are based on the case studies of a particular location, and it was not advisable to adapt these approaches globally.

In the subsequent sections, single band-based methods (rely on a single band for detecting and delineating water bodies) are discussed in detail.

3.2.1 Single Band-Based Techniques/Methods

Surface water delineation methods that use only one frequency band have become increasingly popular because of their simplicity and the fact that they are as accurate as the vast majority of multiband methods. The most critical step in single-band water detection methods is selecting the most relevant band from the bands included in the remote sensing image. The spectra of the objects, being studied, are used to pick the optimal bands for density slicing. It has been demonstrated that the near-infrared (NIR) area of the electromagnetic spectrum is the most suited frequency band for detecting masses of water. This is because nearly all NIR radiation is absorbed by water, causing it to look dark in NIR images. Water bodies can be detected and delineated by simply slicing or thresholding of the pixel values' digital integers. Since the NIR band is accessible by most multispectral and hyperspectral imaging sensors, it is straightforward to develop NIR band-based water identification and delineation algorithms. The Landsat series is the most prevalent source of data for single band-based approaches. Band 5 of the NIR area of the Landsat TM image was determined to be the optimal band for developing a density slicing-based method (Duy 2015). It has been discovered that the single-band density slicing (SBDS) technique is nearly as accurate as more complex procedures such as classification. Many researchers choose SBDS because it is straightforward to execute and yields results in comparison with those of more complex techniques. By employing density slicing of Landsat MSS band 7, Bennett (1987) created a map of the region's water features. After contrasting MSS-derived water body extents with those of digitally captured aerial photos, he found that the former consistently overestimated the volume of water by roughly 40%. Johnston and Barson (1993) investigated the feasibility of using Landsat TM data to evaluate the distribution of lake land ponds and riverine wetlands in western and central Victoria, respectively. A 95% classification accuracy was found for lake pond wetland areas using only basic TM5 (mid-infrared) density slicing, whereas riverine wetland areas were poorly mapped. Oxbow lakes' narrow breadth and too little time for data selection were cited as reasons for the method's failure in riverine wetlands.

The surface water bodies in the research area were successfully mapped by Frazier and Page (2000), using a combination of Landsat TM data, image processing, and machine learning. Specifically, the study demonstrated that the single-band density slicing method, which is both easier and less time-consuming, achieves an accuracy of 96.9%, which is very close to the accuracy achieved by maximum likelihood classification (97.4%). The study also concluded that Landsat TM multispectral pictures benefitted most from using infrared bands, particularly band 5, for water delineation, as compared to the visible spectrum. Data from various Landsat sensors has been valuable for studies aiming to define the boundaries of water bodies at the ground's surface. The NIR band in Landsat data has been found to be the best band for water detection from multispectral pictures, and its availability in the public domain is another benefit of using Landsat data for surface water detection and delineation (Shrestha and Di 2013).

Shadows, cast by mountains and clouds, are the most typical causes of inaccurate categorization. The same can be rectified by incorporating DEMs (digital elevation models) with multispectral/hyperspectral data, leading to enhanced classification accuracy. Elevation data for a landscape or other surface can be found in a DEM, which is often presented in the form of a raster or vector image. Manual surveying is sometimes used; however, remote sensing is typically the method of choice when creating DEMs. DEMs are frequently generated using interferometric synthetic aperture radars like RADARSAT and TerraSAR-X. The recognition and differentiation of water features using SAR data alone have been facilitated by algorithms based on a single band. With this in mind, Verpoorter et al. (2012) developed a method to overcome the challenge posed by the shadows cast by clouds and mountains when extracting surface waters from satellite images. The GeoCover Water Bodies Extraction Method (GWEM) was created. The authors present a six-stage method for water extraction that integrates various methods of classification to improve precision. This method used elevation data to identify shadows, and it removed water surfaces that overlapped with those shadows from the classification set.

Some of the most popular single band-based surface water identification and delineation algorithms are as follows:

3.2.1.1 Thresholding Techniques: Intensity- and Histogram-Based and Density Slicing

Several image processing applications classify pixels into multiple groups using an intensity-based thresholding technique. Pixels can be classified as water or non-water by limiting to the digital values in the image's appropriate bands, as water entities have a unique spectral signature. The most important part of any thresholding-based algorithm is choosing a suitable threshold value, which may vary depending on the context. The threshold determines whether a pixel is considered to be water or not, and from there a value is assigned to that pixel in digital form. Although early research relied on human judgment to set thresholds for images of varying intensities, several methods have since been developed to determine suitable threshold values automatically.

For example, Bolanos et al. (2016) used worldview imagery (50 cm) to collect data on surface waters in their study area. To automatically capture the most uniform water areas and delineate their boundaries, a threshold-based method has been developed for extracting surface water polygons from SAR data, such as non-vegetated water bodies. Both the wide fine scene and the fine quad scene were used for this project. It was found that wide fine scene was effective for extracting medium-sized bodies of water, while a fine quad scene was superior for huge water bodies. They found that their method significantly reduced processing time compared to more involved segmentation techniques. Whenever noisy results are predicted due to the presence of shadows and built-up surfaces, Feyisa et al. (2014) have created a new technique that does not require an additional dataset to suppress shadow pixels or distinct shadow detection methods in those locations. The automated water extraction index (AWEI) approach was created using Landsat 5 TM images. Classifiers, based on machine learning (ML) and the modified normalized difference water index (MNDWI), were compared to it in terms of accuracy and threshold stability at the per-pixel and sub-pixel levels. In areas where shadows and other dark surfaces were the predominant causes of classification mistakes, AWEI significantly improved precision. The AWEI classifier outperformed MNDWI and ML in terms of accuracy when classifying edge pixels, as determined by a study of inaccuracy at the boundary of water bodies at the sub-pixel level. Furthermore, it was revealed that the optimal threshold of AWEI was more stable than that of MNDWI across photos obtained at different times and locations. High accuracy in identifying edge pixels and a stable threshold led the scientists to conclude that their method would be useful in studying the surface water dynamics.

These methods make use of algorithms like Otsu's algorithm and variants thereof. These strategies are based on the histogram of the image and the assumption that there are two types of pixels in it. Using the image histogram, the Otsu approach seeks a threshold that minimizes intra-class variation. Otsu's method is the most widely used approach for surface water identification research utilizing remote sensing images, yet it is not the only histogram-based thresholding algorithm available. Some multiband classification methods use Otsu's thresholding to improve classification accuracy. Duy (2015) applied thresholding to Sentinel-1 SAR images in order to detect autonomous surface water using a modified version of Otsu's method. For images with a unimodel or nearly unimodel histogram, this modified Otsu technique, also known as the valley-emphasis algorithm, was created to address the limitations of the original algorithm. The valley-emphasis technique provides weights to the Otsu objective function based on the image's histogram's valley point.

3.2.1.2 Segmentation Based on Simple Linear Iterative Clustering

Simple linear iterative clustering (SLIC), a super pixel segmentation technique, has been used in water mapping by a select community of scholars. SLIC functions by searching for clusters of neighboring pixels that share some commonalities. SLIC-based segmentation has been proven useful in water mapping studies by Behnamian et al. (2017). The RADARSAT-2 SAR image was segmented using SLIC. The raw SAR image went through several transformations to produce the HV intensity image prior to the SLIC-based segmentation. SLIC has recently gained popularity in image processing applications because of its ease of use and impressive performance on multichannel and grayscale images. The method uses a five-dimensional space, denoted by [labxy], where [lab] stands for the three colors and [xy] stands for the coordinates of individual pixels. This definition is intended for color (RGB) photographs; however, the method may easily be applied to monochrome images with equivalent results. To enforce the color similarity and spatial proximity, a new distance metric based on the size of super pixels is introduced. Achanta et al. (2012) have suggested the precise algorithm and other information regarding the algorithm, including complexity analysis and comparative analyses.

3.2.1.3 Segmentation Using an Active Contour Model

In image processing applications, active contour-based segmentation techniques are commonly employed to separate the region of interest from the background. If applied to the right band or after thresholding on the required band, such algorithms can be useful in delineating surface water. Snakes, or active contours, are level-set functions that grow or shrink according to a force function that can be made to terminate at the image's borders. This makes it a viable option for extracting water features from satellite imagery. Using TerraSAR-X data, Hahmann and Wessel (2010) developed a straightforward active contour-based method for locating bodies of water on the ground. Parametric active contours and geometric active contours are both types of active contour models. Geometric active contours only hint at the existence of curves, but parametric active contours make their presence clear. Both models were shown to be successful in identifying bodies of water in TerraSAR-X imagery. With the help of combined SAR and LIDAR data, active contour-based water mapping was pioneered by Mason et al. (2007). While numerous active contour-based algorithms for picture segmentation have been created and see broad usage today, their applicability to remote sensing images has not been thoroughly studied. Active contour models can be used to identify and delineate water features on Earth's surface since they are simple to construct and yield accurate segmentation results. It has been found that active contour-based algorithms can improve the quality of both single-channel (grayscale) and multichannel (multispectral, hyperspectral) images.

3.3 Important GIS Resources, Software, and Database

Here are some helpful resources (Table 3.1) that will allow users to easily access and experiment with data crucial to effective water resource delineation and management.

3.4 Case Studies

3.4.1 Case Study 1

Mapping wetland cover in the greater Himalayan region: a hybrid method combining multispectral and ecological characteristics

- *Original article reference*: Li, Z., Xu, J., Shilpakar, R.L. and Ma, X., 2014. Mapping wetland cover in the greater Himalayan region: a hybrid method

Table 3.1 Important GIS software and their web sources

Commercial GIS software	*Source*
• ArcGIS (Esri)	https://www.esri.com/
• ArcGIS Pro (Esri)	https://www.esri.com/
• Geomedia (Hexagon Geospatial)	https://www.hexagongeospatial.com/
• MapInfo Professional (Precisely)	https://www.precisely.com/product/
• Global Mapper (Blue Marble)	https://www.bluemarblegeo.com/
• Manifold GIS (Manifold)	https://manifold.net/
• Mallworld (General Electric)	https://www.ge.com/digital/
• MapViewer and Surfer (Golden Software)	https://www.bentley.com/
• Maptitude (Caliper Corporation)	https://www.goldensoftware.com/
• Super GIS (Supergeo Technologies)	https://www.caliper.com/
• IDRISI (Clark Laboratories)	https://www.supergeotek.com/
• AutoCAD Map 3D (Autodesk)	https://clarklabs.org/
• Tatuk GIS	https://www.autodesk.com/
• MicroImages (TNTgis)	https://www.tatukgis.com/
• Map Maker Pro (Map Maker)	https://www.microimages.com/
• XMap (Delorme)	https://mapmaker.com/
• Map Rite (Envitia)	https://www.envitia.com/
Free open-source GIS software	*Source*
• QGIS 3	https://qgis.org/fr/site/
• GRASS GIS	https://grass.osgeo.org/
• Whitebox GAT	https://www.whiteboxgeo.com/
• gVSIG	http://www.gvsig.com/en/products/
• ILWIS	https://52north.org/software/
• SAGA GIS	https://saga-gis.sourceforge.io/
• GeoDa	https://geodacenter.github.io/
• Map Window	https://www.mapwindow.org/
• uDig	http://udig.refractions.net/
• Open Jump	http://www.openjump.org/
• Falcon View	https://falconview.software
• Orbis GIS	http://orbisgis.org/
• Diva GIS	http://www.diva-gis.org/
Open-source satellite imagery data sources	*Source*
• Bhuvan Indian Geo-Platform of ISRO	https://bhuvan-app3.nrsc.gov.in/
• Bhulosk-GSI	https://bhukosh.gsi.gov.in/
• USGS Earth Explorer	https://glovis.usgs.gov/
• Sentinel Open Access Hub	https://scihub.copernicus.eu/
• NASA Earth data Search	https://search.earthdata.nasa.gov/
• Digital Globe Open Data Program	https://www.maxar.com/
• NOAA Data Access Viewer	https://coast.noaa.gov/dataviewer/
• Geo-Airbus Defense	https://www.intelligence-airbusds.com/
• NASA Worldview	https://worldview.earthdata.nasa.gov/

(continued)

Table 3.1 (continued)

• NOAA CLASS	https://www.avl.class.noaa.gov/saa/products/
• National Institute for Space Research (INPE)	https://landsat.usgs.gov/
• AXA's Global ALOS 3D World	https://www.eorc.jaxa.jp/ALOS/
• VITO Vision	https://www.vito-eodata.be/
• NOAA Digital Coast	https://coast.noaa.gov/digitalcoast/
• Diva GIS	http://www.diva-gis.org/
GIS resources	*Source*
• Journal of Remote Sensing	https://spj.sciencemag.org/
• Journal of Applied Remote Sensing	https://www.scimagojr.com/
• Geography and Natural Resources	https://www.springer.com/journal/13541
• International Journal of Applied Geospatial Research	https://www.igi-global.com/
• Applied Geography	https://www.elsevier.com/journals/applied-geography/
• Journal of the Indian Society of Remote Sensing	https://www.springer.com/journal/12524
• Remote Sensing of Environment	https://www.journals.elsevier.com/remote-sensing-of-environment
• International Journal of Digital Earth	https://www.scimagojr.com/

combining multispectral and ecological characteristics. Environmental Earth Sciences, 71(3), pp. 1083–1094.

- *Spatial tools*: GIS (ERDAS and ARCGIS).
- *Main issues addressed*: Mapping of wetland cover of the Himalayas, types and distribution of wetlands, impact of climate change on wetland ecosystems, inaccuracies and restrictions of proposed method.
- *Background*: Wetland habitats like lakes, marshes, and peat lands play a vital role in the greater Himalayan region by regulating the flow of major rivers. Maps used for land-use planning and conservation purposes often fail to accurately depict these ecosystems. The dynamic nature of wetland ecosystems makes precise mapping via digital image processing or human interpretation challenging.
- *Objectives*: To promote the development of a rapid, low-cost wetland mapping technique that may be used to examine the response of high-altitude wetlands to climate and environmental changes in the broader Himalayan region.
- *Data used*: Shuttle Radar Topography Mission (SRTM-DEM), MODIS imagery, existing ecological imagery of the study region.
- *Methodology*: The appropriate data sources were mined for images of the study area, which were subsequently georeferenced. Following image preprocessing and regionalization, three indices and a slope map for each region were used to classify wetland types. Specifically, a slope map and the water index (WI) were utilized to abstract water bodies, while a slope map, the soil moisture index

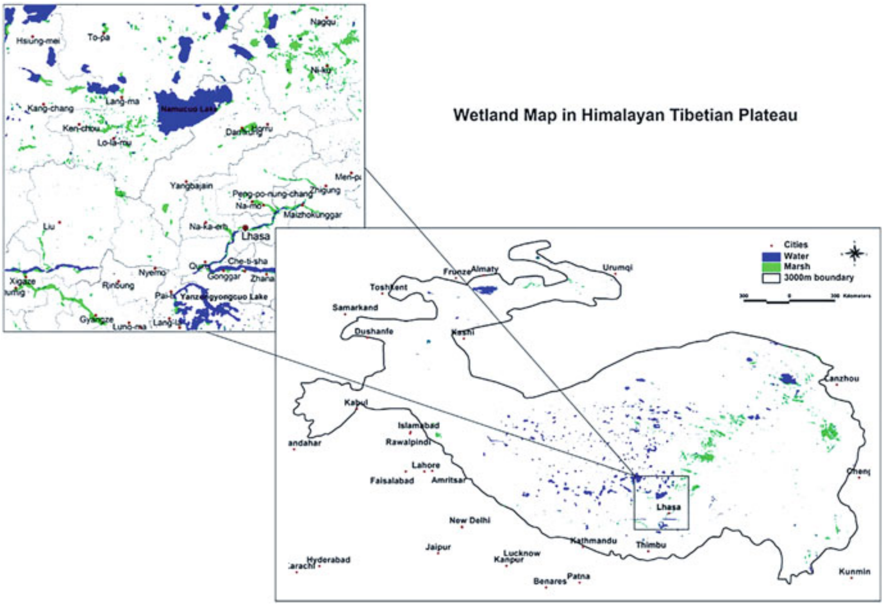

Fig. 3.1 Wetland distribution map of the greater Himalayas. (Adapted from Li et al. 2014)

(SMI), and the ratio vegetation index (RVI) were utilized to abstract flooded soil and marsh.

Combining unsupervised and supervised classification methodologies, a hybrid remote sensing classification with ecological characterization methodology has been employed to build a final classification map for the entire Himalayan region. The training areas were utilized to extract spectral data for each known wetland cover, and the images were picked based on local knowledge gleaned from previous field visits to the research area. The training zones were also determined using a Landsat picture. Further, this image was used to assess the precision of the classification algorithm. Spectral bands or vegetation indices sensitive to water, soil, and vegetation were required, as is a transformation to extract brightness, greenness, and wetness, in order to identify changes in the mixing of surface water, moist soil, and green vegetation (Kauth and Thomas 1976). Water index, ratio vegetation index, and soil moisture index were used in the calculations.

- *Summary*: Wetland covers 107,948 km^2 (2.81%) of the total area above 3000 m (Fig. 3.1), which includes marshes and water bodies totaling 61,627 km^2 (1.6%) and 46,321 km^2, respectively (1.2%). Generally speaking, wetland ecosystems do not persist at altitudes more than 6000 m. Above 4000 m, glacier melt offers fast accumulation of water, and flora produces less biomass and marshland; therefore, there are more lakes and ponds than marshes. Marshes, on the other hand, tend to form at altitudes lower than 4000 m because of the greater availability of suitable flora at those lower levels. Climate and orography determine regional wetland kinds and extent. Region II is predominately wetland (total 66,883 km^2, accounting for 62.2%). Region I have 30,469 km^2 and 28.2% wetlands. This region contains denser vegetation due to increased precipitation and wetness. Region III has the least wetland coverage (10%) and mostly aquatic bodies. Increasing human activity in Region I, massive infrastructure development in Region II (such as the Qinghai-Tibet railway), and conditions that threaten to destroy the small wetlands due to global warming in Region III will have the greatest impact. The scientists discovered that precipitation patterns affected recharge of both surface and subsurface water and evaporation transportation, making climate change a major driver in the distribution of wetlands.

In this study, a hybrid method for extracting spatial patterns of wetland areas was developed. Results were compared to authoritative works on lakes and wetlands written both internationally and in the United States. The method was demonstrated to be capable of accurately and automatically extracting wetland areas, reducing the need for specialized regional expertise. Parameters were adjusted using high-resolution satellite data to facilitate application of the model to a number of subbasin regions (Landsat). These findings are consistent with what experts on wetlands have said in interviews. In order to better understand the distribution and transformation of wetlands as a result of global warming and human activities, the hybrid approach and high-altitude wetland maps have been developed.

3.4.2 Case Study 2

Monitoring of glacial lakes/water bodies in the Himalayan region of Indian river basins

- *Original article reference*: CWC, November, 2021. Report on "Monitoring of glacial lakes/water bodies in the Himalayan region of Indian river basins for June to October 2021," Technical Report Published by Morphology & Climate Change Directorate, CWC, New Delhi, India.
- *Spatial tools*: GIS.
- *Main issues addressed*: Depiction of glacial lake systems on maps, creating a database of all glacier lakes, surveillance of glacial lake levels.
- *Background*: Glacial lakes are plentiful in the high altitude of a glacierized basin. Their source is the accumulation of water in the crevices of glaciers and moraines. Typically, the glacier will drain the water from these lakes by seepage as it retreats from the lake. After the lake has filled, meltwaters will collect in the basin until seepage or overflow prevents further lake expansion. Such moraine-dammed lakes appear to be the most prevalent type of glacier lake. Possible instability in the lake's impoundment could cause a catastrophic discharge of the water that has been stored. There is widespread evidence that the collapse of ice or moraine dams can have devastating consequences. The outburst of glacial lakes can generate sudden flooding, which is referred to as a glacial lake outburst flood

(GLOF). Due to this, it is crucial and important to map and monitor these lakes so that catastrophes can be avoided.
- *Objectives*: Monitoring the spatial extent of the glacial lakes and water bodies on monthly basis during June 2021 to October 2021.
- *Data used*: This research concentrated on the region encompassing the Indian Himalayas. Data from the Indian remote sensing satellite Resourcesat-2's Advanced Wide Field Sensor (AWiFS) has been utilized to track glacial lakes in the current month.
- *Methodology*: This research made use of satellite imagery captured by the Resourcesat-2 AWiFS sensor. After being captured in 2D, they were orthorectified to fix any distortions from the real world. Satellite images have been visually analyzed to determine the boundaries of glacial lakes and other bodies of water. Various color combinations of the multispectral bands have been used for feature identification in panchromatic mode. Image processing methods have been employed in order to better interpret the location of glacial lakes and other bodies of water.
- *Summary*: Researchers in this study recommended keeping a watch on any water body larger than 50 ha, including glacial lakes. All glacial lakes and other bodies of water larger than 10 ha were digitized for the inventory, but only those larger than 50 ha were submitted to observation. The edge of glacier lakes and other bodies of water were captured digitally as a polygon feature using on-screen digitization techniques. Digitized area covered by glacial lakes and other bodies of water was determined by geoprocessing polygons. Researchers were able to determine the overall water-spread area by repeating the aforementioned steps for each time point in the satellite data. The largest water-spread area for each body of water was considered across all satellite dates from June through October 2021 for the final analysis of the change in water spread.

The following parameters were used by the authors to guide their water quality assessments:

- A water distribution area shift of up to ±5% was regarded as negligible.
- Water bodies that were frozen or obscured by clouds have not been accounted for in monitoring.
- It has been mapped how far and wide water has spread that month, and the results have been compared to the same data from 2009.

3.4.3 Case Study 3

Fishery resource assessment of Indian Himalayan region using geoinformatics

- *Original article reference*: Kumar, P., Posti, R., Ingole, N.A., Pandey, N.N., Saxena, A., and Singh, A.K., 2017. Fishery resource assessment of Indian

Himalayan region using geoinformatics. Journal of Environment and Bio-sciences 31(1):131–137.

- *Spatial tools*: GIS.
- *Main issues addressed*: Mapping of lacustrine and riverine resources of Indian Himalayan region.
- *Background*: Upland lakes and rivers are natural repositories of abundant cold-water flora and fauna that must be utilized in a manner that does not upset the ecosystem structure. For their sustainable utilization, it is necessary to develop strategies and policies. Nonetheless, discrepancies in the data supplied by numerous authors regarding the spatial extent of these resources posed as substantial obstacles to the formulation of a comprehensive policy and management strategy for these resources.
- *Objectives*: Delineation of length and spatial extent of the Himalayan fishery resources using remote sensing and GIS tools.
- *Data used*: ASTER, Quick globe, Survey of India shapefiles.
- *Methodology*: The data was obtained from open-source databases such as USGS and Digital Globe, among others. It was first orthorectified, then geo-rectified, and finally analyzed. To identify the length of rivers and spatial extent of highland lakes, a manual method of digitizing was utilized. For data verification, Survey of India shapefiles and Google Earth satellite data were utilized.
- *Summary*: For future planning, cold-water fishery resources were digitized and evaluated using remote sensing (RS) and geographic information systems (GIS) (Fig. 3.2). In Jammu and Kashmir (J&K), Himachal Pradesh (HP), Uttarakhand (UK), Sikkim, and Arunachal Pradesh (AP), the authors discovered large lotic water resources such as rivers and their tributaries with total lengths of 10,893.5 km, 10,464.3 km, 10,927.9 km, and 12,351 km, respectively. Total water-spread area of lentic water resources, including lakes and reservoirs, both naturally occurring and artificially created, have been estimated to be 15,4248.4 hectares (ha) in J&K, 35,481.54 ha in HP, 21,503.7 ha in the UK, 1593.3 ha in Sikkim, and 2808.1 ha in AP. To better plan for the long-term, sustainable growth of cold-water fisheries, this research may help to resolve existing inconsistencies in the availability of aquatic resources.

3.5 Conclusion

Before the emergence of image processing tools for analyzing remote sensing data, change detection examinations on various items on Earth's surface were time-consuming and expensive. Automated algorithms for modeling change detection are made possible by combining the immense amount of information in multispectral images with the capabilities of image processing techniques. The availability of multispectral data on open portals makes it possible to undertake change detection investigations quickly and cost-effectively. Identifying and delimiting water bodies at the surface is important in the study of remote sensing as it relates to detecting changes in those bodies of water. A few universal indices can be used across a wide

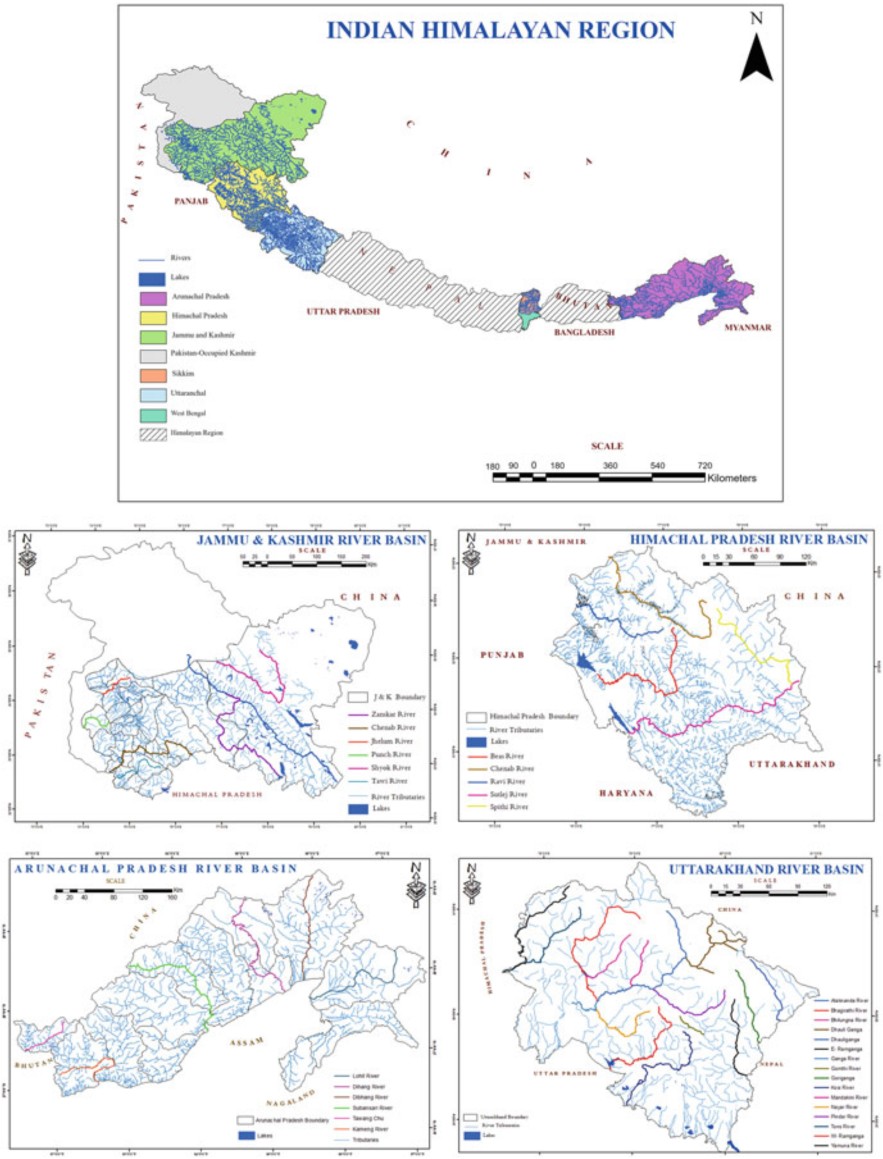

Fig. 3.2 Some digitized cold-water fishery resources of the Indian Himalayan region. (Adapted from Kumar et al. 2017)

range of sensors and programs for surface water detection and delineation. Although several methods have been developed via prior research to detect and delineate water bodies, this is still an unanswered question because no single strategy has been shown to work in every situation and dataset. It is possible to suggest and build improved spectral indices and classification algorithms for use in specific contexts. While level-set theory and active contour-based image segmentation techniques show great promise, they have not been widely used in the delineation of water bodies. In addition to its proven success with RGB and grayscale images, this approach has the potential to be expanded to multispectral and hyperspectral imagery with further study. Although higher-resolution PAN images have been theorized to increase demarcation precision, not much work has been done in this direction. As with multispectral data, digital elevation models (DEMs) can be used with multispectral data to generate a more precise demarcation model, particularly useful for removing shadows, a major issue in water detection applications. More accurate hybrid delineation models could be built using SAR (synthetic aperture radar) images, which remove the effects of shadows from the picture. With the use of contemporary remote sensing multispectral images and the application of suitable digital signal processing algorithms, a completely automated, precise surface water delineation technique may be built, and, in the future, it can effectively conserve limited water supply.

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Fisheries Development in Open Water Resources of the Temperate Himalaya

4

Alexander Ciji and Md. Shahbaz Akhtar

Abstract

The temperate Himalayas are endowed with vast and varied open water resources that have enormous potential to enhance the nutritional and livelihood security of the upland people. However, their full potential is not yet realized. In this chapter, we have provided an overview of diverse open water resources, their fishery and projected potential, and various strategies for enhancing fish production and livelihood opportunities.

Keywords

Rivers · Lakes · Reservoirs · Stocking · Fisheries · Endangered species · Fish production

4.1 Introduction

The cold-water resources in the Himalayan upland are spread as upland rivers, streams, highland reservoirs, and lakes. In the Indian Himalayas, there are approximately 8243-km-long streams and rivers; 20,500 ha of natural lakes; 50,000 ha of reservoirs (natural plus man-made); and 2500 ha of brackishwater lakes (Ali 2010). These resources support wide range of ichthyofaunal diversity, including indigenous and introduced (exotic), cultivable and non-cultivable fish species. The Himalayas harbors 208 fish species (Menon 1962), and about 36 species are endemic to the Himalayan region (Ghosh 1997). Some of these small fish species have enormous

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ornamental value. The indigenous species include mahseer, minor carps, snow trout, minnows, catfishes, loaches, and barils, while rainbow trout, brown trout, common carp, and silver carps are exotic. Fisheries, either subsistence *or* sport/recreational, play a vital role in providing food and livelihood to the people of the Himalayan uplands.

4.2 Major Rivers/Streams in the Temperate Himalayas and Their Fishery

The Himalayan river systems, including the Indus, the Ganges and the Brahmaputra, and their tributaries, support a great piscine faunal diversity (Singh 2018). These rivers are perennial as they receive water from rainfall and snow/glacier melting. The Indus and Brahmaputra rivers are the longest, each with a catchment area of around 160,000 km^2. The Indus river system has five rivers, of which the Beas and the Sutlej have a total catchment area of 80,000 km^2; the Ganga system has nine rivers (Ganga, Ram Ganga, Yamuna, Kali-Sharda, Karnali, Rapti, Gandak, Bhagmati, and Kosi), draining roughly 150,000 km^2; and the Brahmaputra river system has three rivers (Tista, Raidak, and Manas), draining about 110,000 km^2 (Sehgal 1999; Singh 2015). Besides, the central Himalayas (Garhwal and Kumaon) is bestowed with several tributaries and rivulets of major rivers such as Alaknanda, Mandakini, Pinder, Nandakini, Dhauliganga, Bhagirathi, and Bhilangana, which later join with Ganga river (Singh and Agarwal 2013). Most of these rivers flow through deep valleys before exiting the mountains (Sehgal 1999). Himalayan rivers and hill streams are characterized by their fast water flow, rapid cascade, deep pools, and substratum composed of bedrock, boulder, and sand (Sarkar 2021). The distribution of fish species in the Himalayan rivers and hill streams is determined by water flow rate and temperature, the nature of the substratum, and food availability (Sarkar 2021). The eastern Himalaya drained by the Brahmaputra has more fish biodiversity than the western Himalayan drainage (Sehgal 1999). Generally, fish production in hill streams is poor; hence, commercial fishery is on a limited scale. Greater fish diversity and species richness were documented in lower stretches of a given river/stream, which might be attributed to comparatively higher water temperature, lower water current, and higher abundance of natural fish food (primary and secondary productivity) (Dobriyal et al. 1992; Bahuguna 2021). Hill stream fish prefer clear, shallow, fast-flowing water with a high dissolved oxygen level. Fishery in Himalayan rivers and streams is comprised of snow trouts (*Schizothorax richardsonii*, *S. kumaonensis*, *S. plagiostomus*, *S. niger*, *S. curvifrons*), mahseers (*Tor putitora*, *T. tor*, *T. chilinoides*, *Neolissochilus hexagonolepis*), minor carps (*Labeo dero*, *L. dyocheillus*, *L. pangusia*, *Raiamas bola*), minnows (*Garra gotyla*, *Garra lamta*, *Crossocheilus latius*), loaches (*Nemacheilus rupicola*, *N. denisoni*, *N. montanus*, *N. savona*, *N. multifaseculatus*, *Botia dario*, *B. geto*), catfishes (*Mastacembelus armatus*, *Glyptothorax pectinopterus*, *G. madraspatanum*, *G. tilchata*, *Pseudecheneis*), *Barilius* (*Barilius bendelisis*, *Barilius vagra*, *Barilius barna*), etc. The limited biological productivity leads to the predominance of small-sized,

Table 4.1 Major rivers in different hill states of India

Uttarakhand	Alaknanda, Assi Ganga, Bhagirathi, Bhilangna, Beas Ghat, Dhauliganga, Gaula, Gori ganga, Kali, Kosi, Mandakini, Mahakali, Nandakini, Nayar, Pindar, Ramganga, Saryu, Tons, Jamuna
Himachal Pradesh	Beas, Chenab (Chandrabhaga), Satluj, Ravi, Yamuna, Baspa, Parvati, Pabbar, Giri, Jalal, Tons, Andhra, Patsari, Bata, Tirthan, Suketi
Arunachal Pradesh	Kameng, Lohit (Tellu), Dibang (Sikang), Siang, Dihing, Dikrong, Subansiri, Siyom, Sumdorong Chu, Tawang Chu, Tirap, Yepak, Par, Namka Chu, Nyamjang Chu, Emra, Sisiri
Jammu and Kashmir	Jhelum, Chenab, Indus, Ravi, Lidder, Brengi, Markha, Nala Palkhu, Neelum (Krishnaganga), Poonch, Rambi Ara, Sandran, Sind, Tawi, Ujh, Veshaw, Yapola, Doda, Dras, Nubra, Suru, Shingo, Tsarap, Zanskar
Sikkim	Teesta, Rangeet, Rangpo, Lachen, Relli, Jaldhaka, Dharla, Lachung, Lhonak, Ranikhola, Talung, Pabong Khola
Nagaland	Doyang, Dikhu, Dhansiri, Tizu, Milak, Dzu, Langlong, Zungki, Likimro, Lanye and Dzuza, Manglu, Tsurong, Nanung, Tsurang or Disai, Tsumok, Menung
Manipur	Imphal, Iril, Thoubal, Khuga, Tuitha, Barak, Khuga, Nambul, Tiau, Tuivai, Surma-Meghna
Meghalaya	Ganol, daring, Sanda, Bandra, Bugai, Dareng, Simsang, Nitai, Bhupai, Umngot, Myntdu, Umiam, Digaru, Kopili, Piyain, Someshwari, Lubha
Mizoram	Tlawng, Tiau, Chhimtuipui (Koladyne), Khawthlangtuipui (Karnaphuli), Barak, Langkaih, Lungleng, Mengpui, Phairuang, Surma-Meghna
Tripura	Burima, Gomati, Khowai, Howrah, Longai, Dhalai, Muhuri, Feni, Juri, Manu, Muhuri

low-valued fish. Besides, the exotic brown trout, *Salmo trutta*, forms a sizable fishery in Himalayan streams (Sehgal 1999; Sharma et al. 2021). In the nineteenth century, British colonels introduced brown trout (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*) into Himalayan rivers to fulfill their angling desires. Since then, trout has attracted anglers for sport fishing, becoming an essential part of the tourism industry in the Himalayas. Brown trouts are currently well established in the Himalayan streams, whereas rainbow trouts have failed to establish themselves in the stream environment but are commercially being cultured (Sehgal 1999). Several researchers reported a significant decline in catches of indigenous schizothoracids in the Himalayas due to brown trout feeding on their early stages.

Fishing is difficult in hill streams. The majority of fishing gears, used in hill streams, are poor/inefficient in harnessing fishery resources. Commonly used gears include cast nets, gill nets, stake nets, scoop nets, bag nets, and different types of fish traps (Sehgal 1999). In addition, various poisons (lime, the sap of *Euphorbia royleana*, the powdered seed of *Xanthoxylum alatum* and *Cascaria tormentosa*, boiled tea leaves, etc.), spears, horsehair nooses, harpoons with four to five barbed points, and grain fishing are also used in different waters of the Himalayas (Sehgal 1999).

Most of the Himalayan rivers (Table 4.1) are ideal angling spots, particularly to trap mahseer fish. Globally, the rivers that drain the Himalaya are among the most biologically diverse freshwater ecosystems. However, they are increasingly under threat from climatic uncertainty and anthropogenic activities, particularly dam/barrage construction, which has resulted in habitat fragmentation and the extinction or decline of many species (Braulik et al. 2014). The freshwater river dolphins, endemic to the Himalayan rivers, are one of the world's most endangered groups of animals, recognized as endangered or critically endangered on the *Red Data Book* (IUCN 2013). Indiscriminate fishing methods and other human activities have imbalanced the river/stream biota, damaging the fishes and the fish food organisms (Srivastava et al. 2002). Hence, there is an urgent need to develop action plans and strategies to safeguard Himalayan biodiversity and the ecosystem. However, the shortage of information related to limnology/ecology and fish catch/composition data for many rivers, and even the entire Himalayas, makes implementation of management and conservation measures difficult.

4.3 Major Reservoirs/Dams in Temperate Himalaya and Their Fishery

Reservoirs/dams, often known as "man-made lakes," are key resources that provide services such as hydropower generation, water supply and irrigation, navigation, flood control, commercial and recreational fishing, aquaculture, and various other recreational activities. Furthermore, reservoir fisheries have a great potential for supporting the underprivileged fisherfolk of the Indian Himalayan region with food and livelihood security. Despite their enormous fisheries potential, most upland reservoirs are presently not contributing considerably to commercial fisheries owing to their unscientific management practices (Ciji et al. 2021).

4.3.1 Reservoirs in Himachal Pradesh

The six reservoirs in Himachal Pradesh (Table 4.2), including two large, one medium, and three small reservoirs, cover a full reservoir level (FRL) area of

Table 4.2 Reservoirs in Himachal Pradesh, India

Name of the reservoir	Built on river	District	Area (ha)	Fish yield (tons) in 2016–2017
Gobindsagar (Bhakra Nangal)	Sutlej	Bilaspur	16,867	753
Pong (Maharana Pratap Sagar)	Beas	Kangra	24,629	382
Pandoh	Beas	Mandi	200	–
Chamera	Ravi	Champa	100	3.12
Ranjeet Sagar	Ravi	Pathankot (Punjab)	500	1.97
Koldam reservoir	Sutlej	Bilaspur	1302	4.32

43,598 ha. Gobindsagar, which was built across the Sutlej in 1963, is one of India's largest and most scientifically managed reservoirs with a mean water spread area of 10,000 ha. Various approaches like minimum catchable size, gear/mesh size restriction, ban of illegal fishing, a complete ban on fishing during spawning season, and regular fish stocking were practiced for fish conservation and management. Besides, fishing is managed through cooperative societies. The reservoir has been divided into eight zones, with distinct cooperative societies fishing from each zone. Over the last decade, these scientific management measures yielded 48.5–149.2 kg/ha/year from Gobindsagar (Lal and Dua 2018), against the estimated fish yield of 276 kg/ha/year (Jhingran 1982).

The commercial fishery of Gobindsagar consists of Indian major carps, common carp, grass carp, silver carp, minor carps, and, to a lesser extent, catfishes. Indian major carps and common carp are being regularly stocked in this reservoir. *Hypophthalmichthys molitrix* were accidently introduced and are now accounting for a good portion of the reservoir's fish catch. In abundance, the commercially important fish are *H. molitrix*, *Catla catla*, *Cyprinus carpio*, *Cirrhinus mrigala*, *Tor putitora*, *Labeo rohita*, *Labeo dero*, *Mystus seenghala*, *Ctenopharyngodon idella*, and *Labeo calbasu* (State Fisheries Department, Himachal Pradesh, India 2018). Before the damming, golden mahseer (*T. putitora*) was the dominant fishery of the Sutlej river, but it has since declined significantly. During the last decade, catches have fluctuated from 14.0 to 32.00 tons. The decline of mahseer, following impoundment, is linked to the destruction of breeding habitats, restriction of breeding migration, the capture of juveniles, and lack of preferred food such as insect larvae and plankton, among other factors. However, by strictly enforcing closed season and mesh size limits, and increasing the minimum harvestable size from 30 to 50 cm, the mahseer fishery of this reservoir was replenished to a certain extent.

The Pong reservoir, impounded across the river Beas in 1975, has a catchment area of 12,561 km^2 and a mean water spread area of 15,662 ha. Initially, fishes of *Salmonidae*, *Cyprinidae*, *Cobitidae*, and *Sisoridae* dominated the catches. However, with frequent stocking of Indian major and mirror carps, the catch composition altered, and carps began contributing as high as 50–60% of the catches (State Fisheries Department, Himachal Pradesh 2018). An average yield of 22.3 kg/ha/year (18–30.57 kg/ha) was recorded during the last decade. Around 27 species from 6 families have been reported from the Pong reservoir. *M. seenghala*, *H. molitrix*, *C. catla*, *C. carpio*, *T. putitora*, *C. mrigala*, *L. rohita*, *L. dero*, *C. idella*, and *L. calbasu* are the commercially important fish in order of their abundance (State Fisheries Department, Himachal Pradesh 2018). *L. rohita* is the most abundant Indian major carps, while *C. catla* is the least abundant. Mahseer forms a major lucrative fishery, and pong reservoir is the only reservoir in the country that allows mahseer angling. The Reservoirs Fisheries Development Committee prudently manages both Gobindsagar and Pong reservoirs are at the State level. Gobindsagar is well-recognized for its record landings, whereas Pong is known for its fish quality, with Pong fishes fetching the highest unit price (Rs. 251.00/kg in 2018–2019).

The Pandoh reservoir, constructed across the river Beas, was stocked with common carp in 1978. However, the stocking was later discontinued. This reservoir is occasionally utilized for recreational/sport fishing. It has been recorded to have brown trout, *Schizothorax richardsonii*, *L. dero*, *L. dyocheilus*, *T. putitora*, and a few other small stream fishes (Sugunan 1995).

Chamera reservoir, with a water spread area of 1500 ha, was built over the Ravi river in 1994. Fish production of Chamera reservoir is hindered by abrupt rise and fall of average water level, which sometimes takes the shape of a rivulet when the water level falls. During 2015–2016 and 2016–2017, the total fish production from Chamera reservoir was 3.24 and 3.12 tons, respectively (State Fisheries Department, Himachal Pradesh 2018). The Koldam reservoir (impounded across the river Sutlej in the Bilaspur district) and Ranjeet sagar reservoir (built over the river Ravi; only a portion is in Himachal Pradesh, and the rest part is in J&K and Punjab) are the other two small reservoirs having fisheries importance in the State, with fish production of 4.32 and 1.97 tons during 2016–2017, respectively (State Fisheries Department, Himachal Pradesh 2018).

4.3.2 Reservoirs in Uttarakhand

Major reservoirs of Uttarakhand are the Nanak Sagar, Sarda Sagar, Baigul, Tumaria, Dhaura, Baur, Haripura, and Tehri, altogether covering an area of 20,075 ha and harboring rich fish biodiversity (Raveendar et al. 2018). The average yield from the Uttarakhand reservoirs is approximately 25 kg/ha/year, which can be augmented up to 200 kg/ha/year by implementing scientific management measures (Sharma et al. 2005). The Nanak Sagar, impounded across the river Deoha, is the Uttarakhand's largest reservoir, with water surface area and catchment area of 4600 ha and 570 km^2, respectively. The reservoir harbors 30 fish species from 22 genera, comprising Indian major carps, minor carps, cat fishes, weed fishes, and other small fishes (Raveendar et al. 2018). For commercial fishing in Nanak Sagar reservoir, traditional gears, viz., gill net (most commonly used), drag net, hooks and lines, cast net, and rod and line, are employed, and *Gudusia chapra*, *Labeo gonius*, and *Notopterus notopterus* dominated the fish catch. The Indian major carps were represented by *C. catla*, *L. rohita*, *L. calbasu*, and *C. mrigala*; medium carps by *L. gonius*, *L. dyocheilus*, *L. bata*, and *C. reba*; and cat fishes/carnivorous fishes by *Mystus* spp., *Wallago attu*, *Channa* spp., *Heteropneustes fossilis*, *N. notopterus*, and *Mastacembelus* spp. Other fish species reported from Nanak Sagar reservoir include *Tilapia*, *Oxygaster* spp., *Puntius* spp., *G. chapra*, *Xenentodon cancila*, *Chanda* spp., *Salmostoma bacaila*, and *Glassogobius giuris* (Raveendar et al. 2018).

The fishery of Baigul reservoir (water spread area 2693 ha) comprised of major carps, minor carps, cat fishes, and trash fishes. Baigul reservoir has been recorded to have 36 fish species from 13 families (Majhi et al. 2018). The commercial fishery comprises of *L. rohita*, *C. catla*, *L. calbasu*, *L. gonius*, *Puntius* sp., *C. mirgla*, *C. reba*, *M. tengara*, *M. seenghala*, *Nandus nandus*, *G. chapra*, *N. notopterus*, *W. attu*, *X. cancila*, *M. armatus*, etc. The fish yield from this reservoir varied from 28.34 kg/ha/year in 2003–2004 to 74.59 kg/ha/year in 2012–2013 and 58.74 kg/ha/year in 2013–2014 (Majhi et al. 2018). As the reservoir is leased to contractors for fishing (every 5 years), inadequate stocking and irrational exploitation are the primary reasons for the low fish production. The fishing season extends from October to early June, with a complete fishing ban during monsoon (till the end of September). Adoption of the best management measures through community participation, such as the formation of cooperative societies, as being practiced in Gobindsagar, can enhance its productivity.

4.3.3 Reservoirs in Jammu and Kashmir

Jammu and Kashmir have approximately 24,000 ha of lakes, marshy areas, and reservoirs (Table 4.3). Ranjit Sagar is the largest reservoir, with an estimated water spread area of 4087.3 ha. The establishment of cage/pen culture units in reservoirs and lakes as part of the Centrally Sponsored National Mission for Protein Supplement (NMPS) increased fish production to 20,000 tons in 2013–2014 (J&K Fisheries Department).

4.3.4 Reservoirs in Sikkim

The Rangit Hydroelectric Power Project Stage III and Teesta Stage V are Sikkim's two major hydroelectric projects. Rangit Dam, the mainstay of the Rangit Hydroelectric Power Project Stage III, is a hydel project across the Ranjit river, a major tributary of the Teesta river. It has a catchment area of 979 km^2 with a reservoir surface area of 12.9 ha and has been fully functional since 2000. At present, detailed information on the fisheries of Rangit reservoir is scanty. However, the most common species found in the Rangit river are *Schizothorax* spp., *Neolissochilus*

Table 4.3 Major hydel project reservoirs in Jammu and Kashmir

Reservoir	Location	Dam features	Name of the river
Nimoo-Bazgo	Village Alchi, Leh	FRL: 3093 m; length: 248 m; height: 59 m	Indus
Salal	Reasi	FRL: 487.7 m; length: 630 m (rockfill) and 486.75 m (concrete); height: 118 m	Chenab
Uri	Uri Tehsil, Baramulla	FRL: 1491 m; length: 93.5 m; height: 20.0 m	Jhelum
Dulhasti	Kishtwar	FRL: 1266.5 m; length: 186 m; height: 65 m	Chenab
Sewa	Kathua	Length: 1146 m; height: 53 m	Sewa
Chutak	Kargil	FRL: 2781 m; length: 45.6 m; height: 15 m	Suru (a tributary of Indus)
Kishanganga	Bandipora	FRL: 2781 m; length: 45.6 m; height: 15 m	Kishanganga (a tributary of Jhelum)

FRL full reservoir level

spp., and *Garra* spp. The small size of the reservoir offers scope for fisheries development by adopting scientific management approaches.

Teesta Stage V dam was built on river Teesta, 2 km downstream of the confluence of Dikchu and Teesta river near village Dickchu. It has a catchment area of 4307 km^2 and 579.0 m at FRL. As part of the State's reservoir fisheries development initiative, the reservoir at Dikchu has been stocked with mahseer seed on an experimental basis. The Directorate of Fisheries, Govt. of Sikkim, has developed a policy for dealing with fisheries in all Sikkim hydropower projects.

4.3.5 Reservoirs in Northeastern Indian States

The seven states of northeast India, viz., Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, and Tripura, collectively known as the "seven sisters," are divided into five geographic units, namely, the Assam Himalayas, the Brahmaputra valley, the Shillong plateau, the Barak valley, and the Southeastern hill region (Sugunan 1995).

Gumti reservoir, built on the river Gumti, has a catchment area of 547 km^2 at the dam site. The 4500 ha reservoir (Table 4.4) draws water from the river basins of the Barak, Raima, and Sarma. Water turbidity is relatively high due to soil erosion, caused by the denudation of forests in the catchment area by shifting cultivators (*jhoom*). The soil is acidic (pH 5–6), but the water is alkaline, with a pH of 7.5–9 (Sugunan 1995). The reservoir has a rich macrophyte population (Chaudhari 1992). Blue-green algae and copepods dominate the phyto- and zooplankton communities, with considerable seasonal and geographical changes. There is no information about the river's indigenous ichthyofauna prior to impoundment. The reservoir has been reported to have more than 47 fish species, with an average yield of 31.5 kg/ha/year (Anon 1994). The commercially important fish species include *Aorichthys aor*, *C. marulius*, *C. punctatus*, *M. pancalus*, *M. guentheri*, *P. stigma*, *P. ticto*, *P. sarana*, *X. cancila*, *A. mola*, *C. ranga*, *H. fossilis*, *C. batrachus*, *N. notopterus*, *T. tor*, and *L. gonius*. Besides, the Indian major carps (catla, rohu, and mrigal) and exotic carps (silver, grass, and common carp) have been introduced successfully.

Table 4.4 Reservoirs of northeastern states of India

Reservoir	State	Area (ha)
Barapani (Umium)	Meghalaya	500
Kyrdemkulai	Meghalaya	90
Nongmahir	Meghalaya	70
Khamdong	Meghalaya and Assam	1335
Umrong	Assam	979
Gumti	Tripura	4500
Khoupum	Manipur	100
Palak	Mizoram	32
Others	–	600

(Source: Anon 1991; Sinha 1990; Ciji et al. 2021)

Indian major carps breed in the river's upper reaches at Ultacherra, Chitrajhari, Gandacherra, Rangajhari, Sarmacherra, Thakurcherra, and Raimacherra. The isolated breeding, however, does not result in population recruitment (Chaudhari 1992).

The two major reservoirs in Meghalaya, Kyrdemkulai and Nongmahir, are created below the Sumer power station of the Umtru-Umiam Stage I hydroelectric project. Kyrdemkulai reservoir built in 1979 is part of the Umtru-Umiam Hydroelectric Project Stage III. River Umiam has a catchment of about 150 km^2. The river downstream is known as Umtru. The diversion tunnel (167.7 m long) carries water from Kyrdemkulai to Nongmahir, another downstream reservoir (Sugunan 1995). The reservoir, which has a surface area of 80 ha and a mean depth of 4.63 m (at FRL), has a full storage level (FSL) of 3.7 million m^3. The reservoir's water level fluctuates depending on the requirements of the Nongmahir forebay, the incursion of Umiam waters, precipitation, and runoff from the catchment. Dominant fish species in the reservoir are *C. carpio*, *Acrossocheilus hexagonolepis*, *T. putitora*, *P. sophore*, *C. batrachus*, *D. rerio*, *D. acquipinnatus*, *D. dangila*, *H. fossilis*, *Aplocheilus* sp., *Noemacheilus multifasciatus*, *T. tor*, *C. catla*, *L. rohita*, and *C. mrigala*. The estimated production potential of this reservoir is 534–570.6 kg/ha/year (based on the quantity of carbon produced and primary productivity; Sugunan 1995).

The Nongmahir reservoir is somewhat circular with several islands. It has 70 ha of surface water with a storage capacity of 5.8 million m^3 at FRL. The ICAR-Directorate of Coldwater Fisheries Research, Bhimtal, Nainital, Uttarakhand, has taken the initiative in establishing the population of golden mahseer (*T. putitora*) and chocolate mahseer (*N. hexagonolepis*) in this reservoir.

Umiam is another reservoir in Meghalaya situated 15 km north of Shillong. It was created in the early 1960s by damming Umiam river. The principal catchment area of the reservoir and dam is spread over 220 km^2. The reservoir harbors 27 fish species, including 24 indigenous and 3 exotic fish species (Vinod et al. 2000).

The Doyang reservoir, located in the Wokha district of Nagaland, has a catchment area of 2606 ha and is one of the largest reservoirs in the country's northeastern region. The reservoir receives water from the Doyang, Chumeya, Djupvu, Tzuza, and Chubi rivers. The reservoir supports a rich ichthyofaunal diversity, many of which have high ornamental value. The reservoir is regularly stocked with Indian major carps and exotic carp fingerlings. Carps dominated the catches, followed by catfishes, loaches, mahseers, snakeheads, and spiny eels. The reservoir's productivity was estimated to be 79.53 kg/ha/year. Gillnet accounted for 80% of the total catch (Odyuo and Srinivasan 2012).

4.4 Major Lakes in Indian Himalayas and Their Fishery

The temperate Himalaya is bestowed with numerous cold-water lakes, some of them are freshwater, and a few are brackish (saline), the total number and area of which are not fully known. Several lakes in Kashmir, Uttarakhand, and Sikkim were formed as glaciers receded, whereas landslides and tectonic movements resulted in the formation of others. Few of them remain frozen during the winter months. Freshwater lakes in Kashmir Valley are believed to have emerged as oxbow lakes of the river Jhelum. The majority of our understanding of fish and fisheries of the Himalayan lakes is confined to those at lower altitudes. The remoteness and the short summer open water period are the significant challenges for exploring high altitude lakes. Fish production from most of the Himalayan lakes is not well documented. The average fish yield in Kashmir's large floodplain lakes, Wular and Dal, is 16.5 kg/ha/year and 21 kg/ha/year, respectively. The Kumaon lakes of Uttarakhand are relatively smaller, with yields of 0.7–9.3 kg/ha/year, and the fisheries mainly comprised of Indian major carps, common carp, and mahseers. Only a few glacial lakes of Kashmir (3200–3819 m above msl) harbor fish, such as brown trout and the endemic *Diptychus maculatus* (schizothoracid). Trout fishing with a license is permitted. Sikkim Himalaya features about 150 lakes at various altitudes, most of which are sacred (Roy and Thapa 1998). Natural lakes such as Tsomgo lake, Khecheopalri lake, Menmecho lake, Aritar lake, etc. harbor fish species. However, fishing and other recreational activities are not permitted in most Sikkim lakes due to their sacred and holy nature, which are adored by the inhabitants (Roy and Thapa 1998). From Arunachal Pradesh, around 1532 glacial lakes have been mapped recently using Landsat OLI satellite images (2016–2018), covering an area of 93.7 km^2 (Mal et al. 2020). Most of the lakes in Arunachal Pradesh are unexplored.

The Himalayan lakes (Table 4.5) are under serious threat due to sedimentation, ecological degradation, pollution, and other anthropogenic activities. Their water area is rapidly shrinking due to agricultural encroachment and aquatic plant growth on lake margins, which is exacerbated by pollution from the surrounding areas.

4.5 Major Challenges and Constraints in Open Water Fisheries Development

Fisheries being a state subject, management is under individual state control, and the management practices followed by individual states vary greatly from auctioning to nearly free fishing access (Vass and Sugunan 2009). Cooperative societies and the state-level fisheries development enterprises are active in fishing and marketing operations, with varying degrees of involvement within the same state (Ciji et al. 2021). The following are the key constraints for open water fisheries development.

1. *Habitat fragmentation and environmental degradation*: Massive soil erosion and bank sliding, caused by water-level variations, lead to a buildup of debris and sediments at the base of the water bodies. These suspended solids and sediments damage fish habitat and reduce productivity. It also damages fish feeding and breeding grounds. Management practices like landscaping and waterscaping can be adopted to reduce shore erosion and sediment deposition. Further, creation of natural vegetation along the shore helps to stabilize

Table 4.5 Lakes in the temperate Himalayas

Name of the lake and state	Altitude (m) and surface area (ha/km^2)	Fishery (if documented any)
Jammu and Kashmir		
1. *Floodplain lakes*		
Wular lake	1537; 153.6 km^2	*Schizothorax niger*, *S. planifrons*, *S. micropogon*, *S. curvirostris*, *Schizothoraichthys esocinus*, *Labeo dero*, *L. dyocheilus*, *Crossocheilus latius*, *Gambusia affinis*, *Puntius conchonicus*, *Glyptothorax kashmiriensis*, and *Cyprinus carpio*
Dal lake	1585; 11.45 km^2	
Manasbal lake	1587; 2.81 km^2	
2. *Glacial (mountain) lakes*		
Gangabal	3570; 157 ha	Brown trout
Nundkul	3550; 10 ha	
Vishansar	3817; 10 ha	
Kishansar	3677; 40 ha	
Alpather	3200; 8 ha	
Konsernag	3670; 140 ha	
Tarsar	3713; 5 ha	
Seshnag	3570; 51 ha	
Tulian	3750	
Gadsar		Schizothoracine *Diptychus maculatus*
Zumsar		
1. *Alpine (forest) lake*		
Nilnag	2180	
2. *Brackish water (saline) lakes*		
Tso Morari	4541	
Pangong Tso	4329	
Siwalik lakes		
Surinsar	604	
Mansar	666	
Uttarakhand		
Nainital	1938; 48.2 ha	*T. putitora*, *Schizothorax richardsonii*, *Cyprinus carpio*
Bhimtal	1331; 72.3 ha	*Tor tor*, *T. putitora*, *Schizothorax richardsonii*, *Cyprinus carpio*
Naukuchiatal	1220; 44.5 ha	*Tor tor*, *T. putitora*, *Schizothorax richardsonii*, *Cyprinus carpio*
Khurpatal	1670; 13.4 ha	
Sattal	1286	
Himachal Pradesh		
Surajtal	4800	
Chandratal	4270	Brown trout
Renuka	875	
Khajjir	2060	

(continued)

Table 4.5 (continued)

Name of the lake and state	Altitude (m) and surface area (ha/km^2)	Fishery (if documented any)
Rewalsar (Sarkar et al. 2016)	1400; 0.026 km^2	
Sikkim		
Khecheopalri (Kha-Chot-Parli)	1700; 3.79 ha	*Schizothorax* sp., *Cyprinus carpio*, *Garra* sp., *Schistura* sp., *Danio aequipinnatus*
Aritar (Lamphokari)	1402;	
Tsongmo (Changu)	3658; 24.47 ha	
Menmecho	3965;	Brown trout
Samiti		
Tso Lhamu		
Lakshmi Pokhari		
Meghalaya		
Tasek (Hazarika and Kalita 2020)	600; 11.66 ha	*Gudusia*, *Notopterus*, *Oxygaster*, *Salmo stomabacaila*, *Barilius*, *danio*, *Rasbora*, *Accrossocheilius*, *Chagunius*, *Cirrhina mrigala*, *C. reba*, *Garagotyla*, *Labeo*, *Osteobrama*, *Puntius*, *tor*, *Botia*, *Channa*, *Mastacembelus*, *Tetraodon*
Thadlaskein		
Arunachal Pradesh		
Mehao (Sarma et al. 2017)	4 km^2	*Salmo trutta fario*, *Cyprinus carpio*, *Neolissochilus hexagonolepis*, and *Exostoma labiatum*
Ganga (Sarma et al. 2017)	67,500 m^2	*Danio aquipinnatus*, *D. devario*, *Puntius ticto*, and *Rasbora daniconius*

Source: Raina and Petr (1999), Sarkar et al. (2016), Hazarika and Kalita (2020)

shorelines, minimize siltation, and offer shade, resulting in cooler water temperatures.

2. *Introduction and flourishing of undesirable and exotic fish species*: The construction of reservoirs severely disrupts the fish population structure in a river, resulting in the flourishing and multiplication of some fish populations and the decrease or even extinction of others. The accidental and deliberate introduction of some of the exotic fishes harmed native fish fauna. At the same time, a few introduced species proved to be a boon in their fisheries and helped in yield optimization from open waters. In general, the introduction of predatory fish should be avoided. The predominance of weed fishes and the availability of catfishes in good numbers appear to be the key factors inhibiting the development of major carps in sizeable numbers in many of the Himalayan open waters.

3. *Availability of healthy fingerlings for stocking*: A reliable supply of healthy fingerlings of economically important fish species is critical for adequate stocking and replenishment in open water bodies.
4. *Eutrophication and destratification in the deeper waters*: The excessive growth of aquatic weeds, which causes eutrophication, has a negative impact on the fishery. To avoid eutrophication, herbivorous fish species such as *S. richardsonii*, *G. gotyla*, and *Crossocheilus latius*, as well as a few exotic fish such as *C. idella* and *H. molitrix*, can be introduced. On the other hand, decreased sunlight penetration in deeper waters of lakes and reservoirs at certain times of the year limits primary production. Hence, thermal and oxygen stratification are prevalent in lakes and reservoirs. These anoxic conditions reduce habitat availability and have the potential to affect water quality.
5. *Conflicts of interest/stakeholders conflict*: There is always some conflict of interest among the different stakeholders, which impedes the overall development of the open waters. Sustainable development of its fishery would need policy and governance intervention from stakeholders apart from fisheries departments or researchers. Fisheries management plans must be established in consultation with concerned officials from the respective departments of the fishery, irrigation/water resources, tourist, forest and wildlife, power corporations, environment, NGOs, local communities/fishers, and civil society.
6. *Inadequate and lack of scientific management*: Inadequate and lack of scientific fisheries management practices resulting from poor knowledge of their ecology and limnology, paucity of indigenous fish fauna, inappropriate stocking, and irrational/overexploitation of the stocks have reduced the overall productivity and efficiency in most of the upland waters.
7. *Inefficient harvesting systems*: Due to uneven bottom terrains in the most open waters, efficient harvesting of demersal fishes is often challenging. Excessive siltation and soil erosion cause debris and sediment accumulation, making fishing activities cumbersome. Lack of proper planning for fishery activities in reservoirs during the pre-impoundment period (due to submerged tree stumps, rocks, etc.) makes fishing further difficult. Therefore, improving gears for bottom-dwelling fishes needs to be done to ensure an efficient harvest.
8. *Market accessibility*: Most fish caught in upland waters are marketed locally. The establishment of adequate storage, transportation, and marketing facilities will allow the fish catch to be marketed to distant urban areas, increasing fishermen's revenue and profitability.
9. *Poor data collection*: A fundamental gap in formulation of scientific management plans is the lack of reliable catch statistics and production estimates from open water bodies. Most of these resources' production figures are erroneous and unreliable, making it difficult for policymakers to establish strategic development strategies.
10. *Inadequate institutional and political recognition*: The contribution of upland open water fisheries to the national fish production is relatively small, and hence, it receives minimal attention from the government. Most policymakers, for example, are unaware of the relevance of fisheries in satisfying the nutritional

and livelihood security of upland fisher folks. In the majority of these resources, fisheries have been developed as a secondary activity. Hence, fisheries impact assessment studies are typically overlooked or not given due consideration while impounding a river or constructing (pre-impoundment phase) a reservoir (Vass and Sugunan 2009). Therefore, representation from fisheries departments in the open water resource management bodies is essential for better fisheries management. The absence or inadequacy of clearly defined rights and institutional support makes it difficult to obtain political and financial support for fisheries development and management in Himalayan open waters. Hence, new institutional arrangements must be created to coordinate open water fisheries development with other concerned partners.

4.6 Strategies for Enhancing Fish Production and Livelihood Opportunities from Himalayan Open Waters

Aquaculture (cage and pen culture) and stock enhancement (ranching) can help to improve fish production and livelihood support from Himalayan open waters. The establishment of hatcheries and captive breeding of threatened and endangered fishes such as mahseer (*T. tor* and *T. putitora*) and their subsequent ranching into open water bodies can be practiced for stock replenishment. The fish yield would improve further by protecting breeding and feeding grounds, as well as promoting selective and seasonal fishing. While impounding a river for developmental activities, the construction of fish passage/fish ladders to facilitate upstream and downstream feeding and spawning migration must be considered to safeguard the migratory fish biodiversity. The lakes and reservoirs are also popular tourist and recreational places; they must be sensibly used for fisheries development. Certain lakes and reservoirs can be declared as protected and conserved areas to protect natural fish biodiversity. Community ownership and involvement of fisheries cooperatives/federations in managing water bodies will aid in the development and maintenance of sustainable fisheries. Along with this, strict enforcement of rules and regulations (mesh size regulation, catch limits, closed areas, closed season, licensed fishing, etc.) must be ensured to prevent overfishing, and defaulters/encroachers should be punished. In addition, prohibition of destructive fishing methods, such as the use of explosives, poisons, snatches, and fishing traps, and fishing in places at times they congregate for breeding have to be strictly prohibited. Restoration of riparian vegetation around lakes and reservoirs to stabilize the shoreline for reducing erosion and turbidity problems must be considered. Therefore, an extensive program of afforestation of mountain slopes around the water body with appropriate plant species should be initiated. Lastly, establishing postharvest infrastructure and cold chain facilities with the active involvement of fishermen cooperatives can further strengthen open water fisheries development in Indian Himalayas.

Fishery-based ecotourism and fish watching in upland lakes and reservoirs are other emerging potential areas for employment generation. The revenues generated through fishing licenses support fish and wildlife management, while the expenditures by anglers and tourists incurred on recreational fishing contribute to local employment generation. Moving shoals of fishes in various sizes, colors, and shapes always delight visitors, especially children. To attract tourists, such fish watching spots may be developed in upland lakes and reservoirs.

4.7 Conclusion

Himalayan open water resources can become a vital part of inland fishery resources of India, not only by enhancing the country's inland fish production but also by providing food and nutritional/livelihood security to the upland population. However, contribution of Himalayan open water resources to the national fish basket remains minimal. Hence, strict enforcement of scientific management approaches is required to utilize these open water resources to their maximum potential and maintain it at a sustainable level. Strict adherence to fishing rules, formation and active involvement of fisheries cooperatives, and initiation of a number of fishermen welfare schemes such as risk fund, accidental insurance, and fishing closed season assistance schemes, among others, will undoubtedly increase fish production and livelihood opportunities from pristine Himalayan open water resources.

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5 Diversity and Threat to Cold-Water Fishes of the Torsa River at the Terai Region of West Bengal, India

Archana Sinha, Satish Kumar Koushlesh, Kavita Kumari, T. Nirupada Chanu, Aparna Roy, and Pranab Gogoi

Abstract

Rivers are the lifeline of mankind and provide livelihood to the riparian. Biodiversity is an important issue for environmental and biological stability. Biodiversity totally depends on climate, temperature, and natural resources. A huge diversity of flora and fauna are present in Terai and Duars regions of North Bengal, India. The Terai region of West Bengal has the Torsa River as a perennial river with a total length of 358 km. Its origin is from the Chumbi Valley in Tibet, which later joins Kaljani at Balarampur, North Bengal, India, and finally meets with the Brahmaputra by the name of Kaljani in Bangladesh. The Torsa receives a tributary of the Raidak River 29 km southeast of Koch Bihar. More than 100 ichthyofaunal diversities are recorded from this stretch. *Cyprinidae*, *Bagridae*, *Sisoridae*, and *Cobitidae* are the dominating families in Torsa River and its tributaries. However, there are several threats encountered to destroy the fish diversity and their environment. Some of the natural factors like alteration of river flow and sedimentation and anthropogenic factors like water pollution, overfishing, and use of nonconventional fishing gear indicate that the ecosystem is at risk. According to IUCN, 22 species are categorized under the "rare" or "very rare" category. There is an urgent need to investigate further the declining trend of fish species for their conservation. Nevertheless, socioeconomic development is

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nearly absent in this area. It is also marked by the accumulation of varied natural resources like forest, water (both surface and subsurface areas), medicinal plants, ferns and fodders, etc., including human resources. The present chapter explores the possibilities of optimum utilization of resources toward the fulfillment of fishery management and rapid economic upliftment of the people residing in and around.

Keywords

Fish diversity · Riverine fishery · Torsa River · Fishing methods · Conservation

5.1 Introduction

Riverine fishery resources in India provide ample food supply and livelihood security to millions of people, especially in rural areas. The country is bestowed with rich riverine resources having 14 major rivers covering 83% of the drainage basin and contributing 85% of surface flow (Das et al. 2012). The Indian rivers support one of the richest biodiversity reserves in the world (Vass et al. 2011), and the checklist showed that the primary freshwater fish species were 1035 in number (Froese and Pauly 2021). Identification and documentation of fish diversity and its population structure are very important in estimating the fishery potential of the river. The fish species diversity in the rivers mainly depends on various ecological variables, viz., size of the river, surface area, mean annual river discharge, temperature, depth, water movement, channel morphology, substrate, and climate (Welcomme 2002; Bunn and Arthington 2002; Proff and Zimmerman 2010). For the last few decades, riverine ecosystems have suffered the most due to human interventions that have resulted in water quality degradation and habitat loss; consequently, several fish species have become endangered (Lakra et al. 2010). Besides, Indian rivers are under severe threat due to excessive erosion, deposition, shifting of riverbanks (Resmi et al. 2019), and anthropogenic exploitation of fish resources, as is noticed in Torsa River (Sarkar et al. 2015). Inland water resources of Asian countries are heavily exploited due to the rapid growth of populations, increasing demands for irrigation, exploitation of fish, transportation, and industrial development (Dubey et al. 2012). For this, a sustainable river management plan must be carried out comprehensively (Boon 2000). The riverine capture fishery resources showed a declining trend in recent years due to anthropogenic stress resulting from water obstruction, increased sedimentation in the riverbed, environmental degradation due to industrial and domestic effluents, the introduction of exotics, indiscriminate fishing, pollution, and climate change (Boopendranath et al. 2002; Vass et al. 2011; Das et al. 2012, 2013).

Torsa is one of the most important transboundary rivers traversing through hills in Bhutan into the Terai region of North Bengal and ultimately flowing into the Brahmaputra drainage system in Bangladesh. It rises from the Chumbi Valley in Tibet, known as Machu. It flows into Bhutan, where it is known as the Amo Chu, and

Fig. 5.1 A view of Torsa River in Koch Bihar, the Terai region of West Bengal

finally, it flows into West Bengal, India, and Bangladesh, where it is called Torsa. The river is a glacier-fed perennial ecosystem exhibiting fast-flowing mesohabitat in its higher reaches and moderately flowing shallow to deep run along lower stretches. This basin area comprises mainly three blocks which are Cooch Behar-I, Cooch Behar-II, and Mathabhanga-II. All those blocks in this basin area provide huge possibilities for applied geomorphological and hydrological investigation, which have attracted many intellectuals from different fields of knowledge.

This varying degree of longitudinal mesohabitat distribution supports a rich diversity of fishes, many of which are typically associated with cold-water habitat, thus, forming important recreational as well as subsistence-level fishery along the Terai region of North Bengal (Fig. 5.1). The high degree of species richness of fishes has been a subject of study since many decades, viz., Shaw and Shebbeare (1937), Hora and Gupta (1941), Menon (1954), Jha et al. (2004), Chakraborty and Bhattyacharjee (2008), Sarkar and Pal (2008, 2018), Acharjee & Barat (2014), Patra and Datta (2010); Das (2015); Debnath (2015), Dey et al. (2015), and Sarkar (2018). Sarkar et al. (2015) did a rapid survey on ornamental fish diversity of Torsa River and listed 24 indigenous ornamental fish species, belonging to 8 orders, 12 families, and 19 genera. Recently from the river, 53 fish species were reported by the researchers; out of that, 37 species belonged to small indigenous fish species. However, most of these studies had focused on diversity rather than a little on the fishery. The information on the most basic fishery level traits, viz., catches per unit hour, catch composition, and length-weight relationship, could be beneficial for the management of the fisheries sector not only in the Torsa River but also in other ecologically similar riverine stretches of the Brahmaputra drainage system. There is a big threat to indigenous cold-water fishes due to the introduction of exotic fishes. A large number of exotic fishes are recorded by Singh and Lakra (2011).

5.2 Experimental Survey of the Torsa River

The study was conducted to document the status of fish diversity, environmental threat, and socioeconomic parameters covering the representative stream reaches with three sampling stations across the 100-km-long main channel of the Torsa River, located in West Bengal, India (Fig. 5.2), from December 2014 to February 2016. The spatial stratification of the study design was based on the hydrological dynamics, geomorphology, and published literature. The upper stretch of the river is highly rocky and scattered with cobbles and boulders in some parts, while the lower stretch is mainly sandy with dispersed pebbles. The temporal stratification in the study design was based on river basin seasonal hydrology. The selection of stations was based on river geomorphic (stream order, sinuosity), hydro-ecology (intermittent or regular riverine stretch), basin geomorphology, accessibility, and availability of published literature on riverine fishes. These sampling stations were Jaldapara (Site-S1), Kachuban (Site-S2), and Tufanganj (Site-S3) (Fig. 5.1). The station code S1 represents the upper, S2 represents the middle, and S3 represents the lower stretch of the river.

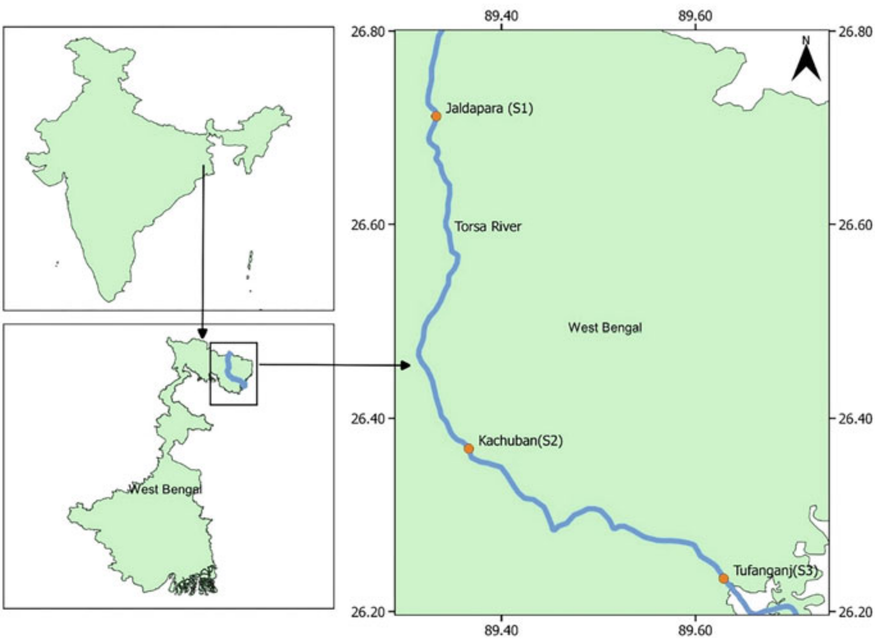


Fig. 5.2 Study area map of Torsa River, West Bengal, India

The sampling strategy adopted ad hoc use of multiple gears of various mesh sizes, viz., gill nets (10–120 mm), scoop net (0 mm), cast net (10–30 mm), deploying hook and lines (no. 25 to no. 10), local traps, etc. to ensure finfish representation across all available habitat guilds. The collected samples consisted of fish specimens caught through diurnal experimental fishing operations employing experienced fishers. Phenotypically distinct fish specimens were identified at the field. The rest of the specimens were fixed in 10% formaldehyde solution and brought back to the laboratory at ICAR-CIFRI, Barrackpore, for taxonomic identification using standard taxonomic keys (Talwar and Jhingran 1991; Jayaram 1981, 2010). The fishes were classified following Van der Laan et al. (2022). The identification and quantification of planktonic community was carried out in laboratory using standard literature.

The station-specific relative abundance (RA) of fish species was calculated using the following formula:

RA = Number of specimens of species (n) × 100/Total number of samples (N).

The fish diversity indices were calculated as per the standard method of Shannon (1948):

$$H = \sum\nolimits_{i=1}^{n} \left(\mathrm{Log} \left(\frac{n_i}{N} \right) \right)$$

where H = Shannon index of diversity; n_i = total numbers of individuals of species; and N = total number of individuals of all species.

Simpson's dominance index (Harper 1999) was used for assessing the biodiversity of habitat toward the number of species and abundance of each species, and the formula used for that was as follows: $D = \frac{\sum n(n-1)}{N(N-1)}$.

where n and N represent the number of individuals in each species and the total number of individuals, respectively. The Simpson index of diversity is measured by subtracting the value of D from 1 and denoted as $1 - D$. Evenness (Harper 1999) was used to measure the relative abundance of different species comprising of the richness of an area and calculated by the following formula:

$$E = \mathrm{e}^{\mathrm{H}'/\mathrm{S}}$$

The Margalef index (d) (Margalef 1968) was used to measure the species richness by the formula $d = (S - 1/\mathrm{Ln}\ N)$, where S is the total number of species and N is the number of individuals in the sample.

5.3 Composition, Abundance, and Diversity of Phytoplankton

The present study recorded the presence of only 25 genera of phytoplankton. The generic diversity was the highest for class Bacillariophyceae (10) followed by Chlorophyceae (7), Myxophyceae (3), Xanthophyceae (2), and Coscinodiscophyceae (2). The lowest species diversity was observed in class Hydrodictyaceae (1). Compositions of six major algal classes represented

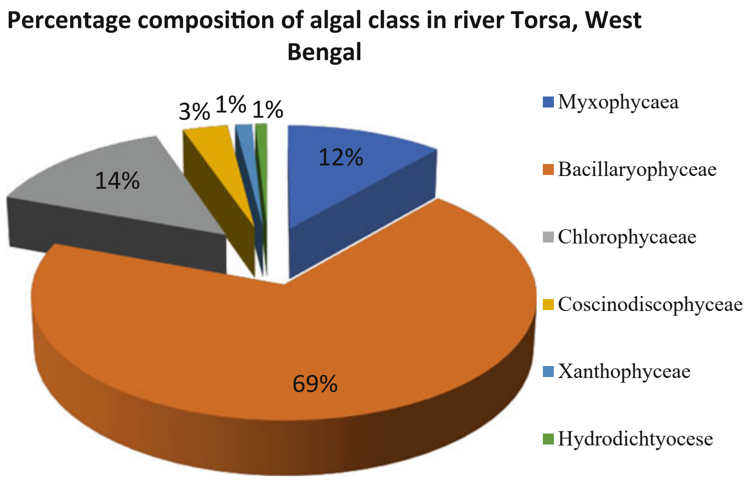


Fig. 5.3 Compositions of algal class in Torsa River, West Bengal, India

(Fig. 5.2) Bacillariophyceae (69.16%), Chlorophyceae (14%), Myxophyceae (12%), Coscinodiscophyceae (3.2%), Xanthophyceae (1.2%), and Hydrodictyaceae (0.8%). The phytoplankton under Bacillariophyceae showed the highest dominance across seasons in terms of abundance and diversity in Torsa River. Among diatoms on a generic level, *Fragilaria*, *Synedra*, *Cymbella*, *Nitzschia*, *Navicula*, and *Gomphonema* had been recorded as dominant taxa from this river. Euryhaline *Coscinodiscus* sp. is recorded only at S3 (Tufanganj) during winter (December). Green algae (Chlorophyceae) comprised of mainly *Spirogyra*, *Chlorella*, *Cladophora*, and *Oedogonium* were found to be common in all stations. Myxophyceae represented by *Oscillatoria*, *Anabaena*, and *Spirulina* were found to be very common during monsoon and post-monsoon season in all stations. *Hydrodictyon* sp. commonly known as “water net” was recorded at S2 (Kachuban) during pre-monsoon (Fig. 5.3).

The phytoplankton community showed varied abundance in different seasons during the study period. The mean quantitative abundance of phytoplankton ranged from 0.54 to $4.9 \times 10^3\ L^{-1}$. Seasonal abundance revealed peak in post-monsoon ($1.3–4.9 \times 10^3\ L^{-1}$) and the lowest in monsoon season ($0.54 \times 10^3\ L^{-1}$ to $2.1 \times 10^3\ L^{-1}$). During post-monsoon, the highest abundance was recorded at S2 followed by S3. The lowest plankton abundance was recorded at S1 in both post-monsoon and monsoon season. Species diversity index (H′), dominance index (D), species richness index (d), and evenness index (J) values showed spatial and temporal variations. Analysis revealed that all stations showed richness and diversity index >1.0 that indicated moderate diversity in total study period. Shannon-Wiener diversity index was found to be the highest at S2 (2.1) and the lowest at S1 (1.2).

Table 5.1 Checklist of fishes recorded from the Torsa River stretch

Sl no.	Fish species	Conservation status (IUCN Red List, 2022)
Order: Cypriniformes; family: Cyprinidae		
1	*Chagunius chagunio*	LC
2	*Labeo catla*	LC
3	*Cirrhinus mrigala*	LC
4	*C. reba*	LC
5	*L. boga*	LC
6	*L. calbasu*	LC
7	*L. dyocheilus*	LC
8	*L. pangusia*	NT
9	*T. putitora*	EN
10	*Garra nasuta*	LC
11	*Tariqilabeo latius*	LC
12	*C. semiplotum*	VU
13	*Oreichthys crenuchoides*	DD
14	*Pethia conchonius*	LC
15	*P. Ticto*	LC
16	*Puntius sophore*	LC
17	*Systomus sarana*	LC
Family: Danionidae		
18	*Salmostoma boopis*	LC
19	*Cabdio jaya*	LC
20	*C. Morar*	LC
21	*Opsarius barna*	LC
22	*Barilius bendelisis*	LC
23	*B. Torsai*	NE
24	*Devario devario*	LC
Family: Cobitidae		
25	*Lepidocephalichthys guntea*	LC
Family: Nemacheilidae		
26	*Paracanthocobitis botia*	LC
27	*Aborichthys elongatus*	LC
28	*Schistura beavani*	LC
Family: Botiidae		
29	*Botia birdi*	NE
Order: Siluriformes; family: Amblycipitidae		
30	*Amblyceps apangi*	LC
Family: Sisoridae		
31	*Pseudecheneis sirenica*	VU
32	*Glyptothorax indicus*	LC
33	*Pseudolaguvia ribeiroi*	LC
34	*Pseudolaguvia foveolata*	DD
35	*Gagata cenia*	LC

(continued)

Table 5.1 (continued)

Sl no.	Fish species	Conservation status (IUCN Red List, 2022)
Family: Ailiidae		
36	*Ailia coila*	NT
Family: Siluridae		
37	*Ompok pabda*	NT
Family: Bagridae		
38	*Batasio merianiensis*	DD
39	*B. batasio*	LC
40	*Mystus cavasius*	LC
41	*M. tengra*	LC
42	*Sperata aor*	LC
43	*Rita rita*	LC
Order: Beloniformes; Family: Belonidae		
44	*Xenentodon cancila*	LC
Order: Gobiiformes; Family: Gobiidae		
45	*Glossogobius giuris*	LC
Order: Mugiliformes; Family: Mugilidae		
46	*Rhinomugil corsula*	LC
Order: Perciformes; Family: Ambassidae		
47	*Chanda nama*	LC
48	*Parambassis ranga*	LC
Order: Anabantiformes; Family: Nandidae		
49	*Nandus nandus*	LC
Order: Anabantiformes, Family: Channidae		
50	*Channa gachua*	LC
51	*C. punctata*	LC
Order: Synbranchiformes; Family: Mastacembelidae		
52	*Macrognathus pancalus*	LC
53	*M. aral*	LC

LC least concern, *NT* not threatened, *EN* endangered, *VU* vulnerable

5.4 Fish Diversity, Conservation Status, and Threats

The survey conducted under the present study recorded 53 fish species under 8 orders and 17 families (Table 5.1) at 3 stations, viz., S1, S2, and S3, during the study period. A taxon-based comparison showed that the catch composition of fishes was dominated by Cypriniformes (29 species) and Siluriformes (14 species). Among family-wise comparisons, Cyprinidae (17 species), Danionidae (7 species), Bagridae (6 species), and Sisoridae (5 species) were recorded as the most dominant in fish catches (Figs. 5.4 and 5.5). The indices-based assessment of fish diversity of Torsa River revealed high diversity along the studied stations S1, S2, and S3 (Shannon H;

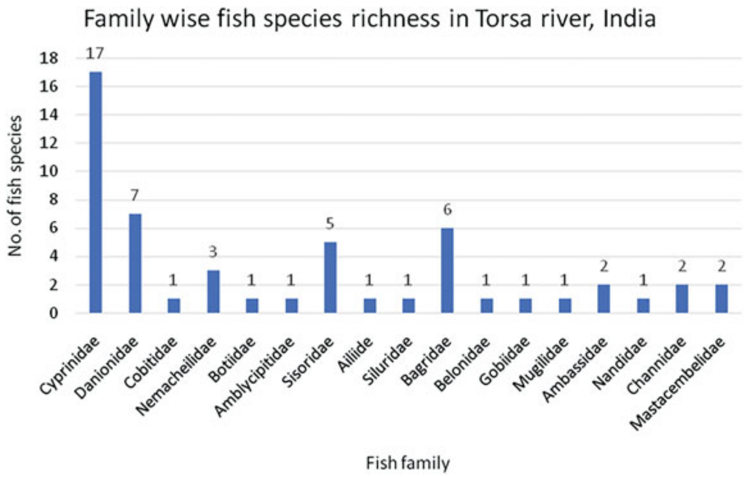
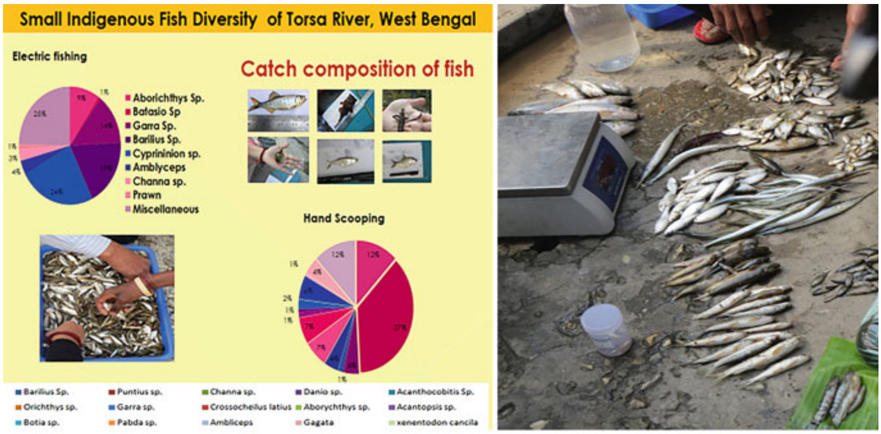


Fig. 5.4 Family-wise fish species richness in the Torsa River, West Bengal

3.294–3.424). The results in Table 5.2 also depicted a high degree of evenness among the fish community across S1, S2, and S3. The present study could record only about half of the cumulative fish diversity as reported by the previous studies (Dey et al. 2015; Sarkar 2021). Menon (1962) recorded 218 cold-water fish species in the whole Himalayas. A total of 218 cold-water fish species were found by Ali (2010) in Assam, 121 in Manipur, 68 in Nagaland, 167 in Arunachal Pradesh, 134 in Tripura, 165 in Meghalaya, and 48 in Mizoram. Recently, Sarkar (2021) has reported presence of 66 cold-water fish species from Torsa River.

The present study indicated that more than two-thirds of the reported fish diversity, i.e., 42 species, were categorized as Least Concern under IUCN Red List criteria 2022 (Fig. 5.4). Among the three fishes identified as threatened, *Tor putitora* is categorized as Endangered (EN), while *Cyprinion semiplotum* and *Pseudecheneis sirenica* as Vulnerable (VU). Despite a large number of the fishes categorized as the Least Concern (LC), the regional fishery managers need to monitor and enforce responsible fishery practices as a review of potential impact of anthropogenic aberrations on fish habitat and its dynamics (Sarkar et al. 2012; Hamilton et al. 2017; Affandi and Ishak 2019) suggests that the fishes inhabiting Torsa River face threats from mining activity in upstream as well as peripheral areas. Construction of high walled cascades of cross river obstacles along the hilly region in Bhutan could, in turn, impact the potamodromous fishes such as *T. putitora* and *C. semiplotum* via altering river discharge dynamics in the downstream areas of Terai region. Also, long-term impact of the slow but progressive sedimentation along the channel basin needs detailed monitoring protocols to establish a mechanism in the fishery dynamics in Torsa River. Bhutan's illegal dolomite mining has severely harmed the Dooars region's rivers. Another potential threat could be from land runoff carrying agricultural chemicals progressively driven by increased deforestation and erosion in the region. Deforestation of mountains has increased soil



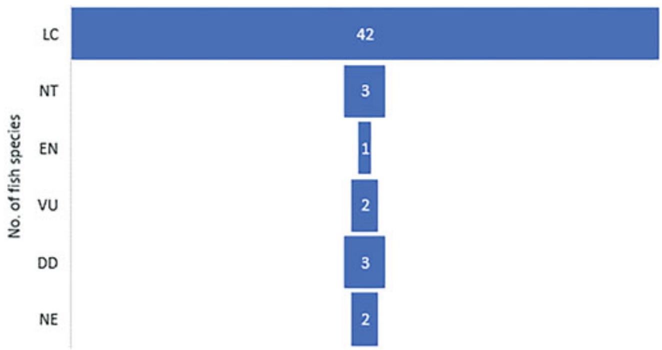


Fig. 5.5 Conservation status of fishes in the Torsa River, India

Table 5.2 Indices-based fish diversity in Torsa River, West Bengal, India

	Jaldapara (S1)	Kachuban (S2)	Tufanganj (S3)
Taxa_S	40	35	32
Individuals	667	561	492
Dominance_D	0.04867	0.0363	0.0423
Simpson_1-D	0.9513	0.9637	0.9577
Shannon_H	3.334	3.424	3.294
Evenness_e^H/S	0.7009	0.8768	0.8423
Margalef	5.997	5.371	5.001
Equitability_J	0.9037	0.963	0.9505

erosion, which has resulted in high siltation of rivers and streams and compromised this fish's basic ecological needs. Further, population size declines because of overfishing or indiscriminate fishing (Sarkar et al. 2008) which has posed as a threat

A. *Barilius torsai*: lateral aspect of holotype, 71.41 mm SL

B. *Barilius torsai* : lateral aspect of paratype, 74.56 mm SL

Fig. 5.6 (**a**) and (**b**) *Barilius torsai*, a new species reported from Torsa River

to the biodiversity in Torsa River. Indiscriminate fishing methods like electrofishing, among others, result in the widespread extinction of fish species and a sharp decline in population size. These methods are posing a risk to the fish recruitment of seasonally migrating potamodromous fishes in the river channel. The risk from invasive species introduction in the river system has also been identified in the Torsa River (Koushlesh et al. 2018; Sarkar 2021). Two new species of fishes *Channa quinquefasciata* (Praveenraj et al. 2018) and *Barilius torsai* (Kumari et al. 2019) were recorded for the river (Fig. 5.6).

5.5 Small Indigenous Fish (SIF) Catch Analysis

Catch composition of small indigenous fishes during winter by cast net, gill net, and lift net was 100%, 33–94%, and 90.4%, respectively, whereas during monsoon, catch composition by gill net and cast net was 44–58% and 48%, respectively (Fig. 5.7).

5.6 Electrofishing in the River

There are several destructive fishing methods due to which the fish diversity is declining in the Torsa River of the Terai region in North Bengal. Electrofishing is one of the methods used as destructive fishing. As this method kills almost complete fish diversity, including live food of the area where electrofishing is operative, it is banned by the Fisheries Department of West Bengal. Even after the ban on such fishing methods, due to its destructive nature, electrofishing is being practiced by the local fishers illegally in the Torsa River, around the Jaldapara National Park

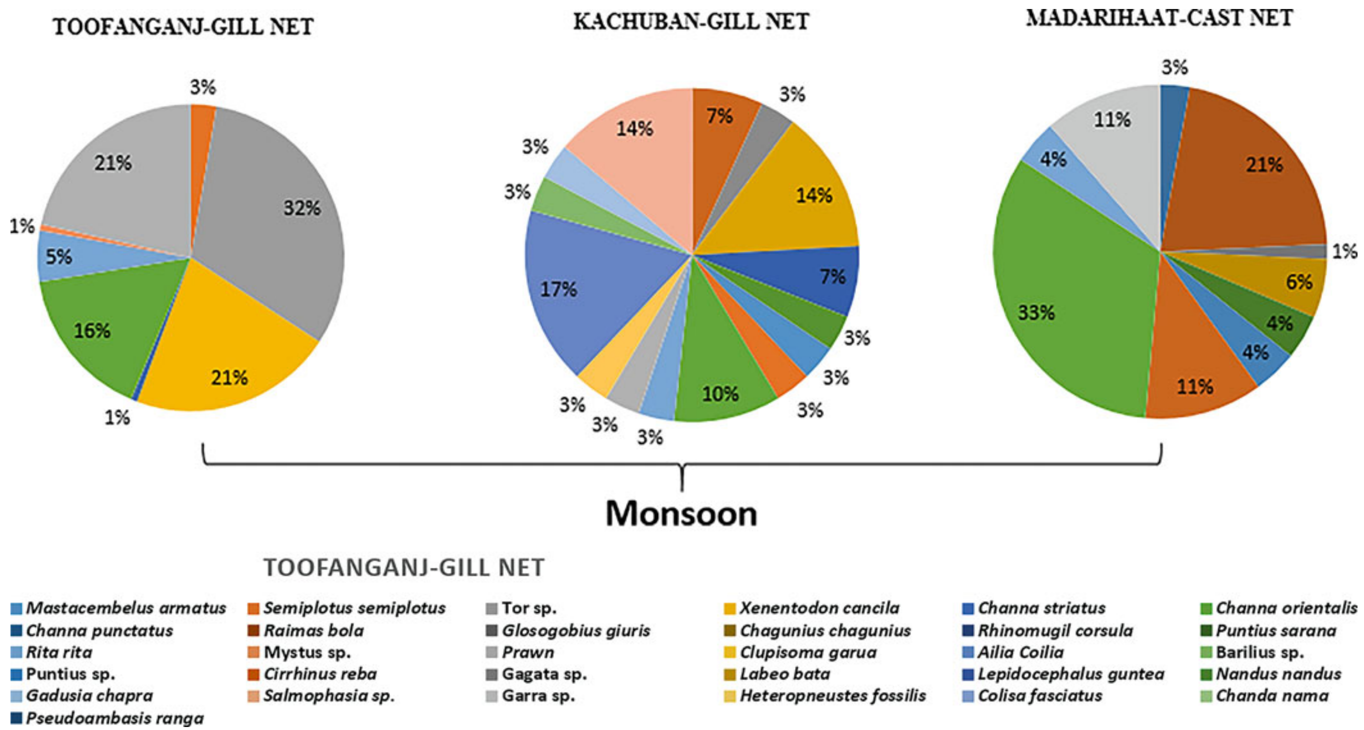


Fig. 5.7 Fish catch composition of Torsa River during monsoon and winter

Fig. 5.8 Electrofishing and fish catch

Complex. Local fishers usually use a battery of a motor car or bike as a source of power for the electrofishing which is usually operated by two men: one man stuns the fishes by providing electric shock, while the other one collects the stunned fishes flowing with water by putting a triangular scoop net downstream. It was observed that, during an hour of electrofishing operations, around 1 kg of small indigenous fishes were caught which were in alive conditions for a certain time (Fig. 5.8). The fish species caught in this process are from different families and orders dominating with *O. pabda*, *C. stewartii*, *Crossocheilus latius*, *Garra lamta*, *Systomus sarana*, *T. putitora*, *Opsarius bendelisis*, *Neolissochilus hexagonolepis*, *Macrognathus pancalus*, etc. Putitora mahseer, *T. putitora* (Hamilton, 1822), an Endangered (EN) species, are also recorded by the researchers in the catch. The method is of course cost-effective, but it is highly destructive and against the sustainable fisheries development. There is a need to make people residing around the river bank aware to protect the wealth for the new generation. Research institutes and government organizations should develop conservation sites for the declining fisheries of the area.

5.7 Assessment of Livelihood Support and Community Knowledge Related to Fishes

In the Terai region, the major problem faced by the fishers was the decline in fish production in the Torsa River, and major reason, as perceived by the fishers, was the use of destructive fishing methods, viz., electric shock, use of poison, and use of dynamites in the river. Use of havoc chemical pesticides in tea gardens was perceived as another reason by the fishers for the decline in fish production from the Torsa River. Use of small meshed fishing nets, siltation, and erratic rainfall were yet other reasons as perceived by the fishers for declining fish production. Tribal population, viz., Rajbansi, Oraon, Rava, and Toto, is quite dominating in the Torsa River stretch area. They harvest fish from the Torsa River by using several indigenous traps like Tapai, Burung, Chapua, Jhakoi, Bonas, Thusi, etc.

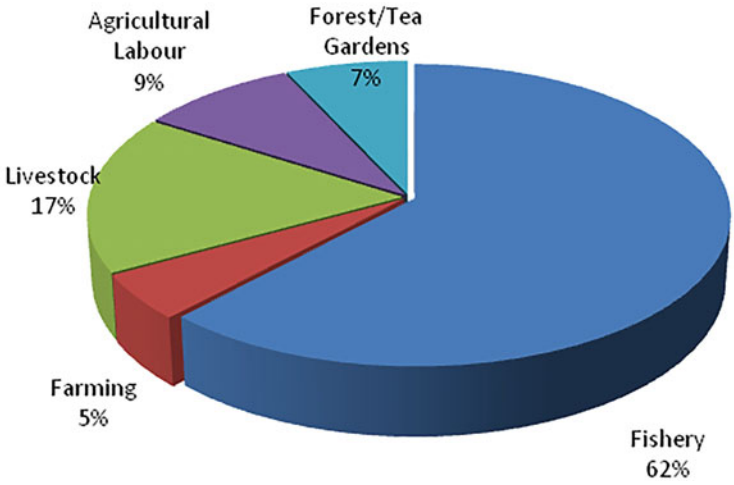


Fig. 5.9 Contribution of livelihood activities in family income

5.8 Gender Desegregation for Activities Performed by Men and Women

In the Torsa River area, particularly in upper stretch from Totopara to Madarihat, women involvement in fishing activities was prevalent. It was found that about 52% of women of fishermen community had high involvement in fish catching, whereas 48% of them had high involvement in fish marketing. Moreover, women were involved in other livelihood activities like livestock rearing and livestock selling and as tea garden laborer. But, the educational status of women was really poor than that of their male counterparts of the fishermen community of Torsa region. Among the women, 50% illiteracy was found (Fig. 5.9). The average annual income of the female-headed family was Rs. 37,250 (~US$ 465) which is lower than the average income of male-headed family, i.e., Rs. 53,100 (~US$ 662). Fish harvest from Torsa river had highest contribution i.e. 62% in the average family income of a fishermen family, followed by livestock rearing (17%), agricultural labourer (9%), tea garden/ forest (7%) and from farming 7%. The expenditure pattern of the fisherfolk was also assessed, and it was found that their maximum expenditure was on food items (59%) and they utilized almost 16% for the education of their children.

5.9 Women's Access and Control over Resources

Women's equal access to and control over resources, i.e., land, capital, knowledge, is critical for the achievement of gender equality and empowerment of women and for equitable and sustainable economic growth and development. Gender equality in the distribution of economic and financial resources has positive multiplier effects for a range of key development goals, including poverty reduction and the welfare of children. But, in Torsa River region, fisherwomen do not have equal access and control over resources. The inability of the fisherwomen to have access to productive resources such as land and capital is the major cause of persistence of chronic poverty among potentially productive groups. Women's access over financial resources is almost nil in Torsa areas; only short-term access is noticed. But, 41% of women have absolute control on housing; that is because in the Torsa River area, the tribal population is also dominant, and in the sampled population, the fisherwomen belonging to tribal community have absolute control over housing.

5.10 Fishery: A Sociocultural Attribute of the Rabha Tribes—A Case Study

The Rabhas belong to the Indo-Mongoloid group and have similarities with other members of the Bodo group, such as Garos, Kachari, Mech, Koch, Hajong, and others. Rabhas are found in 13 states in India, but significant numbers are found in Assam (352,000), followed by Meghalaya (37,000), West Bengal (23,000), Arunachal Pradesh (3300), Nagaland (2700), and Mizoram (200). Rabhas are a unique community, having rich sociocultural inheritance (Roy et al. 2018). According to the rule of lineage, Rabhas belong to the matrilineal family. Rabhas are divided into five Gotras, namely, Rangdania, Pati, Daori, Maytori, and Koch, and after marriage, the Gotras of the women do not change.

Fig. 5.10 Rabhas in traditional fishing dance costume

Fig. 5.11 Dry fish powder prepared by Rabhas

The primary source of livelihood adopted by the Rabhas is agriculture. Jhum, or shifting cultivation, was prevalent earlier. However, nowadays, they cultivate rice, different pulse seed, mustard seed, and other vegetables. In addition to agriculture, considerable sections of the Rabhas are engaged in fishing too. Generally, they are involved in fishing activities in rivers, streams, rivulets, and wetlands for their livelihood. Females are involved in community fishing with handmade traps named as Jhakoi. Other than Jhakoi, the Rabha people use various types of traps like Tapai, Thusi, Burung, etc. for harvesting of fishes.

Fishing is an important activity in the life of the Rabha people, and it is assimilated in their culture in the form of dance, which is performed by the women-folk of the Rabha community for depicting their daily lives. Rabha tribes perform dance with melodious music wearing colorful costumes. Fishing dance (Fig. 5.10) is one of the important dances performed by the Rabha women among the other dances like welcome dance, celebration dance, and war dance. The Rabhas are fond of small indigenous fishes and prawns. They also prepare dried fishes for future consumption (Fig. 5.11). The dried fish powder known as "Nishuchepa" is often taken by the Rabha people, and it is made from the dried prawn or small fishes.

5.11 Conclusion

The riverine stretch of Torsa traversing through West Bengal, India, harbors rich fish diversity throughout its longitudinal reach, thus offering support to subsistence-level fishery activity in the Terai region. Despite many of the fishes categorized as not threatened as per IUCN Red List, it supports endangered *Tor putitora* and vulnerable *C. semiplotum* and *P. sirenia* which highlights its importance as fish refuge and potential for supporting recreational fishery along its periphery. But, channel migration with a varying nature during different time spans is reported continuously. Therefore, the changes in the river course needs to be studied carefully in order to predict the future possibilities which are crucial in understanding the vulnerability potential of a certain region. The cold-water fishery in the Terai region of North Bengal is under threat due to introduction of exotic fishes, overfishing, destructive method of fishing, pollution, climate change, etc. It is, therefore, mandatory to demarcate natural regime as any further encroachment on fluvial regime to escalate the degree of vulnerability of fish diversity for environmental planning with sustainable approach. Public awareness and conservation management of cold-water fishes in the rivers of North Bengal are the need of the day.

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The Endangered Mighty Mahseer (*Tor putitora*) in the Himalayan Waters

6

Md. Shahbaz Akhtar and Alexander Ciji

Abstract

Golden mahseer (*Tor putitora*), also called "mighty mahseer," is a prime fish species in the temperate Himalayas. It plays an important role in the socioeconomic upliftment of the local people in the hill region through fish-based ecotourism and sport fishery. However, due to indiscriminate exploitation and other anthropogenic pressure, the wild stocks of golden mahseer have dwindled significantly in the past, and eventually, it has been declared an "Endangered Species" by the International Union for Conservation of Nature. Therefore, there is an urgent need to conserve and rehabilitate this prime and priced fish species of the temperate Himalayas through different strategies and action plans. The development of breeding technology of golden mahseer helps to provide seeds for stocking in natural and man-made water bodies assuring the conservation of this magnificent fish. The present book chapter briefly describes golden mahseer status, and conservation approaches, emphasizing its captive breeding and seed production.

Keywords

Golden mahseer · Ranching · Angling · Captive breeding · Fish-based ecotourism

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6.1 Introduction

The *Tor* spp., the most magnificent fish group found in many rivers and streams of the Himalayas, is collectively called "mahseer." Taxonomically, mahseer is an iconic group of game fishes belonging to the family Cyprinidae, mostly to the genus *Tor*, but also includes certain species of the genera *Neolissochilus* (e.g., chocolate mahseer, *Neolissochilus hexagonolepis*) and *Naziritor* (e.g., dark mahseer, *Naziritor chelynoides*). Despite some phenotypic similarities, only members of the genus *Tor* are regarded as "true mahseers" (Desai 2003; Nguyen et al. 2008), and this chapter mainly focuses on the *Tor putitora* (Hamilton, 1822), a "flagship" species of the Indian subcontinent. Golden mahseer, king mahseer, mighty mahseer, the tiger of waters, and the king of game fishes (Fig. 6.1) are all common names for *Tor putitora*. The big size, appealing golden color, culinary quality, and fighting abilities of the fish have piqued the interest of the human population, fishermen, and researchers (Bhatt and Pandit 2016). Mahseer has always offered fishermen better sports than salmon (Thomas 1897). There have been reports of 275-cm-long and 54 kg fish in Indian lacustrine waters (Everard and Kataria 2011; Nautiyal et al. 2008). Numerous vernacular names, such as mahseer (big head), mahasaul (huge body), and mahasalka (large scale), are derived from these characteristics (Nautiyal 2014). In addition, mahseers have been revered as "God's fish" for ages over their entire geographic range. Sacred and masculine depictions of fish similar to mahseers may be found in Hindu holy scriptures, symbols, motifs, sculptures, and ancient literature (Jadhav 2009; Nautiyal 2014). At several temple ponds, there is a substantial population of mahseer, and these "temple sanctuaries" or "temple pools" are protected because of the social ideals and feelings of devotees, in addition to the involvement of communities and temple officials (Pinder et al. 2019).

Fig. 6.1 A golden mahseer (*T. putitora*)

6.2 Geographical Distribution

T. putitora (golden mahseer) is found in many Southeast Asian countries including India, Afghanistan, Bangladesh, Pakistan, Nepal, Bhutan, and Myanmar. This species is naturally distributed (Fig. 6.2) throughout the rivers of the South Himalayan drainage (specifically the Indus, Ganges, and Brahmaputra) from Pakistan in the west, all the way through India, Nepal, Bhutan, and Myanmar, with its range extending throughout the Eastern Brahmaputra catchments comprising the north-eastern states of India and Bangladesh (Rahman 1989). In India, golden mahseer primarily inhabits the Himalayan rivers in the foothills, and its range extends from Hindukush-Kabul-Kohistan in the Northwest Himalaya to Sadiya (Brahmaputra) in the Northeast Himalaya. Golden mahseer is a rheophilic species that enjoys rocky/stony/sandy substrates in hill streams (Nautiyal 2014). It also thrives well in semi-lacustrine waters of the Himalayas (Bhatt and Pandit 2016). The mighty mahseer's cylindrical body, muscular tail, and hypertrophied lips enable it to survive in rapidly flowing streams. The temperature range of 15–25 °C is considered optimal for golden mahseer. The species is potamodromous and performs extensive upstream spawning migrations (Bhatt and Pandit 2016).

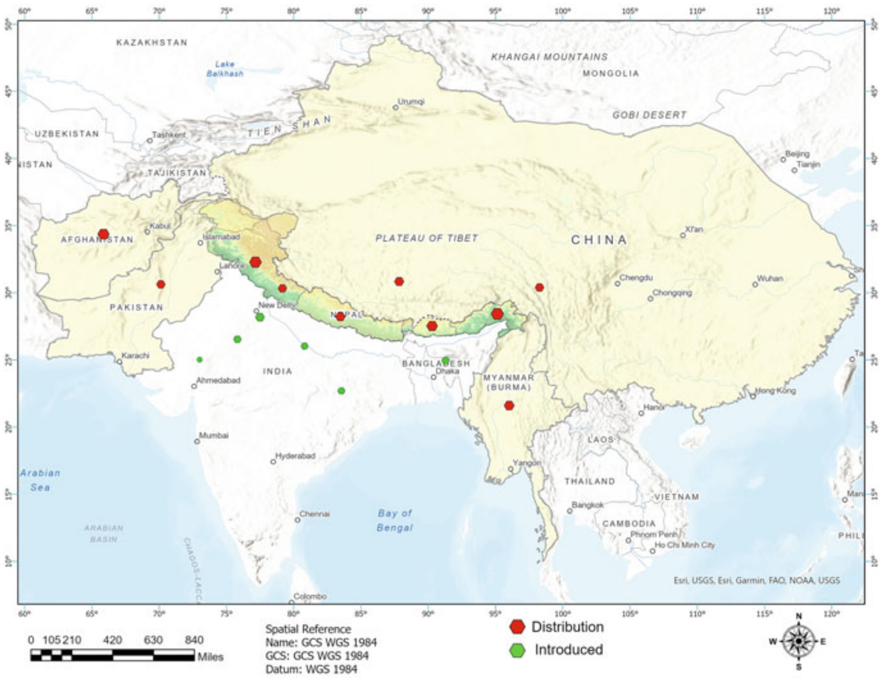


Fig. 6.2 Distribution of golden mahseer (*T. putitora*) across the temperate Himalaya (Map courtesy: Dr. Ravindra Posti)

6.3 Major Threats and Population Status of Golden Mahseer

Mahseer, *T. putitora*, formed a substantial natural fishery in the major riverine and lake ecosystems of the Indian Himalayas. The mahseer population in natural waters has decreased in size and quantity despite once being abundant. The unprecedented population pressure and decline are attributed to anthropogenic activities such as habitat fragmentation, environmental degradation and declining water quality, drainage basin alteration and deforestation, pollution, overexploitation, invasive species, and indiscriminate and destructive fishing (Nautiyal 1994; Sehgal 1999; Dinesh et al. 2010; Akhtar et al. 2017). Inherent biological traits such as delayed maturity, low fecundity, and slow growth rate have also contributed for its population decline over time (Akhtar et al. 2018). Consequently, it is now classified as an endangered species (IUCN 2014) due to the decrease in *T. putitora* populations in several Asian regions (Hussain and Mazid 2001). Females do not attain sexual maturity until they reach 4 years or older (Nautiyal 1994). However, sexually mature males are usually spotted even at 2+ years of their age. The age classes of *T. putitora* most frequently harvested are 2+ to 4+ years. Consequently, catching a significant number of fish before they reach sexual maturity reduces population size (Bhatt and Pandit 2016). Furthermore, *T. putitora*, threatened by overfishing, habitat loss, and degradation, has led to the destruction of its reproductive habitats across the water bodies. It is anticipated that the current proliferation of dams in the Himalayan region, either already built or scheduled to be built, will have a domino effect on the breeding migrations of the species. Because of its economic, sporting, and cultural significance, the golden mahseer has been designated as the "state fish" of four Indian Himalayan states (Arunachal Pradesh, Himachal Pradesh, Jammu and Kashmir, and Uttarakhand). Numerous organizations are working to prevent its further decline (Bhatt and Pandit 2016) through various conservation strategies.

6.4 Food and Feeding Habits

Due to the large mouth opening and size of the golden mahseer, it was once believed that it was a carnivorous fish. Later, studies indicated that food preference varies with age and size (Nautiyal and Lal 1984). For example, hatchlings prefer planktonic food that is abundant in their natural environments, while as fish grows larger, their feeding habit shifts toward carnivory. However, they are opportunists who feed on a variety of plant and animal items. Mahseer has been reported to consume green filamentous algae, small mollusks, insect larvae, and algal coatings on rocks. It was observed that the diet of mahseer fingerlings in the wild comprised of insect matter (81.4%), plant matter (15.9%), and other foods such as fish (1.6%) (Nautiyal and Lal 1984). Hence, the eating preferences of golden mahseer are highly dependent on availability of food. Consequently, several studies classified the species as insectivore, carnivore, herbi-omnivore, and carni-omnivore (Nautiyal and Lal 1984; Das and Pathani 1978; Badola and Singh 1980). In general, the mahseer is a carnivorous fish during its early stage and an omni-herbivore during its adult phase.

6.5 Reproductive Biology

The golden mahseer is a batch spawner, producing eggs intermittently (different size groups of eggs can be seen in the ovary; Fig. 6.3), during its extended breeding season, with the majority of spawning occurring between May and August (monsoon season). No strong sexual dimorphic character is evident in *T. putitora*, although a few secondary sexual characteristics have been documented in hatchery stocks (Fig. 6.4) during the breeding season. Males have bright coloration and an elongated body with rough pectoral fins, whereas females have a dull coloration and a deep body (Arjamand et al. 2013). During spawning season, the ripeness of the female mahseer can be noted by feeling the softness of the abdomen and the pink coloration of the vent. It has a preference for clean water with sandy or gravelly bottoms for breeding and performs potamodromous upstream spawning migrations. It is believed that spawning migration is triggered by turbid waters and elevated

Fig. 6.3 Ovary of golden mahseer containing eggs of different sizes

Fig. 6.4 Captive-reared female (upper) and male (lower) brooders of golden mahseer

water temperatures (Nautiyal 1994; Bhatt et al. 2004). Consequently, during floods, the mahseer ascends to the river's higher reaches, travelling great distances in search of suitable breeding grounds or substratum. They typically lay their eggs in shallow (0.5–3.5 m) streams, containing pebbles, gravel, sand, and silt (Pathani 1994). Suitable spawning environments include riverbanks, where fishes dig nests to lay eggs (Nautiyal 1994). One batch of eggs is released at a time, and the process is repeated numerous times during the breeding season. The fecundity of golden mahseer is very low, ranging from 7 to 25 eggs per gram of body weight (Pathani 1981; Nautiyal and Lal 1985; Nautiyal 2014). The fertilized eggs require 58–192 h to hatch, and because they are demersal, they may sink and die on the muddy riverbeds (Johnsingh et al. 2006). Additionally, their extended developmental period leaves them susceptible to predation. The optimal conditions for egg hatching are high turbidity and temperatures between 16 °C and 25 °C (Johnsingh et al. 2006). In the Indian subcontinent, the predominant spawning grounds of *T. putitora* are distributed throughout the Himalayan river systems (Joshi 1988; Bhatt et al. 2004; Atkore et al. 2011; Shrestha 2002; Dasgupta 1991a, b; Zafar et al. 2001).

6.6 Captive Breeding Technology and Seed Production

After the inclusion of the golden mahseer in the *IUCN Red Data Book* as an endangered species (Jha and Rayamajhi 2010), biologists, conservationists, and policymakers became very concerned about preserving and increasing the existing stock through technological solutions and other conservation methods. Artificial propagation and seed production have been regarded as the most viable strategy for rehabilitating this valuable fish. The production of large quantities of seeds from captive broodstocks, followed by the release of healthy fry into their natural habitat (stock enhancement) has been promoted as one of the possible and pragmatic ways for stock replenishment and conservation (Akhtar et al. 2020). Numerous studies have investigated the reproductive biology/behavior and approach for captive propagation of golden mahseer in numerous Trans-Himalayan nations over the years (Ingram et al. 2005; Sarma et al. 2010; Ismail et al. 2011; Akhtar et al. 2013; Sharma et al. 2016). Unfortunately, golden mahseer fails to complete ovarian development and maturity in captivity due to oxidative stress induced endocrine dysfunctions (Akhtar et al. 2017). Therefore, gravid female brooders, collected from the wild, were exploited in the development of golden mahseer seed production and hatchery technologies in the recent past (Sehgal and Malik 1991; Sunder et al. 1993; Sehgal 1999; Ogale 2002; Sarma et al. 2016). This practice of wild collection of gravid brooders for stripping and artificial fertilization has been demonstrated to be non-sustainable, as gravid wild brooders, collected through gill nets die after stripping (Fig. 6.5). Furthermore, the huge demand of stocking material cannot be achieved from wild brooders. Consequently, the paucity of mature golden mahseer brooders in captivity significantly hindered its large-scale seed production for conservation and rehabilitation.

Fig. 6.5 A trapped golden mahseer brooder in a gillnet (destructive fishing)

Numerous scientists and researchers have attempted captive breeding of golden mahseer using pituitary extract or synthetic hormones during the past four decades with minimal success (Tripathi 1978; Pathani and Das 1979; Pandey et al. 1998; Sehgal 1991). Thus, the lack of mature female golden mahseer brooders in captivity has been a significant barrier to producing seeds on a large scale. ICAR-Directorate of Coldwater Fisheries Research (ICAR-DCFR), Bhimtal, India, the only premier research institute engaged in the research and development of fisheries and aquaculture in the temperate Himalayas, has developed an indoor technology for captive maturation and year-round multiple breeding of golden mahseer (Fig. 6.6) by manipulating different environmental cues (Akhtar et al. 2018, 2020, 2021b). This invention includes a system and method for year-round multiple breeding of golden mahseer to produce fry (Akhtar et al. 2021a, c). Using a unique indoor maturation unit, separate egg incubators, modifying water quality, and simulating breeding and grazing grounds during hatchery operation increased the fertilization, hatching, and fry survival. More than 72% of golden mahseer females were found to respond to egg stripping with the current technology, and a single female brooder was found to breed a maximum of four times and a minimum of two times annually. The average annual relative fecundity of each responding female brooder was calculated to be 9680±811 eggs/kg body weight. As a conservation and rehabilitation measure, hatchery-produced advance fry are now routinely ranched into open water bodies (the temperate Himalayan lakes and rivers), following a 6- to 7-month raising period in nursery tanks.

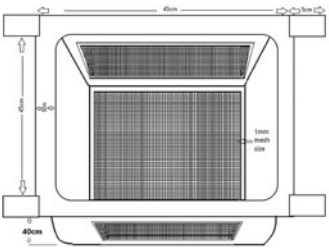
6.7 Mahseer Conservation Strategies

The population of golden mahseer in India is expected to have decreased by more than 50% in the past, and it may reduce by as much as 80% in the future, primarily as a result of the construction of dams across the Himalayan rivers (IUCN 2015;

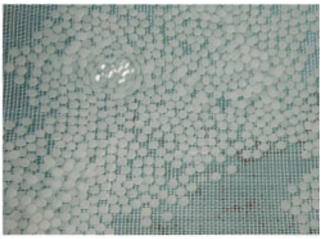
Captive maturation unit

Golden mahseer brooders

Stripping of captive-matured brooder



Golden mahseer egg incubator



Fertilized eggs of golden mahseer matured in captivity

Golden mahseer fry produced from captive-matured brooders

Fig. 6.6 Some important components of the captive maturation and multiple breeding technology of golden mahseer

Sharma et al. 2015). Therefore, the conservation of golden mahseer in the rivers of the Himalayas presents a big challenge for those who work in the conservation field and those who formulate public policy and manage fisheries. To begin the process of recovering golden mahseer, the first thing that needs to be done is to use this species as a “flagship” species to educate people about its positive effects on the environment and the ecosystem (Laskar et al. 2013; Gupta et al. 2014). For the purpose of mounting a mahseer conservation effort that is both effective and focused on achieving particular objectives, recent years have seen the launch of programs like “Project Mahseer,” which is analogous to “Project Tiger” (Nautiyal 2011; WWF 2013). Without stringent protection measures such as the restoration of river connectivity to enable spawning migration, habitat restoration, strict enforcement of rules and regulations (complete fishing ban during monsoon, mesh/equipment size restriction, and penalty for catching/landing small size groups), the establishment of protected areas, etc., conservation and rehabilitation of mahseer may fail. It is possible for various stakeholders, including recreational fisheries groups, to play an important part in the protection of mahseer by practicing catch-and-release fishing. This recreational fishing helps to protect mahseer while also providing employment opportunities and economic benefits to the local fishermen (Bhatt and Pandit 2016; Pinder et al. 2019). It is also recommended that the key sections of the Himalayan rivers be designated as important habitats for the golden mahseer so that it can be protected and brought back to its former glory.

The establishment of hatcheries for ex situ conservation of mahseer is a technique that would be effective over the long run (Bhatt and Pandit 2016). Despite this, there is less number of operational hatcheries in India, dedicated to *T. putitora*. Flow-through mahseer hatcheries have been developed by the ICAR-Directorate of Coldwater Fisheries Research at the Iduli fish farm in Roing, Arunachal Pradesh; the Eco-camp, ABACA, Nameri National Park in Tezpur, Assam; and the Bagua fish farm in Sikkim. If the environment in which we release the fry is fragmented, it is imperative that we adhere to the recommendations made by the IUCN regarding the release, site selection, and longitudinal connectivity (IUCN/SSC 2013). Only then we will be able to successfully disperse hatchery-produced fry into natural water bodies. Ranching operations, in which hatchery-produced healthy juveniles are reintroduced into various temperate Himalayan lakes and rivers, are being carried out on a regular basis by the ICAR-DCFR, Bhimtal, a leading research institute in cold-water fisheries. These ranching operations are being carried out as a step toward mahseer restoration (Fig. 6.7) and rehabilitation.

6.8 Recreational Fishing and Ecotourism Prospects

Ecotourism is a sustainable form of resource use that contributes to the preservation of the natural environment and offers socioeconomic benefits to the people who participate in it. These benefits come from the ecotourism industry’s utilization of natural or biological resources in ways that do not involve direct consumption. Fishery-based ecotourism is growing and has the potential to create new jobs.

In Naukuchiatal Lake, Nainital, Uttarakhand

Kosi river at Ramnagar, Nainital, Uttarakhand

Nainital Lake, Nainital, Uttarakhand

Fig. 6.7 Some glimpses of golden mahseer ranching programs taken up by ICAR-DCFR

Anglers from all over the world travel to the temperate Himalayan rivers to catch the mighty mahseer since sport fishing is quite popular in the Indian Himalayas (Fig. 6.8). About 3800 km lengths of river and stream stretch in the Indian uplands hold sizeable mahseer for angling.

The revenues generated through the sale of fishing licenses help manage fish and wildlife, while the money spent by anglers and tourists on recreational fishing and other logistics generates employment for the locals. Among the Himalayan streams and rivers, river Beas and its tributaries in the foothill region and the river Giri (Himachal Pradesh); Yamuna between Tajwala (Haryana) to Dhak Pathar; Ganga between Rishikesh to Tehri and its tributaries; the Kali, Saryu, East and Western Ramganga, East and Western Nayar, Song, Kosi (Uttarakhand), river Chenab and its tributaries, and rivers Jia-bhoroli, Dibang, Subansiri and Manas (North Eastern Himalayan region) are important fishing sites for mahseer. Apart from these, the lakes of Kumaon (Bhimtal, Naukuchiatal, Nal Damyanti Tal, and Sattal) contribute substantially to mahseer fishery and provide ample scope for fish sports. Besides natural water bodies, the suitable ponds and pools available along the scenic valleys, mountains, or riverbanks in the region could be used to develop mahseer-based sport fishery units with the development of infrastructural facilities. This will help in the overall conservation and management of golden mahseer in the Himalayan waters.

Fig. 6.8 Golden mahseer angling in the North Eastern Himalayan region. (Photo courtesy: Mr. Nausad Ali)

6.9 Conclusion

Golden mahseer has been one of the prides of the temperate Himalayan waters. Therefore, it is the moral duty of all the stakeholders, from researchers to policymakers, to safeguard its population. Dedicated efforts are required to conserve mahseer fishing resources and promote their sustainable development successfully. The conservation initiatives must integrate its capture and culture fisheries with environmental protection programs. Environmental regulations with stringent enforcement mechanisms must be implemented to manage mahseer fisheries effectively. The sustainable development of the golden mahseer fishery would require the intervention of policy and governance from various stakeholders and fisheries researchers. Perhaps, we may have to incorporate our policy research for mahseer into our research initiatives as soon as the program is initiated. There are many identified potential areas in the Himalayan states which can be developed for mahseer-based ecotourism/eco-parks.

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7 Aquaculture Practices in the Temperate Himalayan Region

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Abstract

The aquaculture production potential of the Himalayan region has not been exploited to its fullest. Though this farming practice has a great potential to support the livelihood, the current practice is an almost traditional approach with poorly adopted technologies. Carp farming, integrated fish culture, and trout farming are the major features of temperate aquaculture in the Himalayan region. The existing practice is three-pronged in nature, integrating with horticulture and animal husbandry. Culture of exotic trout farming at high altitudes, exotic carp farming in mid-altitudes, and integrated carp farming in foothill areas are the existing aquaculture practices. Hence, aquaculture productivity in this region is below the average of world standards, with limited candidate species and culture systems. There is a vast scope and potential for improving fish production in the hills by bringing the Himalayan region under scientific management for temperate aquaculture. This would probably reduce the gap between actual fish yield and production potentials.

Keywords

Hill aquaculture · Polyculture · Carp farming · Trout culture · Mid-altitudinal fish farming · Jhora fishery · Pengba culture

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7.1 Introduction

Agriculture including other allied activities such as horticulture, apiculture, piggery, fish farming, etc. is the basic occupation of hill dwellers of the country to support their livelihood. Farmers of the temperate region have several constraints such as small land holdings, short period of cultivation, and low productivity due to lower thermal regime and climatic variation. Hence, farmers also practice the allied activities, and the temperate agriculture is almost an integrated type of farming pattern. Among the allied activities, vegetable cultivation, animal husbandry, and aquaculture support the livelihood of the majority of small and marginal hill farmers as an additional source of income. Cultured as well as captured fish is the best substitute of the cheapest and easily digestible animal protein which supports the nutritional requirement and alleviates malnutrition to the hill dwellers. Therefore, aquaculture is just a traditional and auxiliary practice in integrated rural and family-based temperate agriculture. Though the history of aquaculture in Indian Himalayan region is more than 180 years old, due to variable climatic conditions and low thermal regime in hills, the development of hill aquaculture is still at low level with hardly contributing 1.0% in the total national aquaculture production. Presently, this practice is just a traditional rural aquaculture, which is practiced as subsistence aquaculture. The present aquaculture practice in hill states varies with the geographical altitudes (400–3000 m asl) and location-specific climatic conditions. The low altitude (less than 400 m asl) provides maximum opportunities for fish farming, while the high altitudinal area (>1200 m asl) has limited fish farming activities. Cyprinids are the major candidate species of Indian aquaculture, but due to low thermal regime, Indian major carps are not suitable for hill aquaculture, and only exotic carps are the candidate fishes for the vast mid Himalayan region. Culture of these exotic carps is in practice under monoculture, polyculture, and rice and fish farming system. The high altitudinal area is blessed with cool, clean, and continuous flowing water and culture of rainbow trout (*Oncorhynchus mykiss*) is practiced in this area which has scope of multifold increase and transforming the traditional aquaculture into the entrepreneurship-centric commercial practice. Only high altitudinal areas with sufficient water are suitable for rainbow trout culture. Apart from this, traditional aquaculture with some of the indigenous minor carps is also in practice which is totally unorganized. These species include *Labeo dyocheilus*, *Labeo pangusia*, *Bangana dero*, *Neolissochilus hexagonolepis*, *Osteobrama belangeri*, and *Cyprinion semiplotum*.

7.2 Historical Perspective of Aquaculture in the Himalayan Region

Hill aquaculture was initiated with the introduction of exotic fishes in the Himalayan region. Prior to the introduction of the exotic fish species, there were only a few indigenous fishes such as snow trout and mahseer, which could provide valuable fishery in the hill states, and aquaculture activities were confined only to the breeding and seed production of these fish species. British settlers in India brought some cold-water fishes from overseas during the period of 1810–1939, mainly from the United Kingdom. There is a historical account of transplantation of five fish species, viz., tench (*Tinca tinca*), golden carp (*Carassius carassius*), German strain of common carp (*Cyprinus carpio*), brown trout (*Salmo trutta fario*), and rainbow trout (*O. mykiss*). Mclvor introduced tench during the year 1810 in the Ootacamund Lake which attained the size of 1.2 kg and remained confined to Nilgiri area and did not spread elsewhere in India. Golden carp was also introduced during the year 1870 in the same lake which was a plankton feeder fish and attained the size of 1.2 kg but was not propagated further in uplands. Among these five introduced fishes, common carp and trout were successfully propagated for sport fishing and aquaculture purpose.

British settlers introduced different species of trout in the Indian subcontinent basically to meet their needs for sport fishing or recreational angling during early period of the last century primarily. The very first attempt to implant trout from New Zealand was made in 1863 by Sir Francis Day in Nilgiri hills, and later efforts were followed from 1866 to 1906 that were aimed at brown trout but with little success. Mr. H.C. Wilson, Consultant, Pisciculture, Madras Presidency, constructed a hatchery at Avalanche (Tamil Nadu) in 1909–1910 for brown trout (Sultan 2012). However, due to failure in the case of brown trout, the focus shifted toward the rainbow trout. The first attempt to introduce the brown trout (*S. trutta fario*, Linnaeus) in the Himalayas dates back to 1899 when Mr. F.J. Mitchell brought the eyed-eggs, but he did not succeed due to loss of eggs during the transportation. Further, eggs of brown trout were procured during the year 1900 from Jioweitonin in Scotland and successfully propagated as first success at Harwan hatchery near Srinagar, Kashmir. Therefore, Mitchell established a first regular trout hatchery at Harwan in the history of cold-water aquaculture. The brown trout was spread to other section of Himalayas from this hatchery. This species was transplanted to almost all suitable streams and lakes of Kashmir, Gilgit, Abbolabad, Chitral, Kangra, Kullu, Shimla, Nainital, and Shillong. Himachal Pradesh procured the brown trout eggs from Kashmir during the year 1911 and introduced them in three streams of Kangra and Kullu area of Himachal Pradesh, namely, Baner, Awa, and Binun. Regular efforts were made to establish the brown trout in these streams, but did not succeed due to unfavorable thermal regime, and the stock was completely decimated due to the devastating flood during the year 1947. Mr. Howell, warden of fisheries, Punjab, brought eyed-eggs of brown trout from Kashmir during the year 1909 and got the success to produce swim-up fry and stocked them in streams of Manali and Katrain. Adult specimens of brown trout were found in the streams of Manali and Katrain during the year 1912. This wild stock was brought to Barot in Uhl valley during 1916 and established a brown trout hatchery. Presently, this is the only brown trout hatchery in the Himalayas, and stock was spread to different parts of Himachal Pradesh and hill states. Effort was made to transplant the brown trout in Uttarakhand (erstwhile Uttar Pradesh) and establish a hatchery at Bhowali near Nainital during the year 1911–1913, but it did not succeed due to comparatively high summer temperature prevalent in the area. The initial success was found during the year 1966 for brown trout at Kalyani hatchery in Uttarakhand. Brown trout fingerlings were also provided by Kashmir to Eastern Himalayas and transplanted directly into the streams of Darjeeling and Shillong, but it was not established. Effort was made to establish a brown trout hatchery near Sela Lake in Arunachal Pradesh during the year 1967, but did not get the success for eyed-eggs incubation. Hence, yearlings of brown trout were directly transplanted in certain streams and lakes of Arunachal Pradesh and Sikkim, where they were reported to establish successfully. During the year 1931, brown trout eggs were provided by Kashmir to Jaghoor near Chitral in Pakistan, where they hatched successfully and further propagated to stock in the streams. Yearlings of brown trout were also brought from Kashmir to Nepal and Bhutan during the year 1970–1972 and reported to establish in the streams.

Mitchell achieved the success for hatching and rearing of rainbow trout during the year 1912 which was brought from Blagdon, England, and incubated at trout hatchery, Harwan, Kashmir. This introduction was the formal beginning of rainbow trout culture in India. This species was introduced from Kashmir to trout hatchery Mahili, Himachal Pradesh, during the year 1919 and attained the maturity in the introduced stock during the year 1922. Eyed-eggs of rainbow trout were also transplanted from Trout hatchery, Achabal, Kashmir, to trout hatchery Barot and Patlikuhal in Himachal Pradesh. During the year 1976, rainbow trout eggs were brought from Kashmir to trout hatchery Talwari and Kalyani in Uttarakhand. These hatcheries were established to provide stocking material for the rivers Pinder, Birahi Ganga, and Asiganga which were kept in reserve to provide angling pleasure in Uttarakhand. The European Economic Community (EEC) assisted a project in Jammu and Kashmir with Fish Farms Development Internationals (FFDI) Scotland and Ramboll and Hannemann, Denmark, during the year 1984 at Kokernag in Kashmir. This project is still a landmark milestone in the establishment of rainbow trout culture in India. Further, Norwegian government funded a project for transfer of technology and production of trout in Himachal Pradesh during 1988, which primarily established trout farming activities at large scale in Himachal Pradesh. Under this project, fresh stock of rainbow trout was introduced, and health service was provided in association with the National Veterinary Institute, Oslo, Norway. In peninsular India, eyed-eggs of golden rainbow trout and ordinary rainbow trout were imported from Nikko Laboratory Japan during the year 1968 and incubated at Avalanche trout hatchery. Further, *O. nerka* was also imported from Canada at this hatchery during the year 1969. But, only golden strain of rainbow trout could establish well as a dominant strain from among the all introduced fishes. During the year 2019–2021, the Govt. of India imported more than 25 lakhs of eyed ova of improved strain of rainbow trout from Denmark (Aqua Search Fresh) to India to fulfill the seed requirement of the trout growers of Kashmir, Himachal Pradesh, Uttarakhand, and Sikkim. However, this imported stock was completely female stock and could not propagate further. For many decades, rainbow trout was recognized only for angling and sports purpose. Later on, this species was also realized as food fish, and culture and seed production was started in farm conditions. However, its culture was confined only in some selected locations of Kashmir, Himachal Pradesh, and some parts of the Peninsular India. Presently, the culture and breeding of rainbow trout is being practiced with greater success and accuracy in mid and higher altitudes.

During the past two decades, three more species of salmonids, viz., the eastern brook trout (*Salvelinus fontinalis*), the splake trout (hybrid of lake trout and brook trout), and the landlocked variety of Atlantic salmon (*Salmo salar*), were procured from Canada and North America and kept at state trout hatcheries of Kashmir, but did not get the success in breeding and their survival. Arctic char (*Salvelinus alpines* Linnaeus) were transplanted in Himachal Pradesh during the year 2006, which did not breed due to the unfavorable environment.

Mirror carp, a variety of common carp (*Cyprinus carpio var. specularis*), was imported from Sri Lanka to India during the year 1939 and transplanted in Nilgiris area. Further, this species was transplanted from Nilgiri to Bhowali hatchery during the year 1947. This fish was propagated well and planted in different Kumaon lakes, Himachal Pradesh and Kashmir. ICAR-Directorate of Coldwater Fisheries Research, Bhimtal, Uttarakhand, imported improved Hungarian strains of common carp, "Ropsha scaly (*C. carpio var. communis*)" and "Felsosomogy mirror carp (*C. carpio var. specularis*)," during 2006 at the Experimental Fish Farm, Chhirpani, Champawat, Uttarakhand, where these strains were raised, bred, and assessed for growth performance, both in polyculture system and in monoculture. The imported parental stock showed better growth and breeding response, but the progeny of these strains did not show desirable growth and survival.

7.3 Aquaculture Trends in the Himalayas

The culture systems, adopted in the Himalayan region, vary greatly depending on the altitude and are almost location- and situation-specific.

7.3.1 Carp Farming

Culture of exotic carp fishes in small-sized ponds (0.01–0.03 ha) is a very popular practice in the temperate region. This is a low input culture system and integrated with horticulture and animal husbandry practices. This practice varies from monoculture of common carp to polyculture of three exotic carps, viz., grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*), and common carp (*C. carpio*). Integrated carp farming with horticulture and animal husbandry is popular in rural areas with reduced input cost. Monoculture of grass carp is also popular as low-cost hill aquaculture practice in mid and low altitudes. Basically, this fish feeds on aquatic vegetation of the pond, and farmers also provide supplementary feeding with terrestrial soft plants and grass of the horticultural plots. This practice has been adopted in the Northeastern and Central Himalayan regions.

7.3.2 Monoculture of Common Carp (*C. Carpio*)

Monoculture of common carp in small-sized pond (50–150 m^3) is popular in different Himalayan states. Fingerlings of the size 6–7 cm are stocked in the density of 3–4 fish/m^2. Water temperature has the profound role in determining the growth rate. Higher growth rate is achieved at the water temperature range of 20–25 °C, but lower thermal regime of 9–18 °C reduces the fish growth and results in low production. The average fish production is achieved in the range of 1300–1700 kg/ha/year.

7.3.3 Culture of Exotic Carps in Mid-altitudes

Polyculture of three exotic carps, viz., grass carp (*C. idella*), silver carp (*H. molitrix*), and common carp (*C. carpio*), in earthen ponds of the mid-altitudinal region (800–2000 m asl) is a common practice in most of the Himalayan states. Fish farmers use the ponds of 100–150 m^2 size for this practice. Raw cow dung (RCD) is applied at 9000 kg/ha/year for consistent plankton production in the pond water. Fish seed of the fingerling size is stocked at the rate of 3–4 fish/m^3 with species composition of 4–5:2–2.5:3–3.5 for grass carp, silver carp, and common carp, respectively. Though the average fish production of 0.34–0.48 kg/m^3/year (3400–6800 kg/ha/year) is in lower side with this practice, this is a common rural aquaculture practice in hills by using earthen ponds (Fig. 7.1).

7.3.4 Integrated Fish Culture in Polytanks

Due to low thermal regime in mid hills (1000–2000 m asl), the growth of carps is slow, and the fish remain in hibernation during the entire winter season. In this context, a refined model of carp farming with lining of plastic film in earthen ponds is used by the fish farmers (Fig. 7.2). This practice has numerous merits as it is easily affordable by local poor farmers, and at the same time, it reduces the unproductive hibernation period of fish, thereby giving more profit. This multitier model for carp farming provides increased water temperature for better growth of fish, buffer water stock for irrigation of vegetables' plots, and minimal loss of stored water by seepage due to soil porosity. These polytanks are stocked with exotic carps, and supplementary carp feed is provided at 2–3% of growing fish biomass. Polyfilm in the pond conserves the sunlight energy and keeps the pond water temperature 2–6 °C higher than the conventional ponds which favors the increasing feed intake and faster metabolism resulting in better growth of fish compared to conventional tanks. This polyfilm also acts as insulation between pond water and pond bottom soil and reduces the water seepage from the pond. These polytanks remain comparatively deep (2.0 m) and also retain the buffer stock of water for irrigating the horticulture crops. Fish farmers in mid-altitudes are getting an average fish production of

Fig. 7.1 Carp farming in earthen ponds

0.6–0.7 kg/m^3/year with this refined culture model, which is higher than the conventional carp farming in earthen ponds.

7.3.5 Culture of Pengba Along with Exotic Chinese Carps

Culture of Pengba, *Osteobrama belangeri*, along with Chinese carps for production and livelihood is popular in Manipur (Das and Singh 2017). Farmers of Manipur, India, do polyculture of grass carp, silver carp, and pengba with species composition of 30:30:40 and get average production of 4300 kg/ha/year. The combination of pengba and khabak (*Bangana devdevi*) in the ratio of 50:50 with other exotic carps is also in practice in some parts of the Manipur state.

7.3.6 Jhora Fishery for Rural Aquaculture

Jhora fishery is a low-cost traditional practice in rural areas with culture of exotic carps in unmanaged village ponds. This practice is popular in northeast Himalayan region particularly in the part of West Bengal and Meghalaya state. This is a low

Fig. 7.2 Carp farming in polytanks

input practice with less stocking density and rare supplementary feeding, and hence, low biomass production is achieved which also varies from pond to pond with average fish production in the range of 1700–3500 kg/ha/year. A refined model of this practice has been adopted by the farmers of Kalimpong area in West Bengal for this practice with almost 20% higher fish production. These farmers use multispecies stocking of chocolate mahseer (*Neolissochilus hexagonolepis*), common carp (*C. carpio*), and grass carp (*C. idella*) in village ponds.

7.3.7 Paddy-Fish Culture in Northeast Region of India

This is a traditional fish farming practice which is very popular in Arunachal Pradesh and Manipur. Prepared fields are planted with local variety of paddy and also stocked with common carp. The estimated production in this practice is 683.0 kg/ha of common carp in rearing period of 237 days without any supplementary feeding (Das 2017).

7.3.8 Integrated Fish-Pig Farming in the Northeast Region of India

Integrated fish farming in small scale by resource-poor small and marginal farmers is very common in most of the northeast region. This is low input cost culture practice with better economic efficiency. Integration of pigs with small fish ponds is popular in Tirap district of Arunachal Pradesh, Kamrup district of Assam, and East Khasi hills and West Khasi hills of Meghalaya. During the culture period of 8 months, the pigs attain an average growth of 68–72 kg, while an average production of 5300–5700 kg/ha of fish is achieved in 8 months' culture duration. Generally, they use exotic carps for the culture.

7.3.9 Rainbow Trout Farming

Rainbow trout farming is a high income generating farming practice for better livelihood support to the rural people of higher altitudinal areas in hills. Farmers primarily culture the rainbow trout in earthen or concrete flow-through raceways or ponds in a conventional manner (Figs. 7.3 and 7.4). At present, total annual production is nearly 2500 tons, with an average unit productivity of 10–15 kg/m^3. Based on available resources, the potential scope for sustainable expansion and intensification is enormous across a vast geographic area. Presently, more than 80% of the rainbow trout production comes from only two hill states, viz., Kashmir

Fig. 7.3 Rainbow trout farming in earthen ponds

Fig. 7.4 Rainbow trout farming in raceways

and Himachal Pradesh. However, other hill states, like Uttarakhand, Sikkim, and Arunachal Pradesh, are also coming forward for rainbow trout farming.

Presently, conventional raceway culture with running water system having continuous flowing cool, clean, and highly oxygenated water is in the practice. The average size of this culture raceway remains at 30 m^2 (15 m length and 2 m width) with 1 m depth toward inlet and 1.5 m depth near the outlet. Generally, fish takes 12–14 months to attain marketable size (250–260 g) with this conventional culture system in Kashmir, Himachal Pradesh, and Garhwal region of Uttarakhand. However, comparatively better growth of 500–600 g was also achieved in 12 months in Sikkim state having favorable thermal range of water (14–18 °C) for maximum culture cycle (8 months) and availability of sufficient water volume. In Nepal, the marketable size of 200–300 g is achieved in culture duration of 14–16 months, and fingerlings are stocked at the density of 50 fish/m^2. The marketable size of 300–350 g was achieved in 8 months at trout farms of Idaho, USA, under the raceway culture. In general, production level of rainbow trout in Indian conditions is 300–500 kg per raceway of the size of 15 × 2 × 1 m (30 m^2) in 12 months, which is almost similar to the European countries. However, high productivity of 1 ton per raceway or more has also been achieved by the trout growers of Sikkim and Himachal Pradesh in India with better management practices (Fig. 7.5).

Generally, stocking density of 45–50 fish/m^2 is adopted by the trout growers of Himalayan region, which has the scope to increase up to 100 fish/m^2 with better management practices and sufficient water flow in the raceways. Size and shape of the raceways also varies location-wise without any standard. Earthen raceways are

Fig. 7.5 Entrepreneurship in trout farming

also in practice at few locations of Arunachal Pradesh and Kashmir. Generally, Indian trout farming is conventional type having flow-through systems, in which stream water is used by making a check dam across the adjacent stream at higher elevation and water flows to the farm by gravity without the use of or only minor use of pump energy. Hence, trout raceways are constructed directly into the soil of river valleys close to the stream banks. Generally, a flow rate of 4 L/s is used to support 20 kg/m^3 fish biomass in raceways. However, minimum of 500 m^3/day of water flow is needed for 1 ton of trout produced (Stevenson 1987). Rainbow trout farming is also practiced in mid-altitudes and in the Central Himalaya; average growth was recorded as 300 g (range 260–400 g) at thermal regime of 5.0–22 °C (Vass et al. 2010). This indicates the scope of rainbow trout farming with marketable size trout of 240–400 g within a period of 12 months at marginally higher thermal regime in mid-altitudinal areas of the Himalaya. Integration of rainbow trout farming with cardamom cultivation is an innovative approach for multiple use of water and better

Fig. 7.6 Integration of cardamom crop with rainbow trout farming

production of trout and cardamom at higher altitudes in Sikkim state. The nutrient-rich drain water of a raceway is used for irrigation of 0.4 ha cardamom cultivation plot which results in 30% increase in yield of cardamom (Fig. 7.6). The average net profit to the farmers in this integrated trout and cardamom cultivation is Rs. 214,000 in 0.4 ha farming area. In Indian conditions, the annual rate of return in trout farming is nearly 50–60% of the total annual investment having net profit of Rs. 137,000 in 30 m^3 in 12 months, while it is 39% in Nepal.

The ICAR-Directorate of Coldwater Fisheries Research is the nodal institute responsible for research and development in rainbow trout farming in India. Over the last decade, this institute has made significant contributions to improve rainbow trout production in the country by developing, validating, and introducing new production system models (recirculatory aquaculture systems), high energy feeds with an FCR of 0.8–1.1, pathogen and disease surveillance programs, antimicrobial resistance monitoring, engineered therapeutics, unraveling stress adaptations, stock characterization, and GIS-based site selection tools. In the next 5 years, the target is to sustainably increase the productivity to 20–25 kg/m^3 in flow-through systems and 60–80 kg/m^3 in RAS with minimum use of resources and culture duration through technological interventions.

7.3.10 Entrepreneurship with Ornamental Fishes

There are some fascinating fish species inhabiting in the Himalayan region, in which some indigenous fishes have high ornamental value. The northeast region of the Himalaya has 187 indigenous fish species of ornamental value. Some farmers of

Uttarakhand and the northeast are practicing small-scale enterprise in ornamental fish trade, as a backyard activity in rural areas with exotic fish such as gold fish and koi carp along with other indigenous fish species such as *Garra gotyla*, *G. lamta*, and some species of loaches.

7.3.11 Carp Farming at Higher Altitudes

At high altitude, some farmers are doing exotic carp farming in polyhouse covered polytanks. The size of the polytanks remains at 9.8 × 3.0 m with 1.2 m depth and 1:1 side slope. These polytanks have the capacity of 20 m^3 water volume. This structure remains covered with dome-shaped galvanized iron (GI) pipe polyhouse having the size of 11.0 m length, 4.2 m width, and 1.0 m span with central height of 3.0 m (Fig. 7.7). Polyhouse helps to increase the water temperature by 3.7–9.6 °C and supports better fish growth. Hence, these low-cost polyhouse structures support the increasing water temperature and protection from frost condition. The growth of exotic carps in this culture practice remains in the range of 270–300 g in 12 months' rearing period. Though this practice is not very popular, fish production with this practice at higher altitude supports the livelihood and nutritional security to the unprivileged and resource-poor people.

Fig. 7.7 Carp farming at higher altitudes of the Himalayas

Fig. 7.8 Rainbow trout farming in floating cages

7.3.12 Rearing of Rainbow Trout and Mahseer Seed in Floating Cages

Open water bodies in hills provide opportunities for in situ seed rearing in floating cages, and produced seed is used for the stock enhancement program. Fingerlings of golden mahseer (*Tor putitora*) are being reared with appropriate stocking density and feeding practices in Bhimtal Lake. Floating cages for rainbow trout fingerling rearing are used in Menmoitso Lake of East Sikkim (Fig.7.8). These types of cages are also being used in Gobind Sagar reservoir of Himachal Pradesh for rearing of rainbow trout.

7.4 Constraints in Hill Aquaculture Development

1. Slow growth in culture system due to low thermal regime.
2. Limited candidate fish species for culture.
3. Nonavailability of seed of high valued fish species such as rainbow trout in sufficient quantity.
4. Nonavailability of seed of potential candidate indigenous fish species such as minor carps and barbs.
5. Need to replace the inbred rainbow trout stock by improved strain varieties.

6. Large-scale commercial rainbow trout farming is not in vogue.
7. Trout seed production and trout feed supply are mostly confined in public sector.
8. Need of high input and high output practices such as recirculatory aquaculture system (RAS).
9. Call for soilless aquaponics farming with integration of fish and vegetables for resource-poor farmers.
10. Fish feed for diversified fish species for different developmental stages not available.
11. Poor availability of formulated feeds and higher cost factor.
12. Principle of cluster farming not in vogue which may provide benefit on inputs and marketing of fish.
13. Non-adoption of location- and system-specific culture models which may provide optimum production at low input cost.

7.5 Species Diversification for Hill Aquaculture Development

Exotic carps and rainbow trout are the major candidate fish species for hill aquaculture. But carp farming in hills does not support the good farming economics due to the low valued fish in the domestic and international market and low cost–benefit ratio in comparison with the culture of other valued fish species. Further, consumers today with their increased purchasing power prefer wide spectrum of fish protein. In this context, diversification of the system and species is required for aquaculture in the coming years. Diversification with high valued fish species is needed to make aquaculture more remunerative to encourage the entrepreneur investment. But, introducing any new species into the mainstream aquaculture practice includes consumer preference, seed availability, rearing technology along with the knowledge of their nutrition, physiology, and health management. A number of indigenous fish species have the potential to be a candidate culture species in the Himalayan region particularly in northeast zone having high consumer preference as well as good market value. Some farmers are practicing the culture of indigenous fishes such as chocolate mahseer (*N. hexagonolepis*), *B. dero*, *L. dyocheilus*, *L. pangusia*, *L. gonius*, *Chagunius chagunio*, *O. belangeri*, and *Cyprinion semiplotum*, but the culture of these species is not based on any standard culture system.

7.6 Need for Intensification of Rainbow Trout Farming

Trout farming is coming up as a lucrative venture at higher altitude, and present trout production of the country has gone up from mere 147 tons to over 2500 tons in the last decade that further can be enhanced through expansion and increase in productivity that needs intensification as well as location- and situation-specific efforts in terms of quality seed, low-cost feed, and health management. For vertical expansion, there is a need to develop innovative practices such as RAS-based rainbow trout farming, aquaponics-based rainbow trout farming, efficient fish feed, and climate-resilient trout production. Most of trout farms are distantly located in difficult terrain and have poor accessibility to the market where quick transportation of fish is difficult; hence, the sale of fish is confined to local markets. Being highly perishable commodity, there is a need of value chain and cold chain to ensure high quality of trout meat. The sale of fish is confined to local markets. New trade channels are expected to come up soon, once production blooms with upcoming infrastructure and technological advancement. It required to overcome the deficiencies by adopting cluster-based approach to cover all the segments like culture operation, fingerling rearing, feed supply, and marketing through large-scale operations at potential sites. Respective agencies may develop suitable spots as "trout village" for bulk production and employment using the commerce to involve private sector, especially in feed, marketing, and value addition to bring resiliency.

7.7 Conclusion

Fish is now not only an important source of food and income but also as a commodity for trade and export as blue economy. Considering the vast resources available, there is immense potential to draw economic benefit for the prosperity of the people residing in hill states through multifold increase in aquaculture production by horizontal expansion, intensification diversification, and better management practices. Presently, the temperate aquaculture is almost a traditional aquaculture in most of the hill states. Therefore, standard culture protocols would be the key for way forward. Suitable sites are available in different parts of the hill states, which would be brought under anyone of the three-pronged fish farming having location-, situation-, and system-specific culture models. Further, there is a need to introduce large-scale farming to bring the Himalayan region on international scenario by implementing scientific management practices with a very honest and clear aim to provide protein locally at cheap price and to export the fish and fishery products to gain the foreign currency. Decision support system in the form of GIS and remote sensing would be helpful not only for resource assessment but also for aquaculture development in the hills. Ornamental fish culture for small-scale enterprises in the hills can provide an alternative source of employment. Hence, temperate aquaculture has potential and opportunities to provide animal protein to the people and also supports the other agriculture activities for improving their socioeconomic life.

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Status and Prospects of Rainbow Trout Farming in the Himalayan Waters

8

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Abstract

Rainbow trout (*Oncorhynchus mykiss*) is a member of salmonid family and one of the commercially cultivated species around the world with a total annual production exceeding 916,000 tons. It has a long history of global translocation and has been successfully introduced both in the northern and southern hemisphere of the world. Being a high valued species and also having sports and recreational qualities, the species had been introduced in different Himalayan regions of Asian countries. These introductions are associated with the stories of failure and success in different Himalayan regions. Slowly and steadily, the species established and came under commercial farming. Rainbow trout farming has contrasting progress in different parts of the Himalayan region as it has reached to a significant production value in China, while in India and Nepal, the production is significantly low. Nevertheless, there are ample opportunities in terms of available resources for the expansion of trout farming in the Himalayan region. This chapter deals with the global production and farming status of rainbow trout as well as issues and scope for its expansion and intensification in Himalayan regions.

Keywords

Rainbow trout · Salmonids · Trout production · Trout farming · Himalaya

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8.1 Introduction

Rainbow trout (*Oncorhynchus mykiss*) is a member of family "Salmonidae" native to the Pacific coast of North America and Russia (Ward et al. 2003) and has been widely introduced around the world having suitable temperature regimes (MacCrimmon 1971; Behnke 1992). The species has been introduced into at least 99 countries, with population established in at least 53 of them (Gherardi 2010; Stankovic et al. 2015). It is one of the commercially cultivated species which is traded as "portion trout" that is generally a whole trout (<450 g), as well as in different types of processed form. As mentioned, the species is primarily produced in aquaculture settings; nevertheless, a negligible share of global trout production is also contributed by catches (0.15% of total production, 2019). The global introduction of trout was made to different geographic regions in both the northern and southern hemisphere including Himalayan regions of the world. The Himalayan region of the world includes mainly Hindu Kush, Karakoram, Pamir, Hengduan mountains, and parts of Tibetan plateau apart from proper Himalaya. These mountain systems are the origin and sources of major rivers of the world which includes Indus, Ganges, Brahmaputra, Irrawaddy, Salween, Mekong, and Yangtze (Bandyopadhyay and Gyawali 1994). These rivers are the world's largest suppliers of freshwater which sustains life of more than half of the world's population. Rainbow trout was introduced in almost all Himalayan regions since these areas were conducive for their survival. The enormous available aquatic resources such as reservoirs, lakes, and rivers provided enough scope for establishing its population and further propagation in these natural water bodies. It is worth mentioning that initially, trout (brown trout, *Salmo trutta fario*, and rainbow trout, *Oncorhynchus mykiss*) were transplanted from Europe and introduced in the Himalayan regions primarily for sports fishing or recreational angling (Mitchell 1918; Singh and Lakra 2011). Later on, hatcheries were established for seed production and stocking in the natural stream to sustain the population in the wild. Subsequently rainbow trout, being a high valued species, included in commercial farming in some of the Himalayan countries and hatcheries and farms were established for seed production and culture. This chapter briefly describes about rainbow trout and its global introduction as well as status, prospects, and major constrains in its farming in the Himalayan regions.

8.2 Salmon and Trout

The family Salmonidae consists of 3 subfamilies and 11 genera, including more than 70 species (Zhang et al. 2018). Salmonids of the world are categorized under two groups, based on their geographical distribution and origin: (a) the European and (b) the American. There are four principal salmonids of European origin which are cultured in Europe, North America, Japan, and Oceanic countries. These are (1) brown trout, *Salmo trutta fario*; (2) Atlantic salmon, *Salmo salar*; (3) Danube salmon, *Hucho hucho*; and (4) Arctic char, *Salvelinus alpines*. The salmonids of

American origin are nine species under genus *Oncorhynchus* and three species under *Salvelinus*. Under genus *Oncorhynchus*, the important species are *O. aguabonita* (golden trout), *O. clarki* (cutthroat trout), *O. gorbuscha* (pink salmon), *O. keta* (chum salmon), *O. kisutch* (coho salmon), *O. masou* (cherry salmon), *O. mykiss* (rainbow trout/steelhead), *O. nerka* (sockeye salmon), and *O. tshawytscha* (Chinook salmon). There are different strains of rainbow trout which are known as *normal*, *steelhead*, *shasta*, and *kamloops*, but all are known as *O. mykiss*. However, based on the differences in the life histories, two different forms of rainbow trout exist. The coastal form is called as *steelhead*, and the inland form is known as *redband*. The *steelhead* rainbow trout utilizes both freshwater and saltwater, while *redband* forms always inhabit inland waters. It is believed that presently domesticated or hatchery strains have genes from both the forms (Laird and Needham 1998). There is an albino form of rainbow trout which is popularly and mistakenly called as golden trout and being cultured in many countries and mostly used for ornamental and recreational purposes (Okumus 2002; Woynarovich et al. 2011).

There was a taxonomic ambiguity in the classification and nomenclature of rainbow trout till 1988 (Gold 1977). The confusion of nomenclature in rainbow trout was addressed and settled by the "American Fisheries Society Names of Fishes Committee" that adopted the use of generic name of *Oncorhynchus* for all Pacific trout and salmon to distinguish them from the Atlantic trout and salmon (Smith and Stearley 1989). Furthermore, a number of investigations, based on mitochondrial DNA and osteological data, identified the closer relationship of the rainbow trout to the Pacific salmon than to the Atlantic salmon and brown trout (Berg and Farris 1984; Gyliensten and Wilson 1987; Smith and Stearley 1989; Gall and Crandell 1992). The rainbow trout is one of the highly adaptable species to its environment, and therefore, it has been successfully established around the globe (Wolf and Rumsey 1985).

8.3 Global Translocations of Rainbow Trout: A Brief History

Among different Pacific salmon and trout species, the rainbow trout (*O. mykiss*) is the most widely introduced and successfully established species outside its native range (Crawford and Muir 2008). The rainbow trout has been introduced in the countries of both northern and southern hemisphere of the world wherever the conditions are favorable for its culture and propagation (Fig. 8.1; Table 8.1). The species has been accepted as recreational game fish in Europe and Oceania and as food fish in South Asia. Furthermore, various selective breeding program for manipulation of life history traits aided in the establishment of rainbow trout at several locations worldwide (Gjedrem 2000; Gross et al. 2007; Halverson 2008). Thus, the global introduction of trout was basically aimed for hatchery stocking program and introduction of seed in the wild or natural environment for developing a wild-reproducing, self-sustaining population and recreational fisheries (Gall and Crandell 1992; Crawford and Muir 2008).

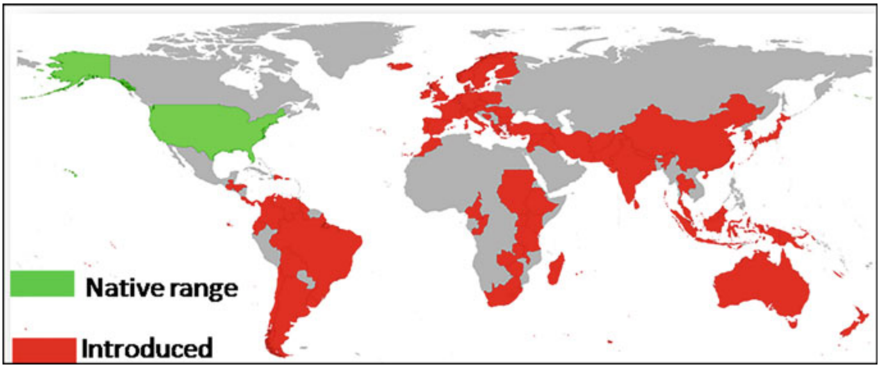


Fig. 8.1 Introduction of rainbow trout (*O. mykiss*) in the world. (Source: Global Invasive Species Database 2022. Downloaded from http://www.iucngisd.org/gisd/search.php on 14-06-2022)

The first rainbow trout spawning station was established on the McCloud River in California in 1879 (Gall and Crandell 1992), and it is the only fish species distributed around the world through eyed egg transfer (Okumus 2002). The first successful transfer of rainbow trout eggs out of North America was made to Japan in 1877 (Wales 1939), and later in 1885, eggs were sent to England and Scotland (Fornshell 2002). The species was also introduced in different parts of America, Africa, Austria, New Zealand, Europe, and Asian countries (Table 8.1). In Europe, rainbow trout was introduced to France in 1879 and later during 1882 to Germany (Stankovic et al. 2015). From Germany, rainbow trout was sent to different European countries and Russia for developing recreational fishing through stocking into streams. The commercial trout farming started in Europe, in Denmark during the 1890s, and hatchery produced stocks were further sent to England and Scotland (Laird and Needham 1998). Among Asian countries, rainbow trout was introduced during 1870s and 1880s and again in the 1920s from the United States to Japan. In other Asian countries, particularly Sri Lanka and India, rainbow trout was introduced from Great Britain. Further, rainbow trout was introduced to India from Sri Lanka, Great Britain, Germany, and New Zealand (MacCrimmon 1971; Welcome 1988; Pethiyagoda 1994). Rainbow trout was also introduced during the 1960s into Hindu Kush regions and Salang/Panjsher watersheds of Afghanistan for aquaculture and recreations (Coad 1981; Welcome 1988). Iran received the rainbow trout from various European sources, including Denmark. Nepal received its first introduction of rainbow trout in the 1970s from India and later from Japan (MacCrimmon 1971; Shrestha 1994). In the northern highlands of Thailand, rainbow trout was introduced from Canada (Piyakarnchana 1989). Most recently, during 2005, the rainbow trout was introduced into Vietnam, and in Sa Pa in Lao Cai Province, rainbow trout farm was established which serves as center for cold-water aquaculture of Vietnam. Rainbow trout was also introduced to African continent during the late 1890s from Great Britain to South Africa and later during the period of 1905–1910, from South Africa to Kenya, Swaziland, and Zimbabwe for developing recreational

Table 8.1 Introduction of rainbow trout in major countries of the world

Country	Year of introduction[a]
Argentina	1904
Australia	1894
Austria	1885
Chile	1887
China	1959
Croatia	1894
Denmark	1894–1896
Finland	1898
France	1879
Germany	1882
Hungary	1882–1884
Iceland	1951
India	1899
Iran	1960
Italy	1891
Japan	1877
Nepal	1981, 1971, 1988
New Zealand	1877–1883
Norway	1902–1906
Pakistan	1899
Poland	1881–1889
Portugal	1898
South Africa	1897
Spain	1977
Sri Lanka	1882, 1892
Sweden	1882
Switzerland	1887
Turkey	1970
United Kingdom	1884
Vietnam	2005

[a]Crawford and Muir (2008), Stankovic et al. (2015)

fisheries (de Moor and Bruton 1988; Welcome 1988; Cambray 2003). Thus, the rainbow trout as a species for recreational fisheries and aquaculture established itself worldwide. Nevertheless, it has also been identified as invasive species in many European countries due to its negative impacts on native fish fauna (Cambray 2003; Stankovic et al. 2015).

8.4 Global Trend of Trout Farming and Production

Rainbow trout is an important commercial and recreational cold-water species, presently farmed in different countries of the world with the total annual production exceeding 916,000 tons (FAO 2020) (Fig. 8.2). The major trout producing countries of the world are European countries, North America, Australia, and Japan. Presently, Iran is the highest producer of rainbow trout in the world, followed by European Union (EU), Turkey, Norway, Chile, and Peru. Other non-EU countries contribute to around 22% of the total global trout production (Fig. 8.3).

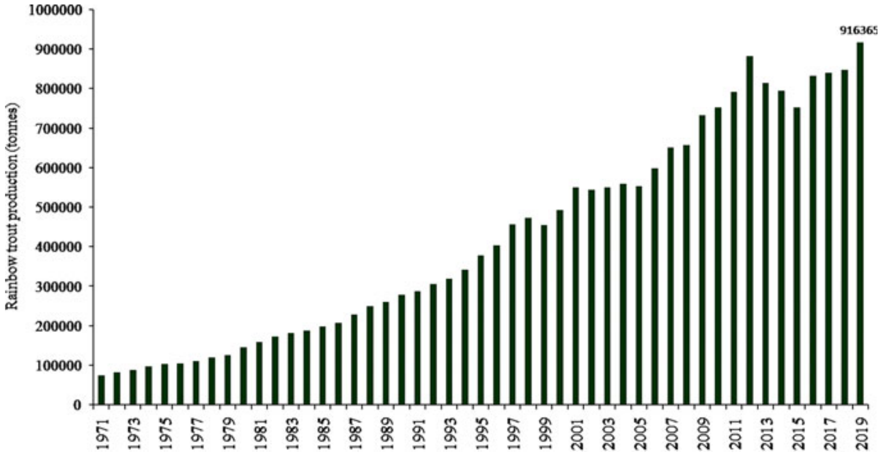
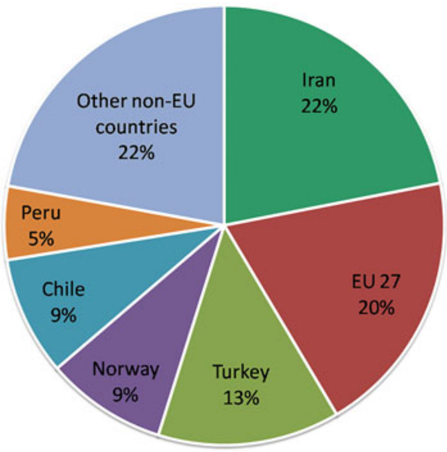


Fig. 8.2 Global production of rainbow trout (1971–2019) (FAO 2020)



Country/regions	Production (2018) ('000 tonnes)
Iran	206.05
EU 27	183.819
Turkey	125.745
Norway	83.489
Chile	82.176
Peru	50.793
Other non-EU countries	207.981
Total	**940.053**

Fig. 8.3 Major trout producing countries/regions in the world and their percentage contribution in the total rainbow trout production of the world (FAO 2020)

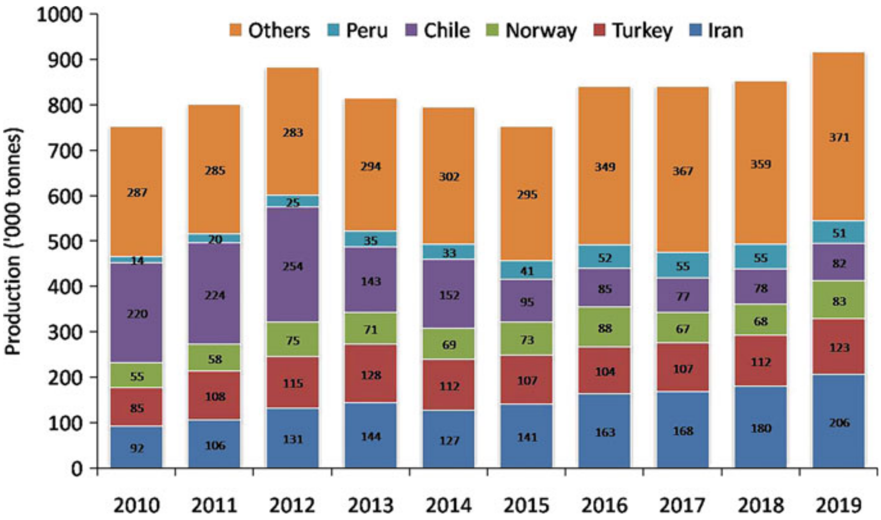


Fig. 8.4 Trends in rainbow trout production by major countries/region of the world (2010–2019) (FAO 2020)

Rainbow trout is among the ten main species, produced in European aquaculture and second widely cultured salmonid species after Atlantic salmon. However, after being introduced in many Oceanic and Asian countries, it has become one of the preferred candidate species for aquaculture industry, and now countries like Iran and Turkey are leading the global production of rainbow trout. Having the ability to acclimatize in different aquatic environment as well as strain variants available for marine and freshwater environment, the aquaculture of trout has utilized different culture system. Production of rainbow trout is contributed from many types of farms which include marine cages, net-pens in sea, freshwater earthen ponds (typically lined with plastic/vinyl liners), concrete raceways, and circular tanks with re-circulatory or filtration system. However, many of the countries in Asia produce freshwater trout using concrete raceways or circular tanks. Over the last decade (2010–2019), the aquaculture production of rainbow trout has increased by 22%. Among different trout producers, Iran and Turkey have significantly increased their production by 125% and 44% respectively in the last decade (Fig. 8.4). EU contributed around 21% of world's farmed trout production, and among different EU countries, France (19%), Italy (17%), and Denmark (16%) remained the main producer of the farmed rainbow trout in Europe.

8.5 Rainbow Trout Farming in the Himalayan Regions

Himalayan regions are characterized by the presence of cold water that harbors different species and provides subsistence to the inhabitants. It is a matter of fact that in spite of having rich water resources, the Himalayan regions are having high poverty and low development (Petr 2003). The natural fish stocks are limited and sparse having low level of wild catches, nevertheless, an important source of animal proteins. In potential streams and lakes in cold-water regions, fish stocks mainly brown trout were introduced mainly for the purpose of sports and recreation. Later on, these species came under commercial farming and now became prime species under cold-water aquaculture setting. Among different Himalayan regions of China, Nepal, and India, trout farming has developed steadily, and over the year, the production has also increased significantly, and these regions have potential to further increase their production.

8.5.1 Rainbow Trout Farming in China

Aquaculture in China is an age-old practice; however, the rapid development of aquaculture started in the 1950s with a breakthrough in artificial breeding of silver carp (*Hypophthalmichthys molitrix*), bighead carp (*Hypophthalmichthys nobilis*), and grass carp (*Ctenopharyngodon idella*) during 1958–1960. Over a period of time, the aquaculture industry has grown tremendously, and presently (year 2018) China contributes 35% of global fish production (FAO 2020). The cold-water fisheries in China started with the introduction of rainbow trout in 1959 from the Democratic People's Republic of Korea (DPRK), and first generation parent fish were grown in 1963 and successfully bred in hatchery condition in the first experimental cold-water fish farm established in the town Hendaohezi of the city of Hailin. However, trout farming has developed fully by the year 1970s, and subsequently by the end of 1998, around 500 rainbow trout farms were established in different provinces of China, and by the year 2000, they produced around 10,000 tons of rainbow trout (Zhaoming and Yuhui 2002). Apart from this, a significant number of trout farms near Beijing serve for tourism and recreation. The major cold-water regions are located in the mountainous area of south, west, and northwestern China. Apart from rainbow trout, other species in the genera *Salvelinus*, *Brachymystax*, and *Hucho* are major cold-water fishes introduced in China, but *Oncorhynchus mykiss* is the most widely cultivated species (Zhang et al. 2018). Most of the market size trout comes from Shandong, Gansu, Beijing, Liaoning, Heilongjiang, Yunnan, and Zhejiang provinces (Zhaoming and Yuhui 2002). Presently (2018), China produces around 38,606 tons of rainbow trout which accounts for around 4.2% of the global rainbow trout production, while the total production of trout, salmon, and smelt fish was 55,301 tons (Fig. 8.5). Apart from concrete raceways, rainbow trout are also cultured in cages in reservoirs of Tibetan plateau along upstream of Yellow River. Re-circulatory aquaculture system (RAS) for trout was introduced from Denmark and established in Xinjiang province. In addition to the progress made in the production and expansion of rainbow trout farming in China, a significant advancement was also made in the genetic improvement of the species. Realizing the economic importance and future scope of species, selective breeding program for rainbow trout began in 2004 (Sun and Wang 2010). The breeding program was aimed for genetic estimation for growth traits and preventing genetic degeneration of

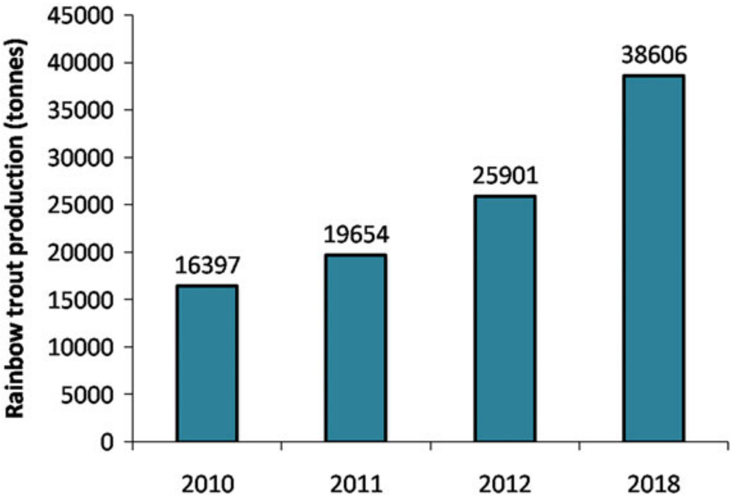


Fig. 8.5 Rainbow trout (*Oncorhynchus mykiss*) production trend in China

the rainbow trout (Hu et al. 2013). Since the first introduction of rainbow trout in the country, China has made significant progress in research and development of cold-water aquaculture and adopted advanced aquaculture systems for increasing trout production. Over the last seven decades, total production from aquaculture in China has increased tremendously, and in 2019, it accounted for 78.4% of the total aquatic products; thus, China has successfully achieved its transformation from fishing to farming (Hu et al. 2021).

8.5.2 Rainbow Trout Farming in Nepal

In the Trans-Himalayan region, Nepal is one of the important countries where mountain and hills make around 77% of the total geographic area. The Himalaya is situated in the northern side of the country, strongly influencing the climate, and therefore, the country has three climatic zones according to altitude: subtropical in the Terai, temperate in the hills, and alpine in the mountain. The Himalaya is the source of freshwater streams and rivers which inhabit 76 native fish fauna and exotic cold-water fishes (Rajbanshi 2002). Nepal being a landlocked country, its aquaculture entirely depends on the exploitation of inland water bodies, e.g., rivers, streams, lakes, reservoirs, and ponds. The rainbow trout (*O. mykiss*) was introduced in Nepal to expand aquaculture in the hills of the country by utilizing the available cold-water resources. In the beginning, salmonids were brought to Nepal in 1969, and two species, namely, Atlantic salmon (*Salmo salar*) and brown trout (*S. trutta fario*), were introduced from Kashmir, India (Gurung and Basnet 2003). Being failed to establish, another attempt was made in 1972 during which brown trout (*S. trutta fario*) and sockeye salmon (*Oncorhynchus nerka*) were introduced from United

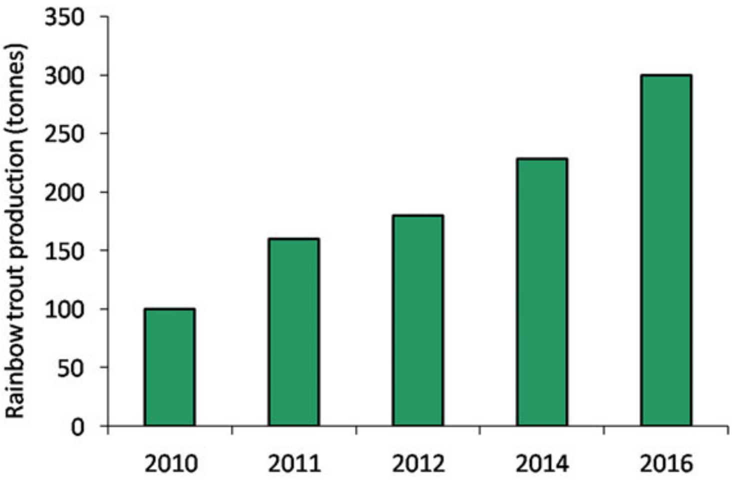


Fig. 8.6 Rainbow trout (*O. mykiss*) production trend in Nepal

Kingdom. But these introductions turned into failure due to lack of technical know-how and management. However, a successful rainbow trout introduction could be made in 1988, and around 50,000 eyed eggs were transported to the Fisheries Research Centre, Godavari, from Miyazaki prefecture of Japan under Technical Cooperation program sponsored by the Japan International Cooperation Agency (JICA) (Rai et al. 2005). Further, rainbow trout was also reared and bred in Trishuli fish farm in Nuwakot district on the bank of the river Trishuli. The breeding of rainbow trout in Nepal started in 1990, and cultivation started during 1993, and over the year, the trout farming was introduced in private sector. A number of farmers were involved in rainbow trout farming and seed production through participatory research and development trials; as a result, the government farms started production in 1995 and private farmers in 1998 (Swar 2008).

With the concerted efforts made by the Nepal Agricultural Research Council (NARC), rainbow trout culture and breeding technology has been developed in Nepal. Rainbow trout farming in Nepal is predominantly carried out in concrete raceways both in government and private sector, and around 60–70% of total trout production (~300 tons, 2016) comes from the private sector (Fig. 8.6). The stocking density in these raceways on weight basis is 10 kg/m^2 (Timalsina et al. 2017). The productivity of rainbow trout is quite low, and there is scope for further increase through adoption of better management practices. To increase the production and productivity, trials were conducted on cage farming of rainbow trout in certain lakes and reservoirs, created after installing hydropower dams. The preliminary studies have given encouraging results with good survivability and increasing productivity in shallow reservoirs, and it was found that these water bodies could be utilized for trout farming during winter to spring season (Nepal et al. 2021). The slow growth in rainbow trout production in Nepal has been attributed to factors such as lack of intensification, high cost of production, and lack of improved technology and management practices (Bhandar and Prajuli 2016). Further challenge in widespread adoption of trout farming is inadequate availability of quality seed for stocking at large scale (Timalsina et al. 2017). Apart from this, efforts are being warranted for developing appropriate linkages between production and marketing of rainbow trout for increasing demand as well as production in Nepal. Nevertheless, trout farming in Nepal provides opportunities for utilization of available cold-water resources both for production enhancement and creating recreational opportunities and revenue generation.

8.5.3 Rainbow Trout Farming in India

The farming or husbandry of trout was started as early as 1853 in North America and Europe (Bardach et al. 1972), and in the Indian subcontinent, brown trout (*Salmo trutta fario*) and rainbow trout (*O. mykiss*) were introduced as early as the late nineteenth and early twentieth century under colonial rule by British from Europe primarily to develop sports fishing or recreational angling (Mitchell 1918). Independent efforts were made in northwestern and peninsular region of the country where suitable cold water for trout is available. The very first attempt to introduce trout from New Zealand in peninsular India, in Nilgiris, was made in 1863 by Sir Francis Day, and later during 1909–1910, a hatchery was constructed in Avalanche, in present Tamil Nadu (Day 1873; Jhingran and Sehgal 1978; Gopalakrishnan et al. 1999). Similarly, brown trout (*S. trutta fario*) was introduced during 1909 in Munnar hills of Kerala which couldn't be established, and then rainbow trout was brought in 1938 from Sri Lanka which thrived in the area. In northwestern Himalayas, the first failed attempt for introducing exotic salmonids (*S. trutta fario*) in the water of Kashmir was made by F.J. Mitchell in 1899. However, in 1900, another consignment of eyed eggs was received from Scotland, and Mitchell succeeded in rearing of this species up to adulthood (Mitchell 1918). He also established the first trout hatchery in 1901 at Harwan near Srinagar in Kashmir valley. And from Kashmir, trout was further transplanted to northwestern and northeastern parts of India (Sehgal 1999). Further introductions were made within the country in cold-water regions particularly in Himachal Pradesh, parts of Kumaun hills in Uttarakhand, and different northeastern Himalayan regions mainly Arunachal Pradesh and Sikkim. Most of these transfers were made either from Kashmir or Himachal Pradesh. Lately with the assistance of Norwegian government, consignment of "eyed ova" of rainbow trout was received at Patlikuhl farm, Himachal Pradesh, during 1991 and reared successfully. These introductions in the hill regions was the beginning of cold-water fisheries and aquaculture in India. With the advent of technology of seed production, and feed availability, the focus has been shifted from recreational fishing to aquaculture (Jhingran and Sehgal 1978; Vass and Gopakumar 2002; Ali 2010).

Following a long history of failure and success of trout introduction in India, finally the rainbow trout (*O. mykiss*) was established as prime cultivable species in the Indian uplands where suitable thermal regime is available. However, the species primarily remained confined to the government farms and hatcheries until late 1990s

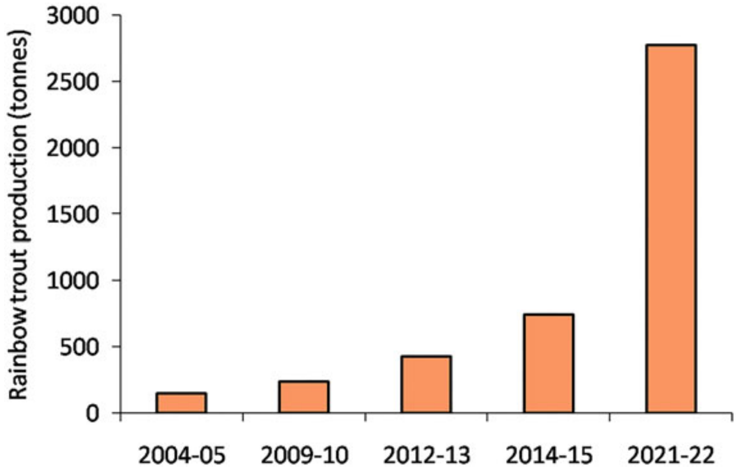


Fig. 8.7 Rainbow trout (*Oncorhynchus mykiss*) production trend in India

(Sehgal 1999). Initially, only two Himalayan states, Jammu and Kashmir and Himachal Pradesh, were having infrastructure for the production of trout, while other hill states lagged behind due to inadequate technical know-how as well as facilities for trout culture and seed production. Moreover, due to a number of constraints in terms of lack of quality seed, availability of feed, and farm management, the expansion of trout farming remained restricted to a few locations (Singh 2002; Vass 2002). In 1984, Jammu and Kashmir, a northwestern Himalayan state in India, received assistance from the European Council (EEC) and established trout farming project at Kokernag, Kashmir. With the assistance of the Norwegian government during 1988–1989, trout infrastructure has been developed in the Himachal Pradesh for rainbow trout production. Rainbow trout farming has progressed steadily over the years in India amid different constraints. The total trout production in the country has increased 18-fold in the last two decades. The present rainbow trout production in India is about 2775 tons (2021–2022) (Fig. 8.7). The trout ova production has also increased with the establishment of new hatcheries both in government and private sector, and the present ova production is around 18.31 million in the country (Fig. 8.8).

The bulk of India's trout production was contributed from northwestern region, while production from other upland areas remained low (Fig. 8.9). Increase in total production has a significant contribution from the private sector mainly from Himachal Pradesh and Jammu and Kashmir. Although, the northwestern Himalayan states remained the main producer of rainbow trout; recently Sikkim, a northeastern state, has shown significant increase in trout production, while other states such as Uttarakhand and Arunachal Pradesh and states of southern India still have meager production.

India is endowed with plenty of aquatic resources in the Himalayan region and thus has scope to increase the trout production through horizontal and vertical

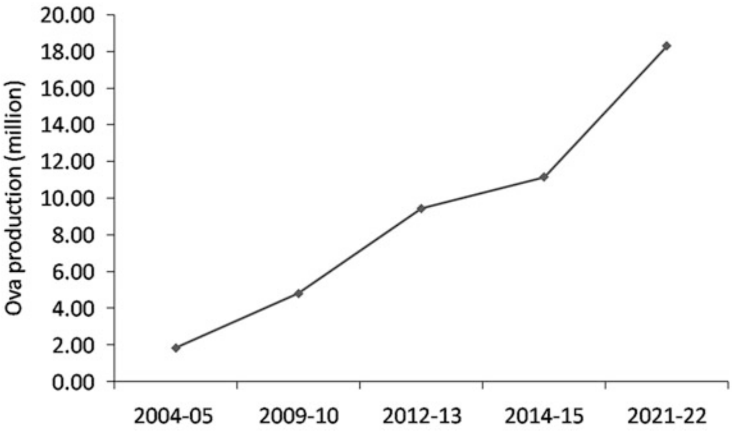


Fig. 8.8 Rainbow trout (*Oncorhynchus mykiss*) ova production trend in India

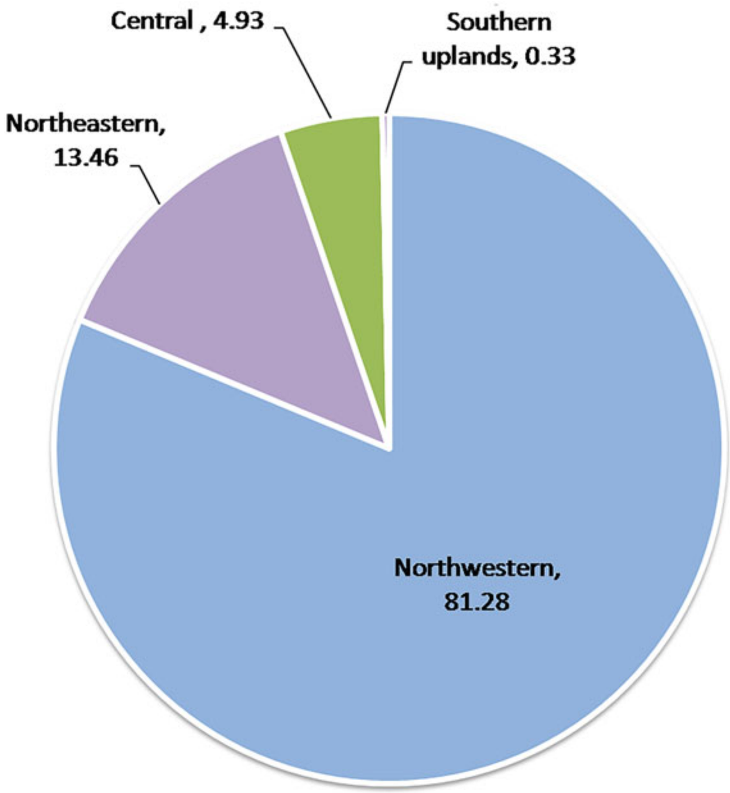


Fig. 8.9 Percentage share of rainbow trout (*Oncorhynchus mykiss*) production from different regions of India

expansion. As water availability and environmental constraints limit the expansion of new farms at many locations, trout farmers and entrepreneurs need greater intensification and increased efficiency for production enhancement. Success of trout cultivation requires expertise and knowledge about different stages of its farming. Requirement of technological advances in the form of improved feed having low FCR, farm design with greater efficiency, optimization of stocking density, broodstock maintenance, and hatchery practices is necessary for the future development of trout farming in India. At present, rainbow trout are produced using traditional flow-through system consisting of concrete raceways. In such a system, the water flow should be sufficient, and turnover rates should be high to maintain adequate water quality (Fornshell 2002). The average production is around 0.6–1.0 tons per raceways (area = ~45–50 m^2), and per unit trout production varies from 10.0 to 20 kg/m^3, depending upon stocking density and management measures applied during cultivation (Dogra and Verma 2014). Recently, ICAR-DCFR has established re-circulatory aquaculture system (RAS) for intensive farming of rainbow trout (Pande et al. 2020). This system will drastically minimize the amount of water, land, and time required for unit production of portion-sized rainbow trout, and trout farming can be done in suitable places where limited water resources are available.

8.6 Issues and Strategies for Future Expansion

Success of trout cultivation requires expertise and knowledge about different stages of its farming. Requirement of technological advances in the form of improved feed having low FCR, farm design with greater efficiency, optimization of stocking density, broodstock maintenance, and hatchery practices is necessary for the future of trout farming in Himalayan region. High capital cost in the construction of concrete raceways is another stumbling block in popularizing trout farming; therefore, efforts must be directed toward developing alternative production system in order to reduce initial investment. Establishment of state-of-the-art hatcheries in different provinces for the production of quality stocking material can ease out demand for fry/fingerlings. There is a need to enhance farming skill through education and training of trout growers, which will be fruitful not only in improving farm management practices but also in the enhancement of quality and quantity of rainbow trout production.

Marketing of the final produce is another constraint in the spread of rainbow trout farming (Vass 2002). Trout is a high value low volume fish and a highly perishable commodity; therefore, it needs to be transported in shortest possible time under refrigerated condition to fetch good price. With increasing possibilities of profitable domestic marketing in high value commodities, it has become imminent that different models of domestic markets are developed through market intelligence studies for ensuring profits to the farmer. As trout farming is progressing, environmental concerns related to the aquatic ecosystem also need adequate attention. Flow-through aquaculture systems like raceways and tanks discharge effluents with enhanced concentrations of nutrients and solids that have impacts on the receiving stream water quality (Green et al. 2002; Pulatsu et al. 2004; Bartoli, et al. 2007) and biotic communities (Camargo et al. 2011). Thus, it is important to evaluate impacts of trout farming on the streams of cold-water regions, and accordingly effective monitoring and management measures should be developed.

8.7 Conclusion

Rainbow trout farming has great potential in the Himalayan region. The present trend toward increasing production and adoption by farmers and entrepreneurs indicates scope for its expansion in potential areas. Production enhancement may be achieved through intensification, better husbandry practices, and improvement of stocks through better handling and management. Comprehensive guidelines and policy for trout farming and its promotion need to be developed for sustainable production in cold-water regions. Strengthening of marketing channel, development of cold chain, and facilities for processing and product development will be helpful to increase demand and production of rainbow trout in the Himalayas.

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9

Fisheries and Aquaculture of Snow Trouts in the Trans-Himalayan Region

Suresh Chandra and Parvaiz Ahmad Ganie

Abstract

The Himalayas play a vital role in the livelihood support of human beings, and the significance of efficiently conserving these diverse natural resources has long been well recognized and established. The trans-Himalayas are home to ten of the world's largest river systems and are widely acknowledged as a center for the evolution and diversification of a wide variety of life forms. Ecologically and economically, significant aquatic biodiversity is found in rivers, streams, and lakes, which feature diverse altitudinal geomorphologies. The Schizothroacinae family of fish, better known as snow trouts, is the most abundant cyprinid family in the mountains. These fish are highly sought after for both their food and esthetic qualities. These fish are primarily herbivorous and have evolved to thrive in rivers and streams that experience high levels of precipitation and flooding. *Schizothorax* spp. and *Schizothoraichthys* spp. are found at lower altitudes, while *Diptychus* spp. are found at slightly higher elevations. Adverse effects on crucial life cycle phenomena have been exacerbated by multiple anthropogenic and climatic uncertainties, leading to biodiversity depletion. Captive culture, breeding, and larval developmental studies have been attempted. However, the upscaling of aquaculture practices for these species is still in the infant stages due to slow growth. Prioritizing snow trout species mapping, in situ and ex situ conservation strategies, upscaling of sustainable culture and breeding techniques, long-term monitoring of cold-water resources, and strengthening location-specific legal frameworks are imperative to conserve this important fishery.

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Keywords

Trans-Himalaya · Fisheries · Schizothroacine distribution · Captive farming · Conservation

9.1 Introduction

The significance of conserving these diverse biological natural resources of the Himalayas or food has long been recognized. The trans-Himalayan region, also known as the Hindu Kush Himalaya (HKH), is spread across eight countries, viz., Bangladesh, Myanmar, India, Pakistan, China, Nepal, Bhutan and Afghanistan. Diverse geomorphology and rich aquatic resources with productive ecosystems are the characteristics of HKH uplands, and the well-being of hilly people primarily depends on the presence and availability of these precious resources (Molden et al. 2014). The extreme climate unpredictability and difficult topography contribute to the HKH's high levels of diversity. An amalgamation of several biophysical and geographic factors, together with altitudinal zonation all along a long and steep elevation slope with a prominent rain shadow zone on the Tibetan Plateau, has resulted to high levels of species diversity and richness (Myers et al. 2000; Sharma et al. 2010; Zomer and Oli 2011).

Plate tectonics, which are responsible for the formation of mountains, have allowed the development of a wide range of climates, ecological gradients, and physical habitats, which together play a role in the diversification of ecosystems (Hua 2012) and the subsequent evolution of their constituent species (Tremblay et al. 2015). Since this area coincides with two very different floras (Palearctic and Indomalayan), its significant diversity of species is the result of both localized speciation from local progenitors and migration of organisms from other regions (Olson and Dinerstein 2002). Dense population with ethnic multiplicity have contributed to the region's high levels of agrobiodiversity, farming system and agroecosystem separation, and domestication of many important food animals and plants, making it one of the productive and intensively cultivated mountain region (Pandit et al. 2014).

Indian cold-water/hill fishery resources are concentrated mostly in the Himalayan region which are suitable for food, ornamental, and sport fisheries. The trans-Himalayas, Greater Himalayas, Lesser Himalayas, and Siwaliks are four different parallel and longitudinal mountain belts (Fig. 9.1 and Table 9.1) that run from south to north and have their own unique physiographic features and geological histories (Sehgal 1999).

There are 19 significant rivers that flow out of the Himalayas. The longest of which are the Indus and the Brahmaputra. Of the remaining 17 rivers, 9 (the Yamuna, Ganga, Ram Ganga, Kosi, Kali-Sharda, Karnali, Rapti, Gandak, and Bhagmati) and 5 (the Indus system's Beas and Sutlej) drain about 150,000 and 80,000 km^2, respectively.

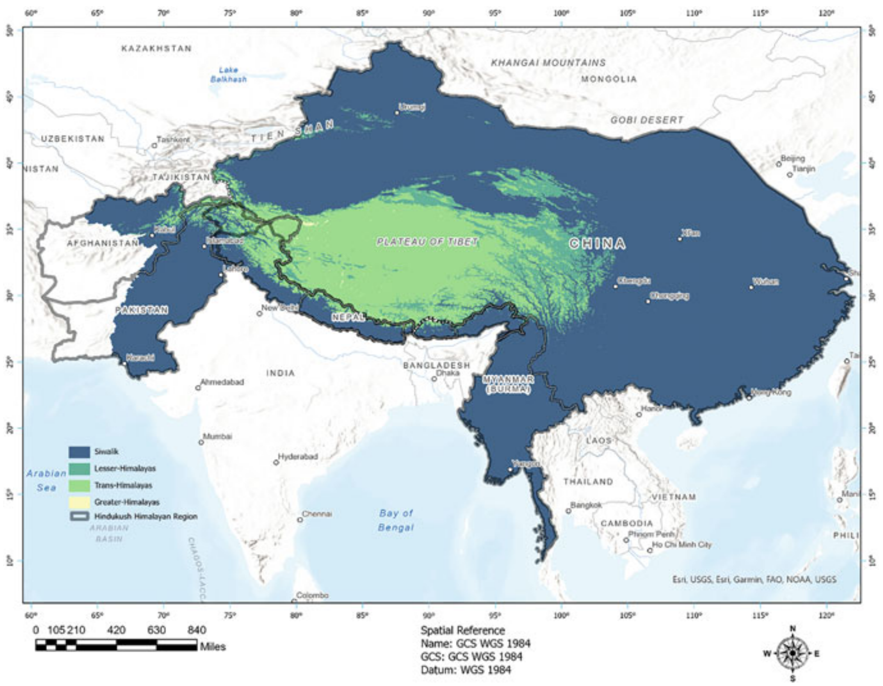

Fig. 9.1 Major Himalayan zones

Table 9.1 Major Himalayan region

S. no.	Division	Altitude	Area features
01	The greater Himalayas (Himadri)	Above 6100 m asl	Continuous and longest, mostly north part of Nepal and parts of Sikkim
02	Trans-Himalayas	Average altitude varies from 4500 to 6600 m asl	From west to east, stretches across the Himalayas
03	Lesser Himalayas (Himachal)	3700–4500 m asl	In the south and north of the Siwalik
04	Siwalik (outer Himalayas)	Average altitude about 900–1200 m asl	Siwalik is narrowest and lowest section of the Himalayas

(Source: Sehgal 1999)

These riverine resources are spread in about 12 states of India, from the north-eastern to northwestern Himalayan region and some parts of the Western Ghats. These rivers are home to a wide variety of fish species, which not only provide food and jobs for the locals but also offer plenty of adventure activities for tourists from near and far. However, a number of physicochemical, geochemical, and biological parameters of water, e.g., water temperature, dissolved oxygen, water velocity, turbidity, substratum, trophic status, food availability, etc., have an effect on the distribution and abundance of various species of cold-water fish (Sehgal 1988). Mostly, cold-water fishes are the natives of the Himalayan and sub-Himalayan regions (Sunder et al. 1999). According to Menon (1962), morphological adaptations let fish survive in the raging waters of the Himalayas. The Himalayan habitat has been recognized as an axis of origin and evolution of several biotic forms, since 17% of the total fish fauna of India has been reported from here (Ghosh 1997). Indigenous snow trouts mahseer, exotic trout, and common carp are among the economically important species found in the Himalayas' huge mountain fishery resources (Singh et al. 2014). Over 268 different fish species have been documented in the Himalayas.

9.2 Schizothoracinae Distribution

Schizothorax is a genus of cyprinid fish that was described by Gray in 1832. In the year 1838, Heckel made the initial discovery of the fish in Kashmir. Schizothoracinae, or "snow trout," are subfamily of the Cyprinidae that includes 10–13 genera and roughly hundred species (Mirza 1991). The physical characteristics of the schizothoracinae fish have led to their classification into three groups: the "primitive group," the "specialized group," and the "highly specialized group" (Cao et al. 1981). Primitive group includes *Schizothorax* and *Aspiorhynchus*. They share more characteristics with the outgroup *Barbodes hexagonolepis*, such as uroneuralia, three or four rows of pharyngeal teeth, reduced degradation of scales, and ambiguous special sexual dimorphism. *Ptychobarbus*, *Gymnodiptychus*, and *Diptychus* make up the specialized group. They are distinguished by the lack of uroneuralia, the presence of just one or two rows of pharyngeal teeth, and a considerable but moderate degree of degeneration of the scales. *Gymnocypris*, *Oxygymnocypris*, *Schizophygopsis*, *Chuanchia*, and *Platypharodon* are all members of a highly specialized group defined by the complete absence of barbels and scales and the presence of a well-developed canalis preoperculomandibularis (Qi et al. 2012).

Parallelly, Heckel (1938) first described the genus *Schizothorax* without assigning it a type. He divided these fish into three groups: A, B and C. The fishes that are distinguished by the presence of a strip of hard papillated structure at the lower jaw, chin, and mouth with a fine cartilaginous horny structure were classified in group "A." Both *Schizothorax plagiostomus* (Fig. 9.2) and *Schizothorax sinuatus* were included in this section. Groups B and C lack the strip of rigid, papillated tissue behind the chin. Without being aware of Heckel's publication, McClelland (1938) explained the fishes under a new genus called *Oreinus* with the species *Oreinus guttatus* (McClelland), *Oreinus richardsonii* (Gray), and *O. esocinus* in his monograph on Indian Cyprinidae. Misra (1962) proposed the genus *Schizothoraichthys* to encompass the species without a suctorial disc that Heckel (1938) had placed within the genus *Schizothorax*. *Schizothorax plagiostomus* and *Orienus guttatus*, according to Tilak and Sinha (1975), are the species with a sucker at the chin; the latter is a synonym of the former. They also backed Misra's (1962) assertion that fish without a

Fig. 9.2 *Schizothorax plagiostomus*

Fig. 9.3 *Schizothorax richardsonii*

hard strip of papillated structure at the chin are appropriately accommodated under a new generic name, *Schizothoraichthys.* The fish with a papillated strip of structure at the chin fall within the genus *Schizothorax*, which was also acknowledged by numerous other writers (Misra 1962; Menon 1971, 1974; Jhingran 1982). *S. richardsonii* and *S. kumaonensis* were both confirmed as two distinct species by Menon (1971). The genus *Oreinus* was reinstated by Talwar (1978), who also combined *Schizothoraichthys* with the genus *Schizothorax* and removed it from the synonymy of *Schizothorax* in 1839. According to Tilak (1987) and Talwar and Jhingran (1991), there are two species of *Schizothorax* in India: *S. richardsonii* (Gray) (Fig. 9.3) and *S. kumaonensis* (Menon). Small-sized head that is five times shorter than the average length distinguishes *Schizothorax kumaonensis* from *Schizothorax richardsonii*. The other genera of fish that include snow trout are *Diptychus*, *Ptychobarbus*, *Schizothoraichthys*, *Schizopygopsis*, and *Lepidopygopsis.* Menon (1974) listed 15 species within the Schizothoracinae subfamily and placed 2 species in the genera *Oreinus*, namely, *Oreinus richardsonii* (Gray) and *O. kumaonensis* (Menon), while placing other species under the genera *Schizothorax*. He also united the genera *Schizothorax* with *Schizothoraichthys*. Jayaram (1999) added *Gymnocypris biswasi* (Talwar) to the list of the 16 species that make up this subfamily. But according to CAMP (1998), this species was thought to be extinct.

The genus *Schizothorax* is mostly found at elevations ranging from 300 to 1820 m. This species has been found suitable for both the upper and lower reaches of a river. Snow trouts, also known as asla, are not only an important natural fishery

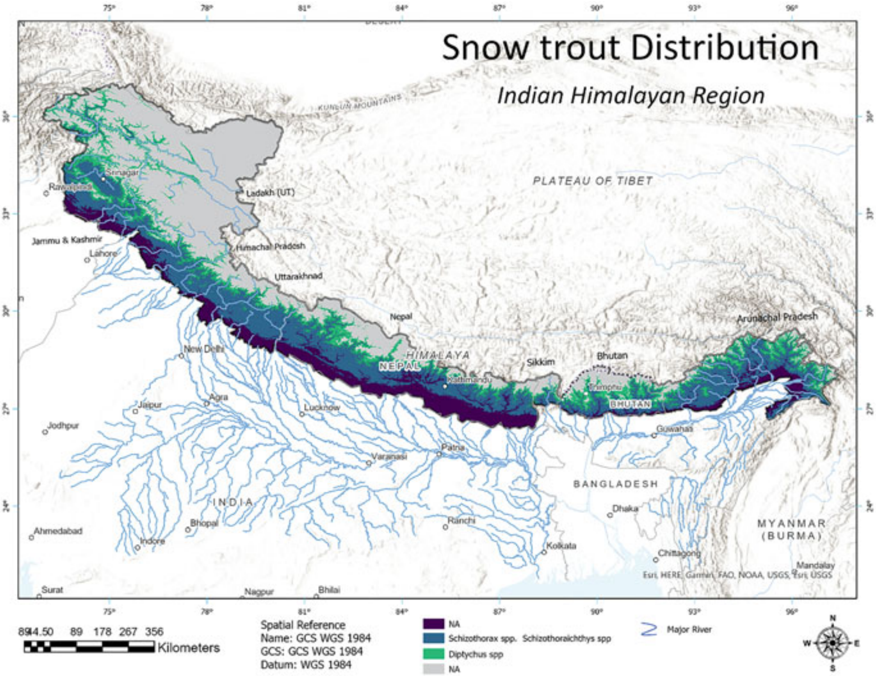

Fig. 9.4 Snow trout distribution in the Indian Himalayan region

in torrential streams, but they are also adapted to lentic systems as well (Sehgal 1988). The cold-water Schizothoracinae groups of fishes are soundly adapted to the Himalayan and Central Asian fast-flowing torrential rivers and streams. The *Schizothorax* spp. and *Schizothoraichthys* spp. are distributed in the regions having an altitudinal range of 750–2500 m asl, whereas the *Diptychus* spp. inhabit a slightly higher altitudinal range of about 2500–3750 m asl (Fig. 9.4).

Schizothoraichthys ecosinus, S. progastus, and *Schizopygopsis stoliczkae* occur in the upper reaches and are known as rheophilic species. In the intermediate hill regions, *S. longipinnis, S. planifrons, and S. micropogon* are common species. In lower altitudinal regions, *S. richardsonii* and *S. niger* are frequently found (Sehgal 1999). Snow trouts inhabit streams from Jammu and Kashmir to Nainital in India (Sundar and Bhagat 1979). According to Jhingran (1982), the distribution of this species ranges from Assam and the eastern Himalayas to Bhutan and Sikkim at elevations between 1100 and 3000 m. From 300 to 3323 m in height and 8 to 22 °C, it has been observed in rivers and lakes/reservoirs of Nepal (Shrestha 1981). The schizothoracine group of fishes has evolved a series of both morphological and physiological traits confined to regions at either high altitudes or high latitudes to adapt to the cold and hypoxic environment and plays important roles in the trophic web (Chen and Cao 2000). The snow trout is a unique fish to the Himalayas and can be found across the region's streams and lakes. It is frequently considered to be a sentinel fish species (Kapila et al. 2002).

Snow trouts have a disputable taxonomy as far as their classification is concerned (Day 1876; Tilak 1987; Wu and Wu 1991; Chen and Cao 2000). Researchers across the globe have documented different numbers of genera under this group. Sharma (1989) has documented 28 species of snow trout from the Himalayas and sub-Himalayas, which span China and Pakistan. Eleven species of snow trout have been identified in Nepal, belonging to three distinct genera: *Schizothorax* (two species), *Schizothoraichthys* (eight species), and *Diptychus* (one species) (Yadav et al. 2014). Tilak (1987) described 12 *Schizothorax* species from India. Nelson (1994) identified 13 subfamilies in Afghanistan and Pakistan. Twelve species belonging to six genera of schizothoracinae have been described from Pakistan: *Schizothorax* (02), *Schizothoraichthys* (05), *Schizocypris* (01), *Diptychus* (02), *Ptychobarbus* (01), and *Schizopygopsis* (01) (Mirza and Awan 1979). Nineteen species of Schizothoracinae have been recorded from Indian highlands, with only *Lepidopygopsis typus* (Raj) being endemic to the Western Ghats (Sunder and Joshi 2002).

As per www.fishbase.org (Fishbase n.d.), snow trouts are grouped into two subfamilies, viz., Schizothoracinae and Schizopygopsinae. The Schizothoracinae consists of 5 genera, viz., *Aspiorhynchus*, *Percocypris*, *Racoma*, *Schizopyge*, and *Schizothorax*, with a total of 69 existing species. Meanwhile, the Schizopygopsinae consists of 9 genera, viz., *Chuannchia*, *Diptychus*, *Gymnocypris*, *Gymnodiptychus*, *Herzensteinia*, *Oxygymnocypris*, *Platypharodon*, *Ptychobarbus*, and *Schizopygopsis*, with a total of 32 species.

9.3 Habitat

The predominant fish in the chilly waters of the hilly terrains is the snow trout (*Schizothorax* and *Schizothoraichthys* species) (Rajbanshi 2002). They thrive in the cold, hyperoxic waters of the hill streams and upland lakes of the Himalayan region and prefer higher altitudes. According to reports, the fish are a short and potamodromous and migrate for feeding and spawning. They move upstream in the summer to find a suitable breeding ground, temperature, and water current for laying eggs and then downstream in the winter months to cope with the sharp drop in water temperature and in quest of suitable food (Yadav et al. 2014). *Schizothorax* species acquire an adhesive organ for attachment in the swiftly moving water as a result of the biological conditions of the hill streams. In hill stream fishes, the anchorage mechanisms take the shape of real suckers, sticky organs with ridges and grooves, or irregular folds (Ojha 2002). In captivity, slow development patterns, a tendency to hide and prefer to take cover behind rocks or gravel, tolerance for a wide range of environmental fluctuations, and circular collecting in the middle of the bottom of ponds and tanks have all been noted. Additionally, despite the species' ability to survive a wide range of temperatures (0–32 °C), it favors snow-fed torrential streams and pools with temperatures between 8 °C and 22 °C (Sharma 1989).

9.4 Feeding Habits

Snow trouts are mostly illiophagic herbivores in nature because of their transverse inferior mouth position. The mouth is well adapted for scratching the periphyton and microbiota that mostly grows over the bottom rocks, stones, boulders, and other substrates. The schizothoracine groups of fish are mostly bottom dwellers. Blue-green or green algae and aquatic insects are predominantly part of its gut content. The early stages, like fry and fingerlings, are generally insectivorous and consume mainly the larvae of *Diptera*, nymphs of mayflies, and larvae of flies. The juveniles consume primarily diatoms, detritus, blue-green algae, and insect larvae. Bigger-sized fish subsist mainly on diatoms, blue-green algae, green algae, insect larvae, and detritus. While browsing the algae from the attached objects, they upturned their bodies, showing their shiner ventral portion in order to grab the algae forcefully. It is reported that change in habitat and husbandry alters the gut microbiota of snow trout and *Cetobacterium somerae* was abundant in wild stock while *Flavobacterium* and *Aeromonads* were dominant bacteria in captive *S. richardsonii* (ICAR-DCFR 2019). Intestinal enzyme profile of riverine *Schizothorax richardsonii* has also been studied to understand the food and feeding habit of the fish (Nilssen et al. 2015).

Food and feeding habits of *S. plagiostomus* have been studied by Jan and Ahmed (2019), and they concluded it to be benthic herbivore with diatoms forming the important constituent of the food. The food items mainly constituted of plant material (62.02%); mud, sand, and detritus (31.01%); and animal matter (6.07%). Sunder (1984) in his study on *S. curvifrons* reported that the gut composition is represented by sand and mud (17.51%), dissolved organic matter (40.33%), zoo-plankton (2.00%), phytoplankton (38.78%), and other miscellaneous matter (1.38%). In their study of the seasonal variations in the gut contents of *S. esocinus* and *S. curvifrons*, Kausar et al. (2012) found that the average percentage of vegetable substance, animal matter, unidentified animal matter, unidentified vegetable matter, and sand particles in the gut contents was 51.25%, 12.43%, 6.25%, 27.67%, and 2.695%, respectively. Sabha et al. (2017) discovered that *S. niger* was a herbivorous fish that mostly consumed green algae, plant fragments, diatoms, detritus, and unidentifiable stuff (scales of fishes, ropes, sand/silt). Detritus, plants that are adhering to rocks and stones (including algae), and the related invertebrate fauna for *S. niger* were all documented by Shaf and Yousuf (2012) from Dal Lake in Jammu and Kashmir, India.

9.5 Trial on Artificial Feeding

Trials undertaken at various farms showed that the bigger-sized fish in the size range of 36–140 g reared and domesticated in flow-through systems for 1 year efficiently consumed floating pelleted feed. The optimum feed intake was found to be dependent on the water temperature. Generally, from April onward, when the water temperature rises above 17 °C, the acceptability of feed gradually increases in captive condition. The optimum feed intake is found during April to September when the water temperature ranged between 17 °C and 24 °C. It has been reported that the feed intake gradually reduces in the winter months with minimal feed intake at the farm. Keeping boulders in raceways during captive rearing not only helps in the development of natural food in the form of periphyton but also provides shelters for the stocked fish. Compounded wet diets have also been tried with the agglomeration of ingredients like groundnut oil cake (20%), soya flour (38%), rice polish (20%), fish meal (20%), and vitamin mineral mix (2%), having crude protein of 35%, soaked in the water to make a small ball for feeding the stocked fish (ICAR-DCFR 2019). The role of vitamin C and *Achyranthes aspera* seeds enriched diets on growth, digestive enzyme activities, and expressions of genes has indicated significant growth in captive reared snow trout, *Schizothorax richardsonii* (Kumar et al. 2021).

9.6 Growth and Reproductive Biology

Regarding growth attainment in the wild, earlier reports indicated that *S . richardsonii* collected from the wild was up to 48 cm with a weight of 1.5 kg (Rajbanshi 1971), 60 cm (Talwar and Jhingran 1991), and up to 5.0 kg (Rai et al. 2002), but the information on the age of this species is lacking. Slow growth in captive conditions under different densities and attainment of maturity at a small size for *Schizothorax richardsonii* were identified as the major constraints (Agarwal et al. 2007; Negi and Negi 2010; Joshi 2006; Mir et al. 2013; Rayal et al. 2020). Compared to other snow trout species, *S. plagiostomus* attains a size of up to 60 cm of 2.5 kg (Raizada 1985).

The snow trout is considered a hardy fish, spawning easily in natural water bodies having a low flow rate. Snow trout generally attains maturity at an age of 3+ years. The breeding and spawning areas are characterized by shallow clear water and sandy and gravelly beds, with very feeble water flow. The mature female lays eggs in shallow pools (50–70 cm depth) and remains attached to the substrate till hatching stage (Sehgal 1988). Spawn of most of the schizothoracids can be observed in the creeks and seasonal tributaries, connecting the main lakes and rivers. The adhesive eggs are laid in the gravel of the pools or on the borders of the main streams. The vitelline membrane of large-sized eggs (3.0–4.0 mm in diameter) is completely filled with the yolk.

In the central Himalayan rivers, *S. richardsonii* usually spawns twice a year during July–October and February–May. However, in Himachal Pradesh, it has been reported that the fish breeds thrice a year during March, May–June, and October–November (Sarma et al. 1998). The batch spawning of *Schizothorax* spp. may facilitate in achieving better offspring survival (Lambert and Ware 1984; Bhatnagar 1964; Qadri et al. 1983). Jan and Ahmed (2019) reported that *S. plagiostomus* spawned twice in a year. The temperature of the water may be the most important environmental factor in synchronizing its breeding (Papoulias et al. 2006). In recent studies conducted at the ICAR-Directorate of Coldwater Fisheries Research (ICAR-DCFR), Champawat Center, fecundity of *S. richardsonii* was found in the range of 10,560 to 35,000/kg body weight with a male to female ratio of 7:3 (ICAR-DCFR 2019).

S. plagiostomus reaches sexual maturity at the size of 18–24 cm in length and spawns twice a year, i.e., in March–April and September–October (Raizada 1985). However, Jhingran and Sehgal (1978) reported that at different riverine elevations, *S. plagiostomus* spawned only once a year.

9.7 Artificial Breeding of *Schizothorax Richardsonii*

Significant success has been achieved in the breeding of farm-reared broodstock at ICAR-DCFR's experimental fish farm, Champawat, Uttarakhand, India (Fig. 9.5). Female brooders, collected from Sarju, Lohawati, Gaudi, Ladhiya, and nearby streams of Chhirpani, were stripped. The rate of fertilization ranged from 35 to 45% and the hatching rate was 60–75%. The overall survival from fertilized eggs to swim-up fry ranged between 20 and 30% and from swim-up fry stage to advanced fry was in range of 65–80%. Success in breeding and seed production of *S. richardsonii* has been achieved with pond-raised captive brooders. The broodstocks were fed with floating pelleted feed at 2–3% of body weight and reared in raceways with a stocking density of 4–6 nos./m^2. Maintaining a water flow rate of 20–30 L/min, monthly cleaning, and providing shelters in the raceways are found useful in attaining gonadal maturity of the stock (ICAR-DCFR, Annual report-2018-2019).

9.7.1 Stripping and Fertilization

For stripping, male and female brooders were selected from the raceways and brought to the hatchery. The dry method of fertilization was followed in the dark, without adding water. By gently pressing the abdomen from the pelvic fin area to the vent area, eggs were stripped. Well-matured eggs were yellowish to yellowish orange in color and uniform in size. A 100 g of fish will typically lay between 1200 and 2000 eggs; four to five females are used in each batch to achieve better breeding output. A similar method is used for the stripping of males for milt collection, avoiding blood and fecal contamination. The milt of two to three males was used for fertilizing the eggs of a single female to ensure superior fertilization. The milt and eggs were thoroughly mixed, and for activating the sperms, water was

Natural habitat of *S.richardsonii*

Captive rearing in raceways at ICAR-DCFR, Champawat

A Haul of snow trout brooders

Mature specimen of *S.richardsonii*

Stripping of eggs

Stripping of male fish

Mixing of gametes

Washing of fertilized eggs

Washed gametes

Incubation of eggs

Fig. 9.5 Captive breeding of *S. richardsonii* added. These eggs were kept in plastic trays for 10–15 minutes to harden. After proper cleaning and water hardening, eggs were transferred into hatching trays for incubation under flowing water conditions. Dead eggs were removed manually.

9.7.2 Incubation of Fertilized Eggs

At a water temperature range of 17–21 °C, the incubation period was recorded to be 5–11 days. The further development of newly hatched spawn to free swimming stage was temperature dependent, ranging from 5 days at 24 °C to 24 days at 12 °C (Fig. 9.6). However, also recorded were >90% at 20–24 °C, 65% at 17 °C, and <50% at 11–14 °C. The hatching rate was higher (50%) during October and November than during February and March (<25%). A low survival and a long incubation in running water conditions are mainly due to a slightly low water temperature during incubation of *S. richardsonii* eggs (Sehgal 1999; Joshi 2004).

9.7.3 Embryonic Development

The yellow-orange colored eggs after hatching develop into creamish-yellow colored sac fry, which are tender with a large yolk sac (Fig. 9.6). The length of the sac fry (alevins) varies from 7.5 to 9.5 mm. Appearance of eye spots and development of eyes started after 20–24 h of hatching, and black color melanin pigments are produced after 72 h of hatching. After the yolk sac absorption, the fry start exogenous feeding on a supplementary diet. Dorsal and caudal fin development begins on the fifth day after hatching, whereas paired and unpaired fins were completed between the 20th and 25th days (Joshi 2004). After complete absorption of the yolk sac, fry were reared in small troughs inside the hatchery, ensuring a running clean water supply. Hatching and rearing troughs were 40–50 cm wide, 20 cm deep, and up to about 2.5 m in length. During the incubation period, developing eggs were treated with formaldehyde for half an hour as a prophylactic measure to prevent the attack of fungal infections. The juveniles, after a rearing period of 1 month, were transferred to small nursery raceways of 30 m^2. The stocking rate may vary from 100 to 500/m^2. The water flow in the nursery tank is maintained at a rate of 20–25 L/min ((ICAR-DCFR 2019).

9.8 Health Issues in Captive and Wild Stocks

Although extensive studies on fish diseases have been made by a number of researches on important cultivable species, however, reports on fish disease incidences on *Schizothorax* spp. are meager. Attempts were made by ICAR-DCFR on captive rearing and other aspects. In captive rearing of *S. richardsonii*, fungal infection during post monsoon months, ulceration over skin due to argulosis in foot hill streams and lakes, white spot diseases, and monogenic trematode infection over

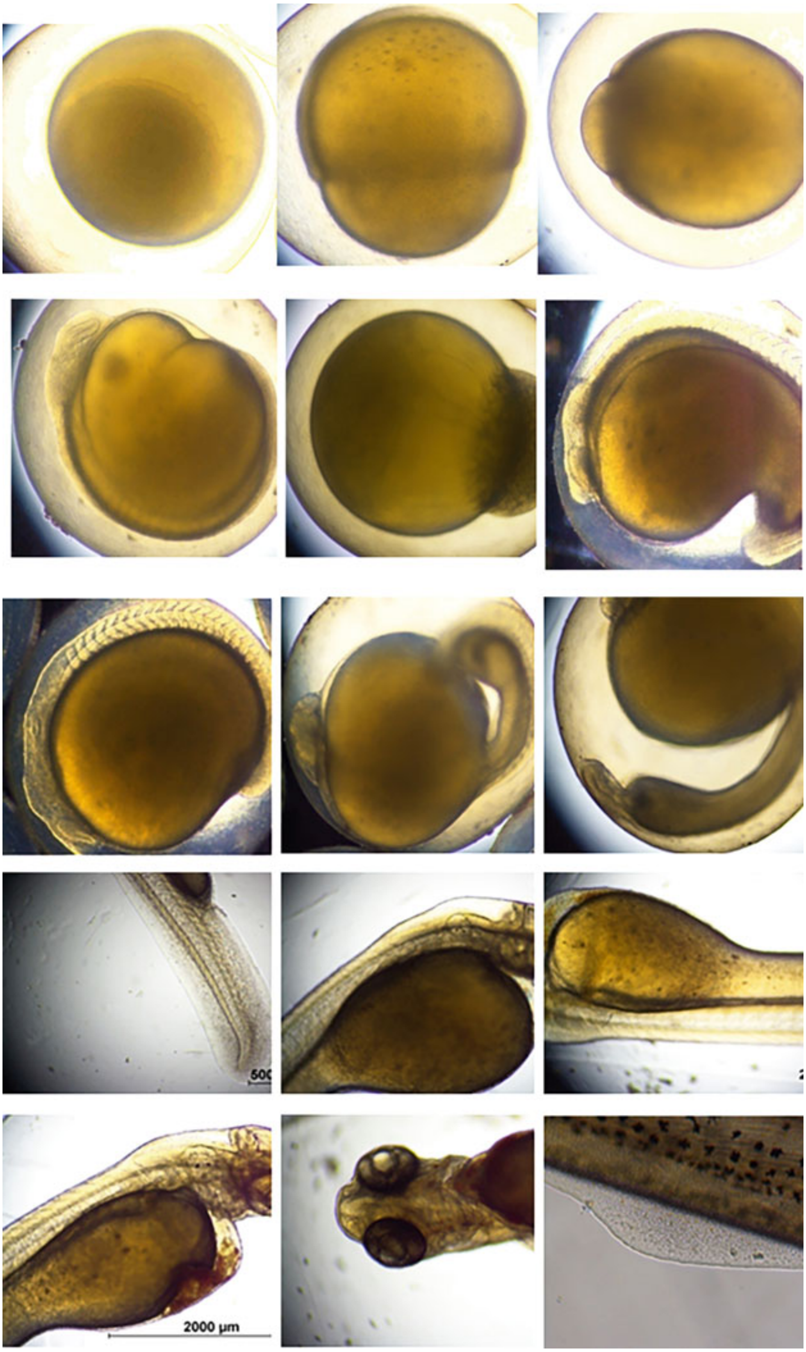

Fig. 9.6 Embryonic development of *S. richardsonii*

the gills have been observed. These parasites typically target the fins and skin, leaving infected fish lethargic and undernourished. Such cases were observed in the wild, mostly likely as a result of environmental pressures. In severe infection, large-scale mortality occurs. Among these, saprolegnia infections and argulosis in cage reared stock located in foot hill areas were common.

9.8.1 Fungal Infections

Frequent incidences of fungal infections are very common. Fluctuations in water temperature, high organic load, and impaired water quality are found to be primarily responsible for fungal infections. Fungal infections are typically secondary in nature, however, they were more prevalent when incubating eggs in cold water due to frequent temperature changes.

9.8.2 Argulosis

Schizothorax sp. has been found to be highly susceptible to argulosis infection (Figs. 9.7 and 9.8). The occurrence has been reported when water temperature ranged between 22.0 °C and 25.5 ± 1.5 °C in cage reared *S. richardsonii* and *S. plagiostomus*. Ulcerations over the skin with abnormal swimming, excessive mucus production, fin erosion, and inflamed skin wounds in body surfaces were observed (ICAR-DCFR 2021).

Fig. 9.7 Fungal infected *S. richardsonii* specimens

Fig. 9.8 *Argulus* sp. collected from infected cage reared *S. richardsonii*

9.9 Threats to Snow Trout Fishery

A region or nation's fish biodiversity has economic and aesthetic significance. However, in a changing environment, there are increasingly substantial risks to both biodiversity and the stability of ecosystems that are felt globally, necessitating the development of a number of strategies and goals. Aquatic resources are facing numerous dangers and are dwindling quickly, which is considered a sign of a global "biodiversity crisis" in freshwater (Abell 2002). The following are the main dangers to the Himalayan region's snow trout fishery:

1. The construction of small and big dams over significant rivers that are home to fishes in the schizothoracinae group threatens the survival of snow touts because dams impede fish migration in addition to causing mechanical harm to fish species. Additionally, the enormous amount of water discharged causes 100% supersaturation of the dissolved gas. When a large amount of water is released, there is strong aeration and high gas pressure at the dam site, which increases the likelihood of gas bubble disease in fish downstream.
2. One of the biggest dangers to endemic snow trout species has been the introduction of foreign species, particularly trout and Chinese carps. These outcompete the snow trouts for food and habitat owing to their resilient nature.

3. As a result of the effects of climate change and global warming, the climate in the Himalayan region is deteriorating, which is harming the region's natural aquatic systems. The pristine feeding and breeding sites of native cold-water fish species like snow trouts will be negatively impacted by the altered ecoclimatic conditions, having an impact on their population, maturity state, and spawning and related important life cycle phenomena. Additionally, it affects phenological fluctuations, food chains, microhabitats, stream flow regimes, and overall productivity.
4. When kept in captivity, snow trouts experience a variety of issues, including delayed growth, a lack of proper feed for the larvae and brood stock, protracted sub-ambient temperatures, etc. These elements work together to impede fish culture by limiting fish growth and reproduction.
5. The reduction of natural habitat area, habitat alterations, loss of germplasm, shrinkage of resources, and so on as a result of reducing water discharge in rivers, siltation, overfishing, pollution of water bodies, and climatic intricacies are some of the factors that are impeding snow trout populations.

9.10 Conservation Strategies

The threats and difficulties that numerous man-made and climatic factors pose to snow trout fisheries are significant, so it is essential to make conservation efforts for fisheries revival through raising public awareness, along with standardization and upscaling of culture and captive seed production for expanding ranching programs. Moreover, any approach to landscape conservation throughout the Himalayas must prioritize the mid-elevation regions, which are the best habitat for snow trout. The following are some of the important considerations that must be made when managing the snow trout fisheries:

1. Prioritizing mapping of the snow trout species over time and space is necessary to understand their current and potential future distributional shifts, if any, and to build effective development and conservation plans.
2. Standardization and upscaling of culture and breeding practices in order to enhance production in lentic and lotic systems along with the development of live gene bank in fish farms.
3. Intensive efforts on reproductive biology in order to prepare population recovery strategies.
4. Thorough preservation and biomonitoring of all cold-water resources over a wide geographic and temporal range to evaluate danger perspectives in relation to biodiversity.
5. A decision must be made regarding resource ownership.
6. A location-specific legal framework must be created and strictly followed.

9.11 Conclusion

The schizothoracinae group of fishes is the most widespread and economically important in the trans-Himalayan region. The main cause of mountain fishery's extreme vulnerability and rapid decline are anthropogenic and climatic externalities. To overcome the challenges and threats, in situ and ex situ conservation strategies, including live gene bank establishment, breeding and seed production protocols, and implementation of strict legislations, need to be formulated and developed to save the snow trout fisheries of the temperate Himalayan region.

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10 Ornamental Fisheries in Hindu Kush Himalayan Region

Pragyan Dash, Pankaj Gargotra, and Ritesh Shantilal Tandel

Abstract

Cold-water fisheries in the Hindu Kush Himalayan region mainly span the highland and midland streams and rivers of eight countries: Afghanistan, Pakistan, Nepal, Bhutan, China, Myanmar, Bangladesh, and India. This paper summarizes the existing information on cold-water ornamental fisheries resources and prevalent hazards in all Hindu Kush Himalayan nations. In addition, the Indian resources and valuable indigenous group of ornamental fishes are described in-depth. The fisheries in the majority of the Himalayan nations are little studied and at significant risk due to several natural and anthropogenic hazards. Construction of hydroelectric power plants in the streams and rivers is recognized as the primary cause for declining fish population. In India, overfishing of ornamental fishes is also becoming a significant issue for the sustainable management of ornamental fisheries.

Keywords

Ornamental fisheries · Himalayan countries · Hill stream fish

10.1 Introduction

The Hindu Kush Himalaya is one of the world's largest mountain systems, spanning 4.2 million km^2 area (Bajracharya et al. 2015) over eight nations from Afghanistan in the west to Myanmar in the east and traversing Pakistan, India, Nepal, Bhutan,

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China, and Bangladesh. The Hindu Kush Himalayan region is source of ten Asia's major river basins including the Ganges, Indus, Brahmaputra, Yellow, Yangtze, Irrawaddy, Salween, Mekong, Amu Darya, and Tarim, and it contains large volume of ice and snow. The Indian Himalayan region contributes the largest share of Himalayan range spreading over 500,000 km^2 (16.2% of the nation's total geographical area) and marks the northern border of the country. The Himalaya is home to diverse flora, and fauna, including a number of different fish species. The rivers and streams in the Himalayan mountains predominantly sustain the recreational or sport fishes such as mahseer, snow trout, etc. and small-sized fishes such as barbs, loaches, catfish, suckers, and minnows with ornamental and food value. Water current is high, and biological productivity is low in the Himalayan hill steams, for which most fishes in this region (except mahseer and trout) are small in size with adhesive organs to protect themselves from being swept away. The fisheries are underdeveloped, owing to severe terrain and inaccessibility in the mountains. Commercial fisheries are mostly carried out in some lakes and reservoirs in some countries. The Hindu Kush Himalayan region is facing several sustainable developmental challenges which include climate change, overexploitation of natural resources, difficulty in implementing infrastructure development plans, and unplanned societal growth. Furthermore, construction of hydropower projects, damming, and the associated habitat degradation are harming the Himalayan fisheries.

10.2 Geography, Ornamental Fish Diversity, and Challenges

The geography, ornamental fish diversity, and their challenges in different regions of the Hindu Kush Himalaya are discussed in the following:

10.2.1 Nepal

Nepal stretches about 800 km along the southern slopes of the Himalayas, dividing the parched Tibetan Plateau to the north and the lush Gangetic Plain to the south. Rugged hills and mountains cover more than 80% of the geographical area. Trans-Himalaya, highlands, subtropical midlands, and tropical lowlands or terai are the primary ecological regions. The major rivers, Koshi, Gandaki, Karnali (originating from the northern slopes of the greater Himalayas), and Mahakali (originating from the high mountains of Nepal), are of primary interest for the cold-water ornamental fish diversity. The ornamental fish fauna of the river Koshi consists of *Barilius* spp., *Garra* spp., *Nemacheilus* spp., *Glyptothorax* spp., *Danio* spp., *Schistura* spp., *Botia almorhae*, *Balitora brucei*, *Olyra longicaudata*, *Puntius conchonius*, *P. phutunio* (pigmy barb), *Channa stewartii*, etc. In the river Gandaki, the important ornamental fish species are *Garra annandalei*, *G. gotyla*, *Devario aequipinnatus*, *Danio dangila*, *D. rerio*, *Chela labuca*, *Glyptothorax pectinopterus*, *Botia almorhae*, and *Channa gachua*. Several species under the genera *Garra*, *Glyptothorax*, *Barilius*, and *Nemacheilus* are also found in Karnali and Mahakali rivers.

Nepal has a wide diversity of indigenous ornamental fishes, but the exotic species such as goldfish, koi carp, and live bearers dominate the aquarium market with a significant share of imports from India (85%) and the remaining (15%) from other countries. Several indigenous fish species, i.e., *Barilius barna*, *B. vagra*, *B. bendelisis*, *Puntius sophore*, *P. conchonius*, *P. ticto*, *Danio devario*, *D. rerio*, *Mastacembelus armatus*, *Xenentodon cancila*, *Mystus bleekeri*, *Channa gachua*, and *C. punctatus*, have been recognized for their ornamental fisheries potential (Husen et al. 2021). However, the breeding techniques of these indigenous fishes need to be standardized to enhance their production and bring them into the international market.

The rising number of hydropower projects in Nepal is causing challenges for cold-water fisheries. Besides the hydropower projects, overfishing, dangerous fishing tactics, and pollution have all contributed to the decline of indigenous fish population. River damming, for example, has a significant influence on river ecology and aquatic flora and fauna, including fish. The lack of technical knowledge among the local farmers and stakeholders is the primary reason behind Nepal's low success in indigenous fish breeding and culture. Considering the ornamental fisheries resources and their positive potential, there is an urgent need to enhance the scientific studies related to breeding, nutrition, and health management.

10.2.2 Bhutan

The Himalayan range of Bhutan is divided into three zones: the southern foothills and plains (altitudes less than 2000 m), the Inner Himalayas (2000–3000 m), and the Great Himalayas (3000–7500 m). Manas, Sankosh, Amo, Wang, and Tongsa are the major cold-water rivers of Bhutan. A few studies have been carried out in Bhutan regarding the ornamental fisheries resources. Important indigenous ornamental fishes, reported from various rivers and streams of Bhutan, are *Barilius barna*, *Danio aequipinnatus*, *D. dangila*, *Bagarius bagarius*, *Nangra punctata*, and *Badis badis* from Manas; *Puntius macropogon*, *P. sophore*, *P. ticto*, *Garra annandalei*, *Rasbora daniconius*, *B. bendelisis*, *Batasio batasio*, *Mystus bleekeri*, *M. vittatus*, and *Nandus nandus* from the Gaylegphug; *B. barna*, *B. bola*, *G. annandalei*, *G. gotyla*, *Semiplotussemiplotus*, *Xenentodon cancila*, and *Channa gachua* from the Phepsu; *B. barna*, *B. bendelisis*, *P. ticto*, *G. annandalei*, *G. gotyla*, *D. aequipinnatus*, *D. dangila*, *Brachydanio rerio*, *Noemacheilus botia*, and *Mastacembelus armatus* from the Sarbhang Khola; and *P. titius* and *G. gotyla* from the Sankosh and Magdi (Petr and Swar 2002).

The indigenous aquatic resources and their potential are recognized in Bhutan, but due to the lack of studies on fish diversity, conservation, culture practices, and poorly developed aquaculture support services, growth of ornamental industry is dormant. Furthermore, the mega hydropower projects on the major rivers possess severe threat to the fish diversity.

10.2.3 China

In 2020, China ranked second in the world for ornamental fish imports ($ 23 million, 8.13% of world imports) after the United States ($ 67 million, 23%). The country's ornamental fish exports account for 1.4% of the global exports worth $ 4 million. Ornamental fish fauna in the temperate regions of China largely covers the Yangtze, Yellow, and Yarlung Zangbo (Brahmaputra) rivers originating from Qinghai-Tibetan Plateau Region and Heilongjiang (Amur) river originating from Siberian-Mongolian border. The Upper Yangtze region consists of the fishes from genera *Leptobotia*, *Pseudobagrus*, *Rhinogobio*, *Beaufortia*, *Anabarilius*, and *Triplophysa*, and the middle-lower Yangtze region consists of fishes such as *Myxocyprinus* (Chinese sucker) and *Nemacheilus* from Catostomidae and Balitoridae and fish from Cyprinidae families. *Triplophysa*, *Leptobotia*, and *Pseudorasbora* are the dominant fish species found in the Yellow river. The ornamental fish fauna in Heilongjiang region contains a large number of species from the minnow, goby, and spiny loach group in the genera *Rhynchocypris*, *Rhinogobio*, and *Cobitis*. Moltrecht's minnow (*Pararasbora moltrechti*, Cyprinidae) and white cloud mountain minnow (*Tanichthys albonubes*, Cyprinidae), the two popular native ornamental fishes of China, are distributed in the Hainan and Taiwan in the south region (Kang et al. 2014; Li et al. 2022). China has suffered population collapse of several freshwater fishes in the Yangtze and Yellow rivers due to climate change, change in river discharge pattern, and construction of dams for hydropower projects (Fu et al. 2003; Xing et al. 2016).

10.2.4 Afghanistan

Afghanistan covers high mountain ranges of the Western range of Hindu Kush, plains, valleys, and highlands with numerous rivers, streams, and lakes. Nearly 75% of the area is covered with mountains. The species diversity of Afghanistan is dominated by Cyprinidae (56.9%), Cobitidae (24.5%), and, to a lesser extent, Siluridae (11.8%). Cold-water fisheries resources are mainly surveyed in the Kabul river and Helmand river originating from the Hindu Kush. Kabul river is dominated by several indigenous ornamental fishes which are popular in the aquarium trade such as *Danio devario*, *Barilius vagra*, *Puntius conchonicus*, *P. sophore*, *Esomus dandricus*, *Nemacheilus* spp., *Channa gachua*, and *C. punctatus* (Petr and Swar 2002). On the contrary, the Helmand river has the least diverse ichthyofauna. *Noemacheilus* spp. are found in all the major drainages of Helmand river (Coad 1981).

The prime reason behind the poor development of cold-water fisheries in Afghanistan is the lack of proper studies. The fish fauna of the Kabul river downstream faces numerous threats from increasing anthropogenic activities such as pollution, overfishing, and societal development (Kelzang et al. 2021).

10.2.5 Pakistan

Pakistan shares <0.5% in world exports and imports of ornamental fish ($ 0.38 million export and $ 0.07 million import). Cold-water rivers and streams of Pakistan are restricted to the higher latitudes of Northern Pakistan, where the Hindu Kush, Karakoram, and Himalayas stretch from west to east. The major rivers such as Indus and Jhelum flowing in the northern part of Pakistan inhabit several indigenous fishes of the group *Triplophasia*, *Nemacheilus*, *Schistura*, *Garra*, *Glyptothorax*, *Puntius*, *Barilius*, *Aphanius*, *Aplocheilus*, *Chela*, etc. (Petr and Swar 2002). The majority of Pakistan's indigenous fish fauna is limited to hilly and submountainous environments. The region is the primary site of damming and stream obstruction which may eventually lead to the extinction of freshwater biodiversity (Zai 2018).

10.2.6 Bangladesh

Bangladesh is situated at the foot of the Himalayas, with most of its parts being floodplains formed by the Himalayan rivers. Hills are confined to the northeast and the southeast regions bordering India and Myanmar. Feni, Karnaphuli, Kangsho, Shangu, Somesswari, Matamuhori, Piyang, and Sari are the cold-water rivers of Bangladesh, and Kaptai lake is the large cold water reservoir, located in one of the hill districts (Petr and Swar 2002).

The ornamental fisheries sector of Bangladesh has not developed much, although the resource potential is well recognized (Mostafizur et al. 2009). Fish keeping as a hobby is becoming popular with the operating system's ease and lower operating costs (Mostafizur et al. 2009); still most of the enterprises are centered in the major cities like Dhaka, Rajshahi, Khulna, etc. Although the country has a long history of introducing ornamental fishes, documentation and quarantine methods have not been standardized and given importance. So far, a few native species have gained importance as ornamental fish, and exotic species are contributing the majority.

The potential of indigenous ornamental fish and gastropod species has been recognized for *Acanthocobitis botia*, *Amblypharyngodon microlepis*, *A. mola*, *Badis badis*, *Botia dario*, *Chanda nama*, *Channa punctata*, *Chela laubuca*, *Macrognathus aculeatus*, *M. pancalus*, *Mystus tengara*, *Parambassis ranga*, *Puntius chola*, *P. conchonius*, *P. gelius*, *P. guganio*, *P. puntio*, *Gagata cenia*, and *Lymnaea stagnalis*.

Various problems have been recognized for the slow growth of the ornamental fisheries sector of Bangladesh, such as lack of information about the import and export data; lack of market channels; lack of knowledge about the breeding, culture, and health management of important indigenous fish species; etc., that need to be addressed at the earliest.

10.2.7 Myanmar

Cold-water fisheries in Myanmar prevail in the northern region, bordered by Tibet and Yunnan in the north and east and Indian hills on the west. Only four northern states of Myanmar, i.e., Kachin, Kayah, Chin, and Shan, are reported to be under the cold-water zone (Moo 2002). The largest river in Myanmar, Irrawaddy, originates in the Kachin state due to the confluence of the N'mai (Nam Gio) and Mali rivers. The Himalayan glaciers of upper Myanmar serve as the source of both the N'mai and Mali rivers. The cold-water fisheries are poorly developed, with least or no studies so far. The ornamental fish industry has shown decreasing trend in Myanmar during the past few years, and export values recorded for the years 2016, 2017, 2018, and 2019 were US$ 32,056, US$ 30,533, US$ 12,405, and US$ 6748. Cold-water ornamental fishes, reported from Myanmar, are *Aborichthys kempi*, *Acanthopthalmus pangia*, *Akysis prashadi*, *Amblyceps murray stuarti*, *Badis badis*, *Botia berdmorei*, *B. dario*, *Bagarius bagarius*, *Balitora brucei*, *B. maculate*, *Barbodes hexagonolepis*, *Barilius bendelisis*, *B. barna*, *B. grandis*, *Brachydanio choprai*, *B. rerio*, *Danio aequipinnatus*, *D. daniconius*, *Chanda ranga*, *Channa burmanica*, *C. gachua*, *C. striatus*, *Chela laubuca*, *Epalzeorhynchus siamensis*, *Gagata cenia*, *Garra gotyla*, *G. gravelyi*, *G. kempi*, *G. lamta*, *Hara filamentosa*, *Indostomus paradoxus*, *Inlecypris auropurpureus*, *Lepidocephalichthys berdmorei*, *L. guntea*, *Macrognathus caudiocellatus*, *Mastacembelus armatus*, *M. dayi*, *M. oatesii*, *Microrasbora erythromicron*, *M. rubescens*, *Monopterus albus*, *M. cuchia*, *Mystus bleekeri*, *Nemacheilus* spp., *Notopterus chitala*, *N. notopterus*, *Ompok bimaculatus*, *O. pabda*, *Oreinus plagiostomus*, *Parasphaerichthys ocellitus*, *Psilorhynchus balitora*, *Puntius* spp., *Rasbora daniconius*, *R. rasbora*, *Schistura malaise*, *S. sikmaiensis*, *Tetraodon cutcutia*, *Trichogaster fasciatus*, *Xenentodon cancila*, *Yunnanilus brevis*, etc. (Moo 2002). The major challenges in assessing the cold-water fisheries resources of Myanmar are the remoteness and difficulty of accessing them. The potential for the development of cold-water aquaculture needs to be studied for combating food shortage and crisis in remote areas.

10.2.8 India

India contributes relatively a small proportion ($<1\%$) to the global ornamental fish trade. Export value for the Indian ornamental fish industry in 2020 was US$ 1.7 million, contributing to 0.3% of the total export. The Indian Himalayan region is spreading across 13 Indian states, i.e., Ladakh, Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Meghalaya, Nagaland, Arunachal Pradesh, Manipur, Mizoram, Tripura, Sikkim, and hill regions of two states Assam and West Bengal, and inhabits numerous ornamental fish species (Table 10.1). The main markets for Indian ornamental fishes are China, the United States, Bangladesh, and Thailand. Indian ornamental fish export basket constitutes around 287 native fish species, 92 exotic fish species, and 45 shrimps. Out of 287 indigenous fishes, 239 are freshwater and 48 were marine fish species. Among the indigenous freshwater

Table 10.1 Diversity of indigenous hill stream ornamental fishes in the Indian Himalayan region

Species name	Common name	IUCN status, 2010
Himachal Pradesh		
Family: Cyprinidae		
Pethia ticto	Ticto barb	LC
Pethia conchonius	Rosy barb	LC
Puntius sophore	Spotfin swamp barb	LC
Puntius chola	Chola barb	NE
Systomus sarana	Olive barb	LC
Osteobrama cotio	Cotio	LC
Salmostoma bacaila	Large minnow	LC
Barilius bendelisis	Hamilton’s barila	LC
Barilius barila	Barred baril	LC
Barilius vagra	Vagra baril	LC
Barilius barna	Barna baril	LC
Barilius shacra	Shacra baril	LC
Danio rerio	Zebra fish	LC
Devario devario	Devario danio	LC
Esomus danrica	Flying barb	LC
Rasbora daniconius	Blackline rasbora	LC
Crossocheilus latius	Gangetic latia	LC
Garra gotyla	Sucker head	LC
Garra lamta	Lamta garra	LC
Nemacheilidae		
Schistura denisoni	Mura	LC
Schistura rupecula	Hill loach/stone loach	LC
Schistura horai	Horai loach	NE
Schistura himachalensis	–	NE
Triplophysa stoliczkae	Stoliczka triplophysa loach	LC
Lepidocephalichthys guntea	Guntea loach	LC
Botia dario	Queen loach	LC
Botia birdi	Birdi loach	NE
Amblyceps mangois	India torrent catfish	LC
Glyptothorax brevipinnis	Mountain catfish	DD
Glyptothorax conirostris	–	DD
Glyptothorax pectinopterus	River cat/Nayid	LC
Glyptothorax stoliczkae	–	LC
Parambassis baculis	Himalayan glassy perchlet	LC
Badis badis	Dwarf chameleon fish	LC
Glossogobius giuris	Tank goby	LC
Jammu and Kashmir		
Puntius conchonius	Rosy barb	LC
Puntius sophore	Pool barb	LC
Puntius ticto	Ticto barb	LC

(continued)

Table 10.1 (continued)

Species name	Common name	IUCN status, 2010
Barilius bendelisis	Hamilton's barila	LC
Barilius vagra	Vagra baril	LC
Garra gotyla	Sucker head	LC
Crossocheilus latius	Gangetic latia	LC
Glyptothorax pectinopterus	Nayid/River cat	LC
Uttarakhand		
Barilius bendelisis	Hamilton's barila	LC
Barilius vagra	Vagra baril	LC
Barilius barna	Barna baril	LC
Garra gotyla gotyla	Gotyla garra/sucker head	LC
Garra lamta	Lamta garra	LC
Puntius sophore	Spotfin swamp barb	LC
Puntius ticto	Ticto barb	LC
Crossocheilus latius latius	Gangetic latia or stone roller	LC
Nemacheilus denisoni	Stone loach	LC
Schistura multifasciata	Stone loach	LC
Schistura obliquofascia	–	NE
Acanthocobitis botia	Mottled *loach*	LC
Botia almorae	Yo Yo loach or chitli	LC
Botia rostrata	Gangetic loach, ladder loach, or twin-banded loach	VU
Lepidocephalus guntea	Guntea loach	LC
Glyptothorax saisii	Pathar-chatti	VU
Glyptothorax telchitta	Sipliya	LC
Glyptothorax pectinopterus	River cat/Nayid/Pathar-chatti	LC
Macrognathus pancalus	Baam	LC
Channa gachua	Dwarf snakehead, sowan, dawla	LC
Northeastern states of India		
Clupeidae		
Nematalosa nasus	Bloch's gizzard shad	LC
Engraulidae		
Setipinna phasa	Gangetic hairfin anchovy	LC
Cyprinidae		
Amblypharyngodon mola	Mola carplet	LC
Aspidoparia jaya	Jaya	LC
Aspidoparia morar	Morar	LC
Barilius barila	Barred baril	LC
Barilius barna	Barna baril	LC
Barilius bakeri	Malabar baril	LC
Barilius bendelisis	Hamilton's barila	LC
Barilius chatricensis	Chatrickongi bariil	VU
Barilius dogarsinghi	Manipur baril	VU

(continued)

Table 10.1 (continued)

Species name	Common name	IUCN status, 2010
Barilius ngawa	Sherou bariil	VU
Barilius radiolatus	Gunther's baril	DD
Barilius shacra	Shacra baril	LC
Barilius tileo	Tileo baril	LC
Barilius vagra	Vagra baril	LC
Brachydanio albolineatus	Pearl danio	LC
Danio nigrofasciatus	Dwarf spotted danio	DD
Danio choprai	Glowlight danio	LC
Devario shanensis	Hora danio	DD
Devario sondhii	Sondhi devario	DD
Chela cachius	Silver hatchet chela	LC
Laubuka laubuca	Indian glass barb	LC
Laubuka fasciata	Malabar hatchet chela	VU
Crossocheilus burmanicus	Burmese latia	LC
Tariqilabeo latius	Gangetic latia	LC
Cyprinion semiplotum	Assamese kingfish	VU
Danio dangila	Dangila danio	LC
Danio rerio	Zebra danio	LC
Devario annandalei	–	DD
Devario acuticephala	Manipur danio	VU
Devario aequipinnatus	Giant danio	LC
Devario assamensis	Assami devaario	VU
Devario anomalus	Chittagongi devaario	VU
Devario devario	Bengal Dario	LC
Devario horai	Hora devario	EN
Devario naganensis	Naga devario	VU
Devario regina	Fowler's danio	VU
Devario yuensis	Yu devaario	VU
Esomus danricus	Flying barb	LC
Garra abhoyai	–	NE
Garra rupecula	Mishmi garra	NT
Garra annandalei	Annandale garra	LC
Garra compressus	–	VU
Garra flavatra	–	VU
Garra gotyla	Gotyla	LC
Garra gravely	Burmese garra	NT
Garra kempi	Kemp garra	LC
Garra kalpangi	–	
Garra lamta	Lamta garra	LC
Garra mcclellandi	Cauvery garra	LC
Garra notata	Tenasserim garra	LC
Garra lissorhynchus	Khasi garra	LC

(continued)

Table 10.1 (continued)

Species name	Common name	IUCN status, 2010
Garra litanensis	–	VU
Garra manipurensis	–	VU
Garra naganensis	Naga garra	LC
Garra nambulica	–	VU
Garra nasuta	Khasi garra	LC
Garra paralissorhynchus	–	VU
Oreichthys cosuatis	Khavli	LC
Pethia atra	-	VU
Pethia meingangbii	–	LC
Naziritor chelynoides	Dark mahseer	VU
Puntius chola	Chola barb	LC
Pethia conchonius	Rosy barb	LC
Dawkinsia filamentosa	Filament barb	LC
Puntius fraseri	Dharna barb	EN
Pethia gelius	Golden barb	LC
Puntius guganio	Glass barb	LC
Pethia khugae	Khuga pethia	LC
Pethia manipurensis	Manipuri pethia	EN
Pethia meingangbii	**Ngakha- meingangbi**	LC
Pethia ornata	–	VU
Pethia phutunio	Spotted sail barb	LC
Pethia punctata	Dotted sawfin barb	LC
Pethia shalynius	Shalyni barb	VU
Pethia stoliczkana	–	LC
Puntius sophore	Spotfin swamp barb	LC
Puntius terio	One spot barb	LC
Puntius ticto	Ticto barb	LC
Systomus clavatus	Stedman barb	NT
Raiamas bola	Indian trout	LC
Raiamas guttatus	Burmese trout	LC
Rasbora daniconius	Slender rasbora	LC
Rasbora ornata	–	VU
Rasbora rasbora	Gangetic scissortail rasbora	LC
Salmophasia bacaila	Large razorbelly minnow	LC
Salmostoma phulo	Finescale razorbelly minnow	LC
Securicula gora	Gora-chela	LC
Psilorhynchidae		
Psilorhynchoides arunachalensis		DD
Psilorhynchus balitora	Balitora minnow	LC
Psilorhynchus sucatio	River stone carp	LC
Balitoridae		
Aborichthys garoensis	–	VU

(continued)

Table 10.1 (continued)

Species name	Common name	IUCN status, 2010
Aborichthys elongatus	Red tailed loach	LC
Aborichthys kempi	–	NT
Aborichthys tikaderi	–	VU
Acanthocobitis botia	Zipper loach or mottled loach	LC
Acanthocobitis pavonacea	–	VU
Paracanthocobitis zonalternans	–	LC
Balitora brucei	Gray's stone loach	NT
Balitora burmanica	Burmese stone loach	LC
Homaloptera modesta	–	DD
Homaloptera rupicola	–	LC
Nemacheilidae		
Schistura reticulofasciata	–	VU
Neonoemacheilus assamensis	–	NT
Neonoemacheilus labeosus	–	LC
Neonoemacheilus morehensis	–	DD
Neonoemacheilus peguensis	–	DD
Schistura carletoni	–	NE
Schistura rupecula	Puinya	LC
Physoschistura elongata	–	VU
Schistura beavani	Creek loach	LC
Schistura cincticauda	–	DD
Nemacheiluscorica	Korica	LC
Schistura devdevi	–	NT
Schistura khugae	–	VU
Schistura manipurensis	–	NT
Schistura minutus	–	EN
Paraschistura montana	Chitai, Gadera	NE
Schistura multifasciata	–	LC
Schistura nagaensis	–	VU
Schistura papulifera	–	CE
Schistura prashadi	–	VU
Schistura reticulata	–	EN
Schistura savona	–	LC
Schistura scaturigina	–	LC
Schistura sikmaiensis	–	LC
Nemacheilus singhi	–	VU
Schistura sijuensis	–	EN
Schistura tigrina	–	EN
Schistura tirapensis	–	LC
Nemacheilus inglisi	–	VU
Schistura reticulofasciata	–	VU
Schistura vinciguerrae	–	LC

(continued)

Table 10.1 (continued)

Species name	Common name	IUCN status, 2010
Triplophysa gracilis	–	NE
Cobitidae		
Acantopsis multistigmatus	–	NT
Acantopsis dialuzona	–	LC
Botiidae		
Botia almorhae	Almorha loach or Yo Yo loach	LC
Botia dario	Bengal loach	LC
Botia histrionica	Burmese loach	LC
Botia lohachata	Reticulate loach	NE
Botia rostrata	Gangetic loach	VU
Lepidocephalichthys arunachalensis	–	EN
Lepidocephalichthys berdmorei	Burmese loach	LC
Lepidocephalichthys guntea	Guntea loach	LC
Lepidocephalichthys irrorata	Puiya/loktak loach	LC
Lepidocephalichthys manipurensis	Yu loach	LC
Lepidocephalichthys annandalei	Gutum/Annandale loach/tilak loach/ pillai loach	LC
Lepidocephalichthys menoni	Gutum/Annandale loach/tilak loach/ pillai loach	DD
Neoeucirrhichthys maydelli	Goalpara loach	LC
Syncrossus berdmorei	Tiger botia	NT
Canthophrys gongota	Gongota loach	LC
Batasio batasio	Bojori/tista batasio	LC
Batasio fasciolatus	–	LC
Batasio niger	–	DD
Batasio spilurus	–	DD
Batasio tengana	Batasio/*Assamese batasio*	LC
Chandramara chandramara	Asian cory	LC
Bagridae		
Mystus bleekeri	Ngacep/singarah/singorah/tengra	LC
Mystus cavasius	Barsingarah/singarah/gulia/kabashi-tengra	LC
Mystus falcarius	–	LC
Mystus horai	Indus catfish	NE
Mystus montanus	Gagol/girlu/wynaad mystus	LC
Mystus pulcher	Pulcher mystus	LC
Mystus rufescens	Meetan mystus	LC
Mystus tengara	Singorah/Bajari-tengra/stripped dwarf catfish	LC
Mystus vittatus	Lal tingara/singorah/kuggur/palwa/ chittu	LC
Olyra kempi	–	LC
Olyra longicaudata		LC

(continued)

Table 10.1 (continued)

Species name	Common name	IUCN status, 2010
	Botsingi/Himalayan olyra/longtail catfish	
Olyra horae	Hora olyra	DD
Amblycipitidae		
Amblyceps apangi	–	LC
Amblyceps arunachalensis	–	EN
Amblyceps laticeps	–	LC
Amblyceps cerinum	–	
Amblyceps mangois	Indian torrent catfish/chikka	LC
Amblyceps torrentis	–	DD
Amblyceps tuberculatum	–	DD
Akysis manipurensis	–	DD
Akysis prashadi	–	DD
Nandidae		
Badis assamensis	Assamese chameleon fish	DD
Badis badis	Blue perch/blue badis	LC
Badis blosyrus	–	LC
Badis chittagongis	–	DD
Badis ferrarisi	–	LC
Badis kanabos	–	DD
Badis tuivaiei	–	EN
Nandus nandus	Gangetic leaf fish	LC
Chandidae		
Chanda nama	Asiatic glassfish/chanda	LC
Parambassis baculis	Chanda/phopa chanda	LC
Parambassis lala	Highfin glassy perchlet/choto chanda/ Lille glasfish	NT
Parambassis ranga	Indian glassy fish/Indian glassy perch/Indian X-ray fish	LC
Parambassis tenasserimensis		DD
Synbranchidae		
Macrognathus morehensis	Baim/Guchi/Indian spiny eel	LC
Macrognathus pancalus	Tire track eel/bami/baam	VU
Mastacembelidae		
Mastacembelus armatus	Tire track eel/bami/baam	VU
Pillaia indica	Hillstream spineless eel	LC
Garo khajuriai	Garo spineless eel	LC
Syngnathidae		
Microphis deocata	Deocata pipefish/kumirer khil	NT
Aplocheilidae		
Aplocheilus panchax	Blue panchax	LC
Belonidae		

(continued)

Table 10.1 (continued)

Species name	Common name	IUCN status, 2010
Xenentodon cancila	Gars/needlefish/garpike/kokila	LC
Strongylura strongylura	Spottail needlefish	LC
Chacidae		
Chaca chaca	Chaca/angler catfish	LC
Mugilidae		
Rhinomugil corsula	Corsula	LC
Sicamugil cascasia	Yellow tail mullet	LC
Sisoridae		
Exostoma barakensis	–	DD
Exostoma berdmorei	–	DD
Exostoma labiatum	Burmese bat catfish/herpak bellap	LC
Exostoma stuarti	–	DD
Exostoma vinciguerrae	–	DD
Gagata cenia	Cenia/Indian gagata/gang tengra/jungle Magur	LC
Gagata gagata	Gang tengra/hudda/Gangetic gagata	LC
Gagata gasawyuh	Blackfin sisorid catfish	LC
Gagata sexualis	Buhani/koel gagata	LC
Glyptosternon maculatum	–	LC
Glyptothorax annandalei	Patharchatta/kapre	LC
Glyptothorax botius	Telcapre	LC
Glyptothorax saisii	–	VU
Glyptothorax conirostris	–	DD
Glyptothorax brevipinnis	–	DD
Glyptothorax cavia	Kani tengra	LC
Glyptothorax sinensis	–	DD
Glyptothorax platypogonides	–	LC
Glyptothorax chindwinica	–	LC
Glyptothorax granulus		LC
Glyptothorax manipurensis	–	VU
Glyptothorax ngapang	–	LC
Glyptothorax striatus	–	NT
Glyptothorax pectinopterus	River cat/nayid	LC
Glyptothorax telchitta	Telchitta	LC
Glyptothorax ventrolineatus	–	LC
Glyptothorax indicus	Catfish	LC
Glyptothorax gracilis	Catfish	DD
Glyptothorax trilineatus	Three-lined catfish	LC
Gogangra viridescens	Gang tengra	LC
Myersglanis jayarami	–	VU
Nangra assamensis	Koshi nangra	LC
Nangra nangra	Gang tengra/koshi nangra	LC

(continued)

Table 10.1 (continued)

Species name	Common name	IUCN status, 2010
Nangra robusta	–	NE
Oreoglanis setiger	–	DD
Parachiloglanis hodgarti	Torrent catfish	LC
Pareuchiloglanis kamengensis	–	DD
Pseudecheneis crassicauda	–	DD
Pseudecheneis sulcata	Sulcatus catfish/sucker throat catfish	LC
Pseudecheneis ukhrulensis	–	VU
Pseudecheneis sirenica	–	VU
Pseudecheneis koladynae	–	NE
Sisor barakensis	–	VU
Sisor chennuah	–	DD
Sisor rabdophorus	Chenua/sisor catfish/bistuiya	LC
Akysidae		
Akysis manipurensis		DD
Akysis prashadi	Indawgyi stream catfish	LC
Erethistidae		
Erethistes horai	Elongate moth catfish hora/terai hara	LC
Erethistes pusillus	Giant moth catfish	LC
Erethistes hara	Indian moth catfish	LC
Erethistes jerdoni	Anchor catfish	LC
Conta conta	Kuta kanti/conta catfish/konta	DD
Conta pectinata	–	DD
Erethistoides montana	–	DD
Erethistoides sicula	–	DD
Hara hara	Gagot/kosi hara/hara	LC
Pseudolaguvia ferula	–	DD
Pseudolaguvia inornata	–	DD
Pseudolaguvia muricata	–	DD
Pseudolaguvia ribeiroi	Kani tengra/painted catfish/bistuiya/ tinkantiya	LC
Pseudolaguvia shawi	Kani tengra	LC
Pseodolaguvia spicula	–	NE
Osphronemidae		
Osphronemus goramy	Gaint gourami	LC
Ctenops nobilis	Frail gourami	NT
Trichogaster fasciata	Banded gourami	LC
Trichogaster lalius	Dwarf gourami	LC
Trichogaster chuna	Honey gourami	LC
Trichogaster labiosa	Thick-lipped gaurami	LC
Tetraodontidae		
Tetraodon cutcutia	Ocellated puffer fish	LC

LC: Least concern, *DD*: Data deficient, *NT:* Near-threatened, *VU:* Vulnerable, *EN:* Endangered, *NE*: Not evaluated

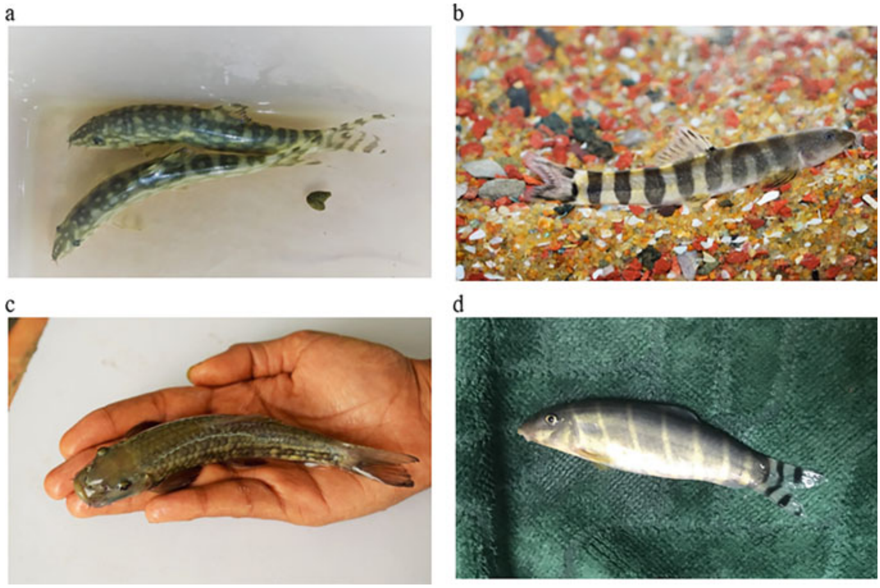

Fig. 10.1 Coldwater ornamental fishes from India: (**a**) *Botia almorhae*, Yoyo loach, Collection source: Ramnagar, Uttarakhand; (**b**) *Schistura beavani*, Creek loach, Collection source: Assam; (**c**) *Garra lamta*, Lamta garra, Collection source: Nainital, Uttarakhand; (**d**) *Botia dario*, Queen loach, Collection source: Assam

species, the greater number of species belongs to the family Cyprinidae (Jayalal and Ramachandran 2012). Around 85% of native fishes are collected from Northeastern India and reared to meet the export demand. Of the total shipping of ornamental fish, only one-tenth comes from organized aquaculture. Hill stream loaches, barbs (Fig. 10.1), and snakeheads contribute the most important share in indigenous ornamental fish export basket on a continuous basis.

10.3 Indigenous Ornamental Fishes of India: Their Importance and Prospects

10.3.1 Snakeheads, *Channa* spp.

Among the endemic ornamental freshwater fish species of India, the export of snakeheads (*Channa* spp.) is showing an emerging trend, with an increase of approximately sixfold (>90,000 no.) than that reported in 2014 (around 15,000 no.) (Harrington et al. 2022). As of now, 21 distinct taxa of channids are reported to occur in India, out of which 18 species belongs to the Gachua group of channids endemic to the Northeastern Himalayan region (Rüber et al. 2020). This Gachua group of *Channa* is primarily caught from the wild for their potential value in the ornamental fish trade but has also been considered as food by the local people.

Channa gachua species-group, viz., *Channa andrao*, *C. aurantimaculata*, *C. barca*, *C. bipuli*, *C. bleheri*, *C. gachua*, *C. pardalis*, *C. pomanensis*, and *C. stewartii*, from Northeastern India are commonly traded in the Indian aquarium hobby (Praveenraj et al. 2019).

Some of the *Channa* spp. are reported to have been induced bred in captivity. Nayak et al. (2020) and Marimuthu et al. (2009) documented the captive breeding of *Channa bleheri* and *C. punctatus* by using the synthetic hormone GnRH (ovasis and ovatide). *Channa aurantimaculata* was induced to spawn naturally by manipulating the habitat, as reported by Hazarika et al. (2014). The exploitation of *Channa* spp. from the wild for the ornamental fish trade and food has to be restricted to conserve the natural resources. Hence, captive breeding program could be undertaken as an ex situ conservational approach for the potential risk spp. and also to support the demand for *Channa* in the ornamental fish trade (Harrington et al. 2022).

10.3.2 Algae Eaters, *Garra* spp.

Algae eater fishes are a popular choice for the fish aquarist to control the algae infestation in aquarium tank. There are around 13 popular algae eater fish group in aquarium tanks, namely, *Otocinclus* or South American algae-eating catfish, black mollies, common pleco or suckermouth catfish, twig catfish, siamese algae eater, and *Garra*, commonly known as stone suckers. In light of the increasing awareness of the limited use of the most popular algae-eating ornamental fish, the common pleco, as a result of its threat to native fishes in a number of countries, including India, it is high time that few *Garra* species are to be chosen as the algae eaters in aquarium tanks. The genus *Garra*, commonly known as stone suckers or patharchatta, is widely distributed, with around 134 species inhabiting in fast-flowing hill streams of Asia and Africa. *Garra* fishes are popularized as algae eaters in the aquarium trade, a few of which are named as *Garra annandalei*, *Garra cambodgiensis*, *Garra ceylonensis*, *Garra congoensis*, *Garra flavatra*, *Garra imberba*, *and Garra rufa*. These groups of fishes are widely recognized as algae eater and popularly used in the fish spa mainly the *Garra rufa*, doctor fish. The price of the *Garra* species in the local market varies between US$ 0.3 to 0.6, depending upon the species and size.

Fry and juveniles of *Garra* spp. feed on insect larvae and planktons, while the adults usually feed upon the detritus and algae grown on the glass in aquaria. Most of the *Garra* species are known to be seasonal spawner, which spawns during May to July. The seed production and larval rearing protocol of *Garra gotyla* (Patiyal et al. 2020), *Garra annandalei*, and *Garra lamta* in captivity have been standardized in India by the Directorate of Coldwater Fisheries Research, Bhimtal, in captivity by inducing hormones.

10.3.3 Loaches

Loaches are important group of freshwater species that have global distribution. These loach fishes are primarily used for aquarium purposes due to the small size, coloration, bright bands, hardiness, and compatibility which make them suitable for rearing in aquarium throughout their life span. The inability of brood fish to reach sexual maturity in captivity is one of the most significant challenges in loach breeding. In addition, the availability of wild loaches is seasonal, with the majority being collected after the monsoon season. The popular loaches which dominate the aquarium markets are of the genera *Botia*, *Balitoria*, and *Schistura*. These loaches lead a nocturnal life but adapt quickly to captive condition.

Botia spp. are popular in the aquarium trade globally due to their colorful bright bands, peaceful nature, and lesser scales. So far, nine species of *Botia* are known to be distributed in India, out of which few have been recognized as vulnerable such as *Botia rostrata* (Gangetic loach or ladder loach) and *B. dario* (queen loach). Important *Botia* species with ornamental value are *Botia dario*, *B. almorhae* (Yo yo loach), *B. histrionica* (golden zebra loach), and *B. lohachata.* The fish feed during the daytime in captivity and prefer live feeds such as *Daphnia*, snail, worms, and brine shrimp.

Schistura represents the largest genus of small, hill stream, stone loach fishes, belonging to the family Nemacheilidae, widely distributed in the streams and rivers of Asia, Europe, and Ethiopia, as documented by Lalronunga et al. (2013). Species of *Schistura* described from the Himalayan regions of India are *Schistura andrewi*, *S. obliquofascia*, *S. corica*, *S. rubrimaculata*, *S. multifasciata*, *S. rupecula*, *S. savona*, *S. nagodiensis*, *S. sharavathiensis*, *S. scaturigina*, *S. tirapensis*, *S. vinciguerrae*, *S. manipurensis*, *S. kangjupkhulensis*, *S. prashadi*, *S. sikmaiensis*, *S. tigrinum*, *S. reticulata*, *S. khugae*, *S. fasciata*, *S. aizawlensis*, and *S. minutes*.

Schistura spp. can be identified by the presence of brown-colored transverse bars against the pale-yellow-colored body, a black bar at the base of the caudal fin base, and two black markings on the base of dorsal fin as reported by (Lokeshwor and Vishwanath 2011). In general, the fish are omnivores like other loaches and show preference toward zooplanktons, especially crustaceans, insects, and worms, and rarely feed on phytoplankton and detritus matter. Under captive conditions, they can accept a mixture of pellet and live, frozen brine shrimp, bloodworm, and daphnia. At present, captive breeding of *Schistura* spp. has not been reported in any study and needs to be emphasized at the earliest.

10.3.4 Hill Trouts

Fish belonging to the genus *Barilius* are commonly known as hill trouts. *Barillius bendelisis*, *B. barila*, *B. barna*, *B. vagra*, and *B. bakeri* are very much popular for their ornamental and food value. The species are beautifully colored with vertical bands or blotches or cluster of dots. These fish fetch prices around US$ 0.3–0.64 per piece in the domestic ornamental market. Out of all *Barilius* species, *Barilius vagra* and *B. bendelisis* have a wide range of distribution and are found in India, Bangladesh, Pakistan, and Nepal. Some of the *Barilius* species, viz., *B. canarensis*, *B. lairokensis*, and *B. dimorphicus*, are categorized under endangered, near-threatened, and vulnerable category, respectively.

B. bendelisis is known as the "Indian hill trout" or "Hamilton's baril" in the home aquarium trade and is also reported to be exported from India as an ornamental fish. It is also regarded as one of the most important commercial hill stream fish in the majority of streams and rivers in the Eastern, Western, and Central Himalaya. *Barilius* spp. lives on the surface of water streams and swims quickly. While *B. bendelisis*, *B. barila*, and *B. barna* are omnivores, *B. vagra* is a carni-omnivore that prefers largely aquatic annelids, insect larvae, microcrustaceans, rotifers, and soft aquatic plants. After reaching maturity, male *Barilius* acquire breeding tubercles on the snout, lower jaw, or head area of the body. The gonado-somatic index in *B. bendelisis* has a bimodal pattern, with two peaks in March–May and August–September, reflecting the common spawning season of fish (Saxena et al. 2019). *B. vagra* spawns in batches once in a year during August–September (Riyaz 2020).

10.3.5 Barbs

Puntius are the small barb fish species, widely distributed in India, Nepal, Pakistan, Afghanistan, China, Bangladesh, Bhutan, and Myanmar. *Puntius ticto*, *P. sophore*, and *P. gelius* are considered as the important hill stream ornamental fish species among the *Puntius* group. These fish feed upon algae, zooplankton, insects, and plant leaves (Mitra et al. 2022). *Puntius* fish are reported to spawn during July to August in the wild. In captivity, the spawning occurs freely by scattering the eggs on the bottom, exhibiting no parental care. Recent reports have shown a decrease in the population of this species from the natural water bodies due to heavy fishing and anthropogenic causes (Gupta 2015; Sarkar et al. 2019).

10.3.6 *Badis* spp.

Badis is an important genus of ornamental freshwater fish species, distributed in Southeast Asian countries from the family Badidae. Several *Badis* species such as *B. assamensis*, *B. blosyrus*, *B. chittagongis*, *B. badis*, *B. singenensis*, *B. kaladanensis*, *B. dibruensis*, *B. pancharatnaensis*, *B. autumnuam*, *B. kyanos*, *B. kanabos*, *B. tuivaiei*, *B. soraya*, *B. dibruensis*, *B. triocellus*, *B. britzi*, and *B. laspiophilus* inhabit paddy fields, streams, and ponds of all the northeastern states of India (Basumatary et al. 2016; Ramliana et al. 2021).

Badis group can be identified based on the presence of a sharp spine on the opercle, villiform teeth, anal fin with three spines, colour pattern, benthic ecology, habitat, and rounded caudal fin (Geetakumari and Kadu 2011). The fish exhibit parental care and grow up to 5 cm in total length. These dwarf chameleon fishes are gaining popularity among hobbyists due to their beautiful color and easy maintenance. Their price may vary from US$ 0.1 to 0.2 per piece in Indian markets and US$ 1 to 2 per piece in global markets.

10.4 Conclusion

Ornamental fisheries can benefit greatly from the aquatic resources found in the hills, but only under the scientific intervention these resources be effectively managed. In the national perspective, mountain fish resources and their promotion for better aquaculture and fisheries are extremely important. Nevertheless, emerging anthropogenic pressure, stream flow regimes, and climate change have a negative impact on cold-water fisheries. In countries like India, Pakistan, and Bangladesh, the indigenous ornamental resources are plenty, but most of the farmers concentrate on breeding the exotic fishes which have a high demand and price and are ultimately sold to the internal market rather than the export market. Some exportable ornamental fishes such as barbs are successfully bred under captivity, and there is an immense scope for strengthening the breeding protocol and larval rearing of these ornamental fishes. The lack of a consistent seed production process and the breeders' lack of interest in indigenous fishes are the primary causes for the restricted export of native ornamental fishes. Upscaling of the seed production of fishes having export demand such as *Botia* spp., *Balitora* spp., *Puntius* spp., and *Channa* spp. in homestead ornamental units is the need-based approach in coming years.

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11 Recirculating Aquaculture System for Intensive Fish Farming in Indian Himalayan Region: An Overview

Manchi Rajesh, Biju Sam Kamalam, and Debajit Sarma

Abstract

In this era of increasing population, food supply challenges, environmental sustainability concerns and limiting natural resources, fish farming is globally moving towards land-based recirculating aquaculture systems and technologies that could produce traceable, safe and healthy fish and seafood. Recirculating aquaculture system (RAS) is a resource-efficient and climate-resilient technology in which the dependence on water, land and climatic factors is substantially minimized. As the name suggests, RAS works on the principle of reusing the culture water after various levels of filtration, targeting to provide optimum water conditions for better fish growth and welfare. This chapter provides an overview of a RAS, including its rationale, advantages, design aspects, water quality requirements, RAS components/equipment, operational management of the system and challenges and opportunities in adapting this aquaculture technology with particular reference to cold-water fish culture.

Keywords

Recirculating aquaculture systems · Water quality requirements · Total suspended solids · Settling unit · Dissolved oxygen

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11.1 Introduction

Over the last three decades, fish production from capture sources has stagnated at around 80 million metric tonnes (mmt). Nevertheless, during the same period, global fish production increased from 101 to 178.5 mmt, mainly due to the expansion and advances in aquaculture practices. According to FAO, aquaculture alone contributed 114.5 mmt, including 82.1 mmt of aquatic animals in 2018 (FAO 2020). Several aquaculture practices such as pond aquaculture, cage, pen culture, flow-through system and in-pond raceway systems (IPRS) are being used to extensively or semi-intensively or intensively farm aquatic animals on large scales. Intensive aquaculture practices have lately come under the radar of environmental sustainability issues, for example, clearing of mangrove forests for coastal aquaculture, converting agricultural lands into aquaculture ponds, effluent discharge, disease outbreaks and transmission of diseases to the natural or wild population (in the case of cage culture) and biodiversity issues and decline of the natural population (when exotic fish and shellfishes are introduced to enhance productivity). In this context, expansion and annual growth rate of aquaculture is expected to decrease from the current rate of 4.3% to 2.3% during 2018–2030 (FAO 2020). Furthermore, aquaculture activity is limited due to strong enforcement of environmental regulations, competition for limited resources (especially for the use of water and land by other food-producing sectors and industries), urbanization, disease outbreaks due to intensive culture practices and increasing consumer awareness towards safe and sustainable aquaculture products. Therefore, farming fish in a sustainable way is the only option to meet the future fish and seafood demand to achieve global nutritional security (Naylor et al. 2021).

Recirculating aquaculture system (RAS) is recognized as one of the most sustainable aquaculture technologies (Naylor et al. 2021), where aquatic animals are cultured either in partially or completely controlled conditions, in high densities, with the reuse of water after removing faecal waste, ammonia, carbon dioxide and addition of oxygen. The water recirculation efficiency varies from 70 to 99.5% depending on the filtration system in place (e.g. 70% in a partially recirculating system to 99.5% in a completely circulating system where water required can be as low as 0.3 m^3/kg fish) (Timmons et al. 2018; Bregnballe 2015; Espinal and Matulić 2019). RAS is considered environmentally sustainable and offers several advantages over the current aquaculture practices, such as low water and land requirements, high unit productivity, resilience to weather and climate change and effective control of farm effluent discharges (detailed comparative advantages are provided in Table 11.1).

Table 11.1 Advantages of recirculating aquaculture system over traditional aquaculture practices

• 10–100 times reduction in water usage (in the case of rainbow trout, 0.5–1 m^3 water is required per kg of fish produced in RAS, compared to 50–120 m^3 water requirement in flow-through system)
• 3–10 times lower land footprint (in intensive pond aquaculture, to produce 40 tonnes of fish, 1 ha of the land area is required. But the same can be achieved in RAS with less than 0.1 ha of land area)
• Faster growth rates due to controlled conditions (in the case of rainbow trout, 5–6 months of crop duration in RAS compared to 10–14 months in flow-through system)
• RAS also makes aquaculture possible in places where conditions are naturally not conducive, in terms of water availability and climatic conditions (e.g. unsuitable lands for agriculture, near to the market, hot or cold arid desert. Salmon and yellow tail are produced in Middle East countries, and tilapia, shrimps or warm-water fishes are cultured in the cold regions of the world in RAS)
• Resilient to weather and climate change
• Better feed efficiency and reduced feed cost due to controlled conditions
• Proper health management due to better water quality control and easier biosecurity measures
• Lower eutrophication potential as concentrated effluent can be easily treated
• Easy nutrient valorisation is possible through the utilization of sludge/effluent for biogas and bio-fertilizer production
• Integration with agriculture to utilize nitrate-rich wastewater can reduce fertilizer requirements in agriculture
• Aquatic invasion and escape of exotic fishes can be curtailed due to controlled operations
• Reduced labour costs and fish can be sold as per the market demand

11.2 More Crop Per Drop and RAS as a Climate-Smart Farming Solution to Productivity and Production Issues

In pond aquaculture practice, the biological productivity (in terms of fish production) of a pond is limited (0.4–1 kg fish/m^3) by dissolved oxygen availability (and diurnal dynamics of dissolved oxygen in a pond), while additional aeration can enhance the fish productivity to 4 kg/m^3 of water. Nevertheless, further productivity enhancement is limited by waste (faecal matter) and metabolite (ammonia) accumulation that necessitates water exchange, resulting in effluent discharge issues. To overcome the increased requirement of dissolved oxygen and flushing of the metabolites and waste generated, a flow-through system is used to culture certain fishes (e.g. rainbow trout, a cold-water fish), where productivity can be achieved >30 kg fish/m^3 of water. However, this results in a large volume of dilute effluent discharge, and this practice entirely relies on a continuous supply of good quality natural water resources (requiring 50–120 m^3 of water flow for every kg fish, produced in the case of rainbow trout). Besides, these systems are vulnerable to extreme weather events and adverse changes in water quality/quantity during floods and landslides, as raceways are normally located near streams and rivers. In the case of RAS, the above issues are taken care of through a systematic series of inline treatment procedures, enabling higher fish productivity in the range of 60–120 kg/m^3 of water. In RAS, fishes are reared in separate culture tanks, which are connected to a

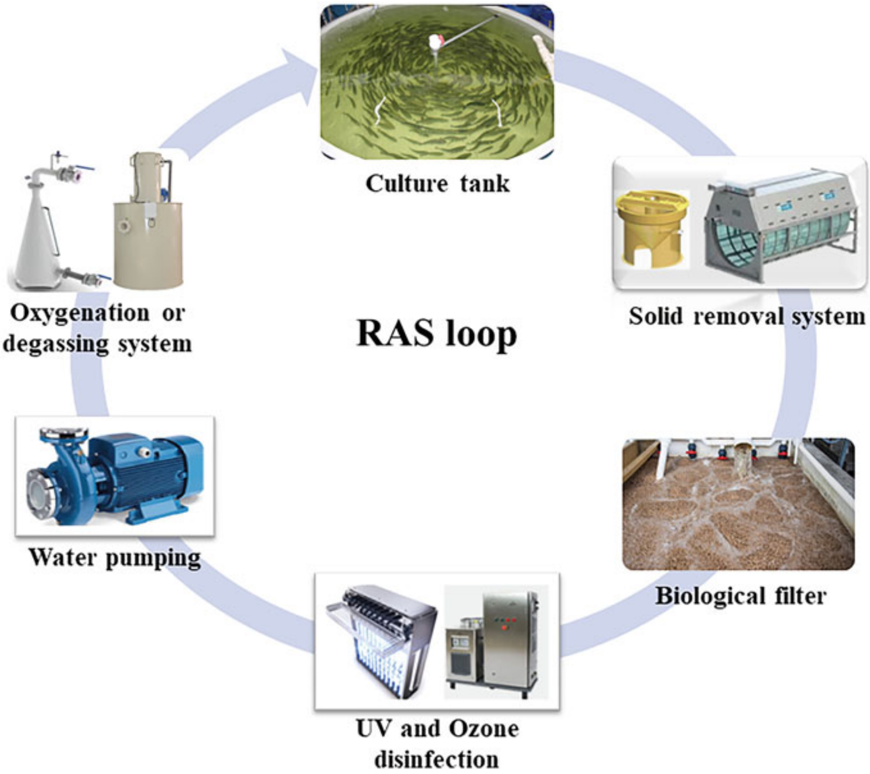

Fig. 11.1 Major components of a commercial recirculating aquaculture system (RAS) loop

series of filtration systems and equipment, such as mechanical filters (to remove solids), biological filters (to remove ammonia, nitrite and nitrate), disinfection units (to reduce pathogenic microorganism load), degassing and oxygenation units (to remove CO_2 and nitrogen and to add oxygen in the system) and pumps (to pump the water back to fish rearing tank) (Timmons et al. 2018; Bregnballe 2015). A commercial RAS loop is depicted in Fig. 11.1.

11.3 Things to Consider Before Starting Fish Farming in RAS

Like any other farming activity, the first thing before starting up a RAS is to choose a suitable fish species depending on the market survey (e.g. demand in the local and international market) and the availability of good quality fish seed and feed. Generally, the culture of premium or high-value fish (INR > 500 or US $ 6.5) is profitable in RAS, considering the electricity cost and initial investment. Once the species is decided, the scale of operation and production targets is set before the RAS design is prepared. In the current chapter, rainbow trout is considered as an example as it is a high-value cold-water aquaculture species in India and across the globe.

Designing a RAS system primarily involves several calculations and requires estimates on paper or in excel. This includes aspects such as water flow rate, accordingly choice of pump, sizing of fish tanks, mechanical filter, the volume of biological filter, degassing, aeration and oxygenation capacity, plumbing and total area required for all the operation and building specifications required to produce a given quantity (in tonnes) of fish. A good RAS design aims to provide optimum water quality for fast growth of the fish with minimum operational cost and complexity. RAS designing also provides a basic idea of the budget required and the projects economic viability. Once the project is convincing, the blueprint is prepared, and the project is executed.

11.4 Principle for the System Design

A grow-out RAS aims to grow and produce fish that requires optimal feeding. Only a portion of the feed is converted into fish muscle, and the rest is excreted as faeces, ammonia and carbon dioxide. As Fig. 11.2 depicts, when a kg of feed (42–45% protein and 16–20% lipid) is fed to rainbow trout, only 70–75% of the consumed feed is digested. The remaining 25–30% is excreted as faeces, contributing to the total suspended solids in the fish tank. Further, as fish utilizes amino acids for energy production, ammonia is excreted, corresponding to the protein content of the feed (i.e., the TAN = protein content of a feed multiplied by 0.92; if the protein content is 45%, the TAN produced will be around 41.4 g/kg feed). Similarly, 0.4 kg of carbon dioxide is produced for every kg of feed metabolized, relative to oxygen consumption. Fish also requires nearly 0.3 kg of oxygen to metabolize every kg of feed. Accordingly, based on the maximum feed consumed during the production cycle, the water flow rate is calculated, and different filtration systems are designed to flush and remove/detoxify waste before the water is recirculated. It should also be kept in mind that the above values may change depending on the species and quality or composition of feed, e.g. tilapia requires low protein feed (35%). A good quality feed that meets all the nutritional requirements of the fish, with high digestibility and faecal decantation rate, is, thus, a prerequisite for the success of RAS operation.

11.5 Water Quality Monitoring and Management

Though water requirement in RAS is much less than conventional aquaculture production systems, water is still required to fill the system initially and for daily exchange and makeup 5–20% of the system volume. This quantity depends on the system's hydraulic retention time or recirculation efficiency, which in turn depends on the efficiency of filtration and the kinds of filtration in place. On the other hand, the physical and chemical quality of source water (especially temperature, dissolved oxygen, nitrogen, carbon dioxide, pH, hardness, fluorides and heavy metals) needs

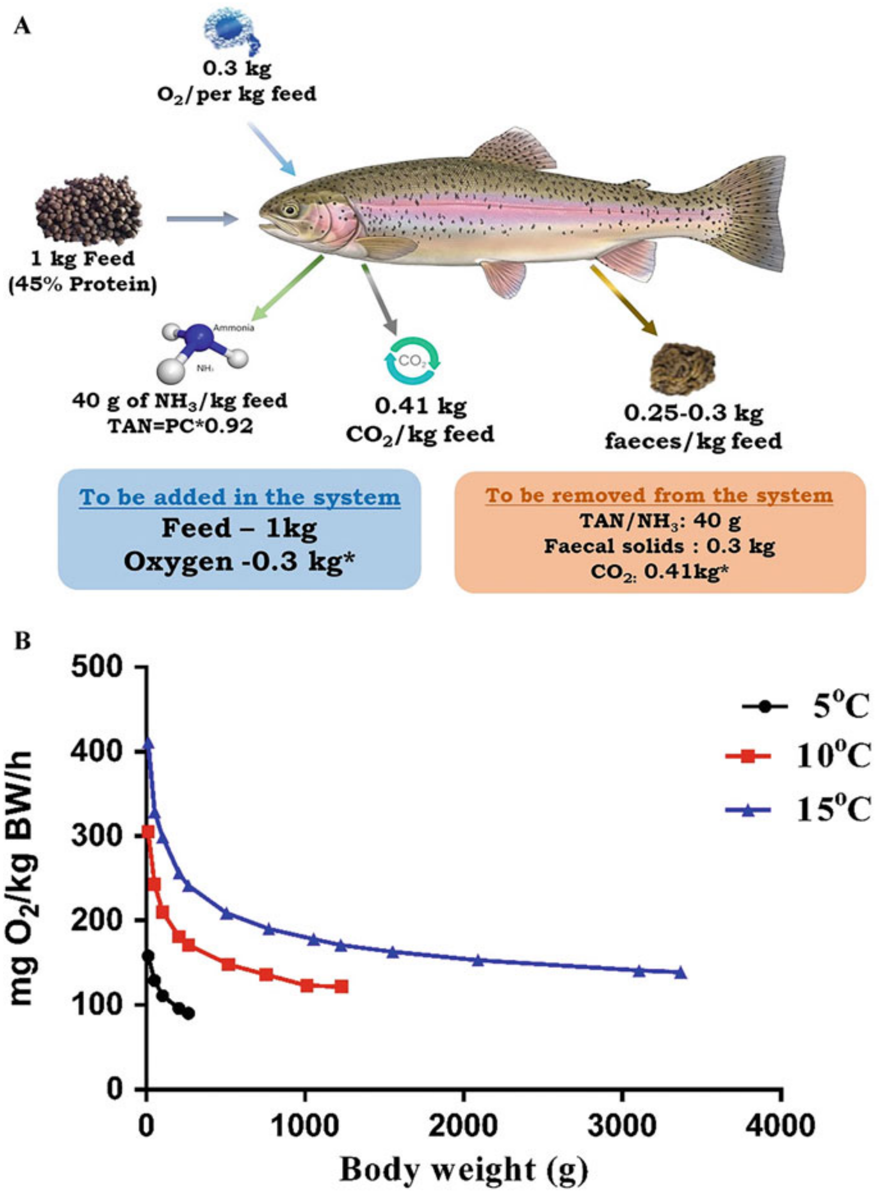

Fig. 11.2 (**a**) A schematic mass balance diagram of feeding fish in RAS. PC, the protein content of feed; faecal matter is given on a dry matter basis (on wet basis, it will be 1.25–1.5 kg faeces/kg dry feed). (**b**) The size and temperature-specific estimated oxygen consumption in rainbow trout. With increasing rearing water temperature, oxygen consumption increases, and similarly, oxygen consumption decreases with increasing body size (Cho and Bureau 1998)

Table 11.2 Optimal water quality requirement for fish farming in RAS (adapted from Timmons et al. 2018)

Parameters	Rainbow trout	Tilapia
Temperature (°C)	12–18	25–30
Dissolved oxygen	>80% saturation	>80% saturation
Dissolved oxygen (mg/L)	6–9	4–6
Dissolved oxygen at outlet (mg/L)	≥ 5	≥3
Ammonia ($NH_{3.}$ N) (mg/L)	<0.02	<0.6
TAN(NH_3 + NH_4) (mg/L)	<1	<3
Nitrite (mg/L)	<0.5 or 0.1 (soft water)	<1
CO_2 (mg/L)	<20	<40
Alkalinity (mg/L)	50–300	50–300
Nitrate (mg/L)	0–400	0–400
pH	6.5–8.5	6.5–8.5
Phosphorous (mg/L)	0.01–3.0	0.01–3.0
TSS (mg/L)	10–20	20–30
Hardness (mg/L)	50–300	50–300
Chloride (mg/L)	>200	>200
Ozone (mg/L)	<0.005	<0.005

to be checked for suitability. Generally, groundwater is suitable for RAS application as it provides enough alkalinity and is usually free from pathogenic microorganisms. Open-source water drawn from springs, rivers, sea and lakes may require disinfection before use and the addition of alkalinity. The following table (Table 11.2) summarizes the conducive range of water quality parameters that need to be maintained for the optimal growth and welfare of a cold-water and warm-water fish (rainbow trout and tilapia). These values are targeted to achieve while designing a RAS (species specific).

11.5.1 Temperature

Though fishes have a broad temperature tolerance range, the optimum range for growth or reproduction (production traits) is very narrow and is species- or strain-specific. For example, for rainbow trout, 12–18 °C is considered an optimum range for growth, while for reproduction, it is 8–12 °C. Narrowing further, the maximum feed utilization is observed at 1618 °C (Molony 2001). So in RAS, it is good to maintain a temperature of 16–18 °C by heating or cooling the water to achieve maximum fish growth. However, the economic benefits of heating or cooling need to be evaluated as long as fish are in their broader optimum range. It should be kept in mind that temperature is also an essential parameter for the performance of a biological filter. Low temperature decreases the performance of the biological filter; at temperatures below 8 °C, the biological filter becomes least functional. In our experiments, we have observed that at 6 °C, the biofilter ceases to function (Rajesh et al. unpublished data).

11.5.2 Dissolved Oxygen

Dissolved oxygen (DO) is the most critical parameter, and the adverse changes in their levels can lead to fish mortality within minutes when fish are reared at high density. Such events generally happen due to the break-down of equipment, efficiency reduction or power failure. Thus, a backup arrangement is essential for maintaining the desired oxygen level at all times. It is one such parameter which needs to be measured at least twice daily or continuously monitored. DO is mainly supplied in the water flow through external oxygenators or aeration devices; sometimes, aeration is also provided in the fish tank. Oxygen levels in the tanks should be always above 80% saturation, e.g. for salmonids, it should be >6 mg/L and tilapia >4 mg/L all time (Timmons et al. 2018). The dissolved oxygen level in the outlet should not be below 5 and 3 mg/L for salmonids and tilapia, respectively. Feed intake ceases at the DO level < 4.5 mg/L, in the case of rainbow trout. The dissolved oxygen consumption pattern in rainbow trout is depicted in Fig. 11.2b; it increases with rearing temperature and decreases with body size. Thus, the juveniles require higher dissolved oxygen than the table-sized fish for given biomass, and the juvenile fish need to be stocked at a low stocking density (in terms of biomass or kg/m^3).

The saturation levels of DO decrease with increasing altitudinal location above the mean sea level (or with lowering of partial pressure of oxygen). For example, at 100 m.s.l. altitude at 15 °C, DO saturation value is 9.97 mg/L, and at 1500 m.s.l., DO saturation level is 8.39 mg/L. Likewise, oxygen solubility decreases with temperature. For example, at 10 °C, the saturation of DO is 11.28 mg/L at sea level, and at 25 °C, it is 8.26 mg/L (DO ⇆ % Saturation Calculator; waterontheweb.org). This is very important because, at high temperatures, the increased oxygen demand of fish coupled with low DO saturation levels can result in significantly lower growth and survival. On the contrary, when pure oxygen is used as a source for oxygenating the water, DO levels can be supersaturated (~40 mg/L), which is required for sustaining standing biomass of >35 kg/m^3 (Timmons et al. 2018; Summerfelt et al. 2000). It should also be kept in mind that even biofilter requires oxygen to carry out nitrification (i.e., conversion of ammonia to nitrate). Every gram of ammonia nitrogen requires nearly 5 g of oxygen for its oxidation into nitrate, so DO in biofilter should be above 2 mg/L all the time. Further, it is also essential to avoid anoxic zones in the system; an anoxic zone with the accumulation of organic matter could produce H_2S and eventually kill the fish. There are few reported cases of large-scale fish mortality due to H_2S toxicity in commercial salmonid RAS.

11.5.3 Carbon Dioxide

Carbon dioxide is generated in the system due to the respiration of fishes and bacteria. Carbon dioxide is also a part of the complex equilibrium in water, with carbonate and bicarbonate ions. Although different values are reported for carbon dioxide toxicity, the carbon dioxide concentration for rainbow trout should not be more than 20 mg/L. Further, the toxicity of CO_2 apparently increases with reducing pH and at low dissolved oxygen levels (3–5 mg/L) (Lloyd and Jordan 1964). Prolonged high CO_2 levels may also lead to the development of nephrocalcinosis, and this is also associated with the use of agriculture lime as an alkalinity source (Timmons et al. 2018). Generally, carbon dioxide is not an issue when aeration is used for oxygen supply, as aeration strips out carbon dioxide. However, when pure oxygen is used to improve dissolved oxygen at high stocking densities, carbon dioxide levels in water can go high, thus requiring a carbon dioxide stripper or degasser unit (Summerfelt et al. 2000; Colt et al. 2012).

11.5.4 Ammonia

Ammonia is the primary nitrogenous excretory product, generated from protein and nucleotide metabolism in fish, and it is excreted mainly through the gill. The toxicity of ammonia is pH- and temperature-dependent. As pH decreases towards the acidic range, most ammonia is converted to ammonium (NH_4^+) form, but as pH increases, most ammonia is transformed to free form or unionized form (NH_3). For instance, at the TAN value of 5 mg/L at 15 °C, the free ammonia fraction is 0.0165 mg/L, which is below the toxicity level. But at pH 9, free ammonia increases to 1.3 mg/L, which is highly toxic. As free ammonia can easily pass through fish gill by simple diffusion, it is toxic at very low levels (0.02–0.6 mg/L) as compared to ionized form, which cannot enter the gill (Ip and Chew 2010). Most ammonia test kits measure total ammonia nitrogen, abbreviated as TAN, as only nitrogen molecular weight is considered for standard. To get absolute total ammonia value, TAN must be multiplied by 1.21 (i.e., $NH_3 + NH_4^+ = TAN * 1.21$). When TAN, pH and temperature are known, both fractions and concentrations of NH_3 and NH_4^+ forms can be individually calculated from the NH_3-NH_4^+-pH-temperature tables or online software (e.g. Free Ammonia Calculator (JavaScript) (iastate.edu)). Allowed TAN concentration in RAS is 1 and 3 mg/L for cold- and warm-water fishes, respectively (Timmons et al. 2018).

11.5.5 Nitrite and Nitrate

Nitrite is an intermediate product of nitrification. Nitrite spike in RAS is observed due to several reasons such as immature biofilter (during the initial period of RAS operation), insufficient biofilter surface area, application of therapeutics against infection (e.g. formalin, hydrogen peroxide, etc.), disruption of water flow due to power/pump failure, ozone failure and increased total suspended solids due to inefficient solid removal. Ammonia and nitrite spikes generally do not occur in well-designed and matured biofilters (adequately designed based on the daily feed loading) and when DO levels in the biological filter are sufficiently high (>2 mg/L). Toxic nitrite levels convert haemoglobin to methaemoglobin, reducing its oxygen-carrying capacity and thus causing physiological hypoxia. The toxicity level of nitrite varies from 0.1 to 1 mg/L depending on the species. Nitrite toxicity can be reduced by adding chloride ions (NaCl); this neutralization requires nearly 20 times chloride ions for every mg/L of nitrite (cautionary note: chloride ions should not be confused with chlorine). Marine fishes are therefore more tolerant of high nitrite levels. Generally, in RAS, it is advisable to maintain 200 mg/L of chloride ions in water to prevent stress due to sudden spike in nitrite and also for other osmoregulatory benefits of NaCl. Nevertheless, the application of chloride ions to overcome nitrite toxicity is the only temporary or quick-fix remedy in RAS. But, for the long-term success of RAS operation, the reason for the nitrite spike must be identified and addressed with proper solution. During nitrite spike, exchanging water and stopping feeding is also advisable to prevent further building up of nitrite. In contrast, nitrate is the end product of biological nitrification and is not toxic even at high levels (>500 mg/L). Some studies have reported feed intake reduction due to high nitrate levels. Nitrate levels in the RAS are generally reduced by water exchange or through the denitrification process (Timmons et al. 2018).

11.5.6 Total Suspended Solids

For the success of RAS operation, controlling total suspended solids (TSS) is very important. If a proper solid removal system is not in place, TSS can go very high, especially when feed loading is high with increasing standing biomass. Every kg of feed generates nearly 0.25–0.3 kg of dry solid or 1.3–1.5 kg of wet solids. TSS levels above 20–30 mg/L are not suitable for the operation of RAS (Timmons et al. 2018; Couturier et al. 2009). High TSS may not kill fish immediately, but they reduce the efficiency of the biological filter, carbon dioxide stripping, oxygenation and UV filter and increases ozone dosage requirement. Further, they cause irritation in gills and reduce the visibility in water for fish and operators, resulting in difficulty in feeding and removing dead fish. This ultimately leads to the reduction of feed efficiency and further deterioration of water. High TSS favours the growth of geosmin and 2-methylisoborneol (MIB) producing bacteria and pathogenic bacteria, causing off-flavour and disease outbreaks in cultured fish, respectively. High TSS also favours the formation of anoxic zones resulting in the production of toxic hydrogen sulphide (H_2S).

11.5.7 pH, Alkalinity and Hardness

The pH of the water should be around 6.5–8.5 for successful fish farming in RAS. Very acidic pH impairs biological nitrification and causes carbon dioxide toxicity, while very basic pH may cause an increase in ammonia toxicity and reduce carbon dioxide stripping efficiency, apart from its direct effect on the aquatic animal. Biological nitrification continuously reduces the pH of water as this process consumes bicarbonate and generates H+ ions, thus necessitating the addition of base or alkalinity. The alkalinity of RAS water should be maintained at >100 mg/L for the proper functioning of the biological filter. As alkalinity is consumed in the process of nitrification, for every kg of feed fed, nearly 150–250 g of sodium bicarbonate must be applied, depending on the water exchange rate (HRT) and alkalinity of source water (Summerfelt et al. 2015; Timmons et al. 2018). Major sources of alkalinity supplementation are agriculture lime ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), sodium hydroxide (NaOH) and sodium carbonate ($NaCO_3$). Hardness is mainly due to the presence of Ca and Mg ions in water, and the recommended water hardness range is 50–300 mg/L for RAS. Hardness also decreases the toxicity of metals in water.

11.6 Components of RAS Culture System

11.6.1 Culture Tanks

Culture tanks are the vessels which hold the water where fishes are reared in RAS. They can account for 20–40% of the total capital cost of the system, depending on the material used. Many tank materials are available, such as plastic tanks, fibre-reinforced plastic (FRP), concrete, steel, HDPE and lined tanks supported either by GI mesh or wooden planks or tin sheets, depending on the local availability and the purpose. For example, plastic tanks can be used for nursery tanks, but for large tanks (>20 m^3), this may not be suitable. The most commonly used tank material is FRP, which can be shaped as per the requirement, constructed onsite or shipped in modules and assembled for large diameters.

The shape of the tank plays an important role in solid removal and providing uniform water quality for fish to grow. Circular tanks are mostly preferred for their excellent solid removal ability. They enable uniform water quality, and fishes distribute evenly when water inlets are appropriately designed. Further, circular tanks provide a continuum environment for fish swimming (see Fig. 11.3). Though raceways (rectangular tanks 2 m width and 15–50 m length) are widely used for farming rainbow trout in the flow-through system for space saving and easy operation, they have poor solid flushing ability, and regular manual brushing and cleaning are essential. A lot of water needs to be flushed during this process, and it also plumes the solids causing turbidity or fine solid load, which is not desirable when water needs to be recirculated. There is space wastage with circular tanks, which can be minimized through octagonal tanks that provide similar characteristics to that of

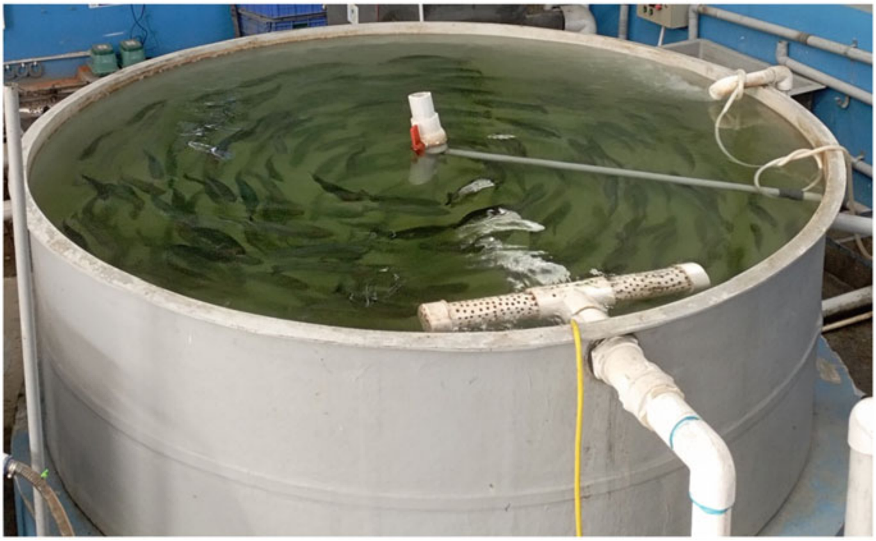

Fig. 11.3 FRP culture tank used at ICAR-DCFR, Bhimtal, for culture of rainbow trout in RAS

the circular tanks. One of the major advantages of circular tanks is that circular movement of water can be created by placing the inlet tangent to the tanks wall, and this causes the concentration and settling of solids at the centre bottom due to the teacup effect. Unlike the raceway system, this mechanism completely removes settleable solids without brushing or flushing. The diameter-to-depth ratio of 1:3–1:6 should be considered for proper distribution of fishes and easy operation and to enable visual observation of the health of the fishes and removal of dead fish (Timmons et al. 2018). There are several instances where fish farming has failed to operate in silo tanks (larger depth-to-diameter ratio). Contrarily, a higher diameter-to-depth ratio may be needed for certain fishes (e.g. flounder or shrimp), which do not distribute in the entire water column (Timmons et al. 2018).

Many outlet designs have been proposed to take advantage of the teacup effect of circular tanks, and at least two patents are available on the tank outlet design (particle trap, US Patent # 5636595, Lunde et al. 1997; and water treatment system, US Patent # 5593574, Van Toever 1997). In one of these designs, both the outlet systems are located at the centre. Most solids (up to 80% of settleable solids) are concentrated through a particle trap located at the bottom centre of the tank (through annular plates), drawing 5–10% water to a settling unit (swirl separators) located adjacent to the tank, while the remaining 90–95% of water is drawn out from elevated perforated screen plate. Cornell dual-drain outlet design also has two outlets, i.e. the central drain and side wall drain. Fifteen to twenty-five percent of water is drained through the central drain, which carries concentrated solids (Davidson and Summerfelt 2005; Timmons et al. 2018), and the side wall drain carries very less solids (TSS $<$2 mg/L) when compared to the central drain (~19 mg/L). Further, in Cornell dual-drain tanks, fish distribute uniformly and utilize the entire space available in the tank, enabling high stocking densities compared to other single- or double-drain tank outlet systems. Overall, dual-drain tanks have economic advantages as this reduces the required size of the microscreen drum filter, the number of backwash cycles, electricity cost and freshwater requirement. The mixed cell raceway is a new hybrid tank design incorporating raceway and circular tank characteristics by correctly positioning tank inlets and central outlets along the raceway bottom (Timmons et al. 2018).

11.6.2 Solid Removal Systems

Solids are generated from two primary sources, faecal matter and uneaten feed. Fish excretes almost 250–300 g of faecal matter for every kg of feed fed (dry matter basis), considering 70–75% dry matter digestibility. However, on a wet basis (75–80% moisture), this could be around 1–1.2 kg of faecal matter. The specific gravity and particle size distribution of the faecal matter are two major properties which decide which kind of solid removal system to be used. The above property also depends on the fish species reared, diet composition, faecal characteristics, water temperature and turbulence in the system. The three major principles for removing solids in water are gravity separation, filtration and floatation.

11.6.2.1 Settling Units

Early RAS models utilized inline large settling basins to separate and remove the solids before being recirculated. Settling basin is one of the cheapest ways to remove solids, as it does not require electricity and specific equipment (Timmons et al. 2018). However, due to labour requirements, poor solid removal efficiency and more space footprint (low hydraulic loading) as compared to other filtration methods, settling basins are mostly not used in modern RAS systems, and their use is primarily limited in effluent treatment systems of RAS.

When dual-drain culture tanks are used, settling tank dimensions can be reduced to a very small size (0.5–2 m diameter), as in the case of the Cornell dual-drain tank system where radial flow settlers (RFS) or swirl separators (SS) are used to settle the solids generated from 10–20% water drawn from the bottom drain (Davidson and Summerfelt 2005). Both SS and RFS are cylindrical-shaped tanks with conical bottom (Fig. 11.4). The major difference between them is the mode of entry of water into the settling tank. In the case of SS (also called as teacup settlers or hydro-cyclones), water enters tangentially to the tank surface, while in the case of RFS (also known as centre feed basins), the inlet water is injected centrally into the tank through a cylinder. Some studies suggest that RFS are more efficient in TSS removal as compared to swirl separators (TSS removal efficiency of 77 versus 37% in commercial salmonid RAS) (Davidson and Summerfelt 2005). In another model, the Aqua optima particle trap dual-drain tank utilizes very small swirl separators, as only 5% of water is drained from the bottom outlet, and it is claimed to collect nearly 80% of the settleable solid generated. In our study at ICAR-DCFR, Bhimtal, with a dual-drain tank, we observed that with an increase in hydraulic retention of

Fig. 11.4 Radial flow settler with radial entry of water (cylinder not shown) and swirl separator with tangent entry of water

10–15 min, the swirl separator collected 40–60% of the total solid generated. Further, we observed that the solid collecting ability of the swirl separator is also affected by the turbulence created by aeration in the culture tank and feed composition and size (Rajesh et al. unpublished data).

11.6.2.2 Microscreen Filter

Microscreen filter is the most widely and commonly used solid removal system in commercial RAS, as it provides automatic backwash function, with no head loss like in sand or bead filter and provides good TSS removal efficiency. There are at least three types of microscreen filters, namely, microscreen drum filter, belt filter and disc filter. Typically, a drum filter is used for RAS in-line removal of solids, while belt filters are mostly used for off-line dewatering of the solids before discharge and sometimes specifically used for typical solid waste of certain species (e.g. eel or to remove shrimp excavates) (Vinci et al. 2001).

Microscreen drum filter consists of stain steel mesh of varying micron size (30–70 μm), which is shaped as a cylinder or a drum with the help of cylindrical steel reinforcement or guide. The microscreen drum is connected to an electric motor with the help of gears to rotate the drum. Water passes through the microscreen drum filter and removes the TSS from water, and when the screen clogs, it prevents water from passing through, resulting in an increased water level. The water-level sensor in the drum filter then triggers the backwash mechanism where spray bars spray a jet of water onto the outer drum surface with simultaneous rotation of the drum screen, resulting in the cleaning of the trapped solids from the mesh (Fig. 11.5). The waste solids are collected in the tray provided below the top surface of the drum (as shown in Fig. 11.5) and are directed towards the effluent treatment facility.

The selection of a right-sized microscreen is very important since this has economic implications. A finer microscreen requires more repeated backwash, a large volume of backwash water and a larger drum filter, hence more operating costs than a larger microscreen. For example, when microscreen filter mesh size is

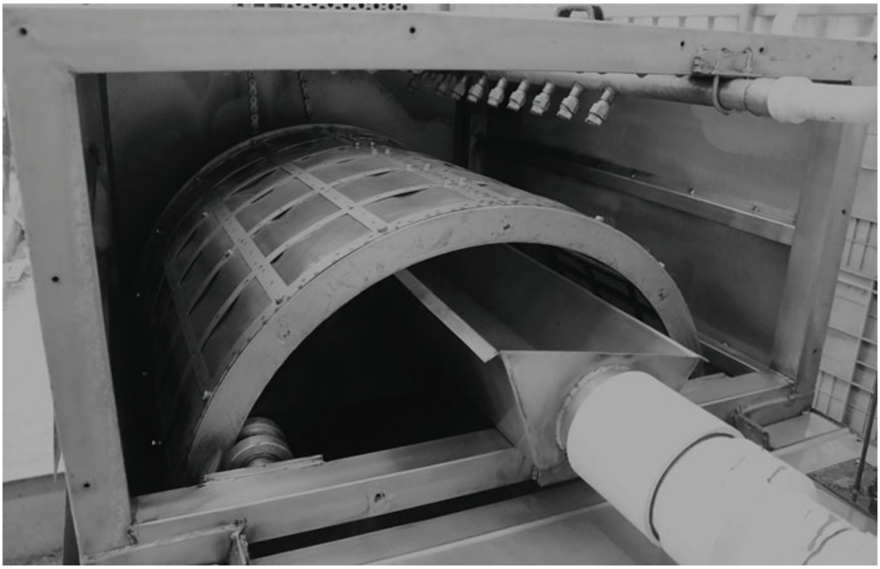

Fig. 11.5 Microscreen drum filter (screen size 50 μm) used in the cold-water RAS facility for rainbow trout production at ICAR-DCFR, Bhimtal

decreased from 100 to 30 μm, the amount of backwash water required increases from 50 to 200 L/kg feed with subsequent improvement in TSS capture efficiency from 21 to 90% (Mortensen 2000). Generally, the TSS capture efficiency of microscreen drum filter varies from 30 to 80%, and this depends on the inlet TSS level, i.e. the efficiency increases with an increase in inlet TSS level (Vinci et al. 2001).

Another commonly used solid removal system is granular filter media or sand filter or bead filters. These filters work as a solid removing system and as a biological filter. The use of swimming pool-type down-flow sand filter is not suitable for the RAS system because of the higher TSS load than the swimming pool and requires frequent backwash; thus, their use in RAS is discouraged. However, up-flow sand filters (fluidized sand filters) are used as biological filters, especially in cold-water RAS. The pressurized sand filter could be used for offline water polishing for specialized purposes like display aquariums or hatcheries. To overcome problems with the pressurized sand filter, bead filters were invented, where floating plastic beads (3–5 mm) were used in place of sand, and they work as both solid removal systems and biofilters (Malone and Beecher 2000). Bead filters require significantly less water and can be easily back washed through propeller-based or bubble injection. These bead filters are suitable for small-scale RAS and lightly loaded systems (special purposes like hatchery or brood stock maintenance). However, in large-scale commercial operations, granular filters are rarely used because of head loss caused by the bead or sand.

11.6.2.3 Foam Fractionators

Fine suspended and dissolved solids are one of the major issues in RAS, which increases as the culture of fish progress, decreasing the efficiency of all filtration devices (biofiltration, UV and ozone system). Foam fractionators remove fine and dissolved solids in water by injecting fine air bubbles; this precipitates the dissolved protein (other surfactants) on top of the bubble at the water surface. Foam is generated due to surfactant in water (protein and lipid), and if you see white foam on top of the water, it could be primarily due to decaying fish in the tank. Therefore, removing dead fish is very important; this requires good visibility through water (clear water) to see the dead fish at the bottom of the tank. The foam-precipitated particle size is mostly less than 30 μm, and foam fractionation is the most effective in salt water due to the formation of smaller bubble and higher surface tension of the seawater. The effectiveness of protein skimmer in freshwater is still a researchable issue, and studies have reported that foam fractionators removed only ~25% TSS in freshwater as compared to ~55% at 10 ppt salt water (Jafari et al. 2022). Nevertheless, another study found that foam fractionators along with ozone can work equally well in freshwater RAS in removing particulate matter and improving turbidity and UV transmittance (de Jesus Gregersen et al. 2021).

11.6.3 Biological Filter

In RAS, the ammonia excreted by fish needs to be removed (detoxified) before the water is recirculated to the culture tank, and this role is generally played by nitrifying bacteria grown on biofilter media (refer to Boxes 11.1 and 11.2). A biofilter's primary function is to provide a suitable surface area for the growth of nitrifying bacteria (biofilm; autotrophic bacteria like nitrifiers require some substrate to grow). Different types of biofilters such as rotating biological contactor (RBC), trickling filter, submerged gravel bed filter, moving bed bioreactor (MBBR), floating bead filter, fluidized sand filter, etc. are available to choose. Each type of biofilter has its advantage and disadvantage over the other. Its efficiency is calculated in terms of specific surface area (m^2 cross-sectional area/m^3 bio-media volume), hydraulic loading rate (m^3 water/m^2 biofilter cross-sectional area), volumetric nitrification rate (g TAN/day/m^3 of bio-media) and areal TAN conversion rate (g TAN/m^2 cross-sectional area per day) (Timmons et al. 2018). Here, we discuss only three types of biofilter which are commonly used in cold-water RAS.

Box 11.1

Box 1.
Biological filter utilizes the natural nitrifying microorganisms for detoxifying ammonia in water through a two step biological process.
Ex: Nitrosomonas
$2\,NH_4^+ + 3\,O_2 \rightarrow 2\,NO_2^- + 2\,H_2O + 4\,H^+$ (1)
Ex: Nitospira*, Nitrobacter
$2\,NO_2^- + O_2 \rightarrow 2\,NO_3^-$ (2)
* Nitrospira is a dominating nitrifier in the biological filter of a coldwater RAS.

Box 11.2

Box 2. **Overall nitrification**

$$NH_4^+ + 1.83\,O_2 + 1.97\,HCO_3 \longrightarrow 0.0244\,C_5H_7O_2N + 0.976\,NO_3^- + 2.9\,H_2O + 1.86\,CO_2$$

- A gram ammonia oxidation requires 4.18 g oxygen and 7.05 g alkalinity for biological nitrification.
- Therefore alkalinity of recirculating aquaculture water should be maintained > 100 mg/L $CaCO_3$ through the addition of alkalinity sources and dissolved oxygen in biological filter should be maintained > 2 mg/L.
- Thumb rule : every kg feed fed in the system requires 0.25 kg of $NaHCO_3$ to maintain desired alkalinity level in the recirculated water (Timmons et al., 2018).

11.6.3.1 Moving Bed Biological Reactor

Moving bed biological reactor (MBBR) is commonly used in treating municipal wastewater to remove nitrogen based on the above principle. MBBR consists of a reactor tank filled with specially designed bio-media (HDPE Kaldnes media K1–K5, the density of 0.96–0.98 g/cm^3) up to 30–65% of the reactor volume. These media are kept in the water column through the aeration process, and water from the fish tank (after treating for solid) is passed through the reactor (Fig. 11.6). The nitrifying bacteria grow over the surface of bio-media (internal and external surface) and convert ammonia to nitrate in a two-step process. These bio-media have a volumetric nitrification rate (VNR) of 500–1400 g TAN/day/m^3 and are suitable for high hydraulic loading rates. The major advantage of these MBBRs is that they are maintenance-free as media do not trap solids and hence do not require cleaning. The life span of these media is around 15 years.

11.6.3.2 Gravel Bed Biofilter

The gravel bed biofilter is the cheapest media as they are locally available, and the authors have personally observed that gravel-based biofilter matures faster than

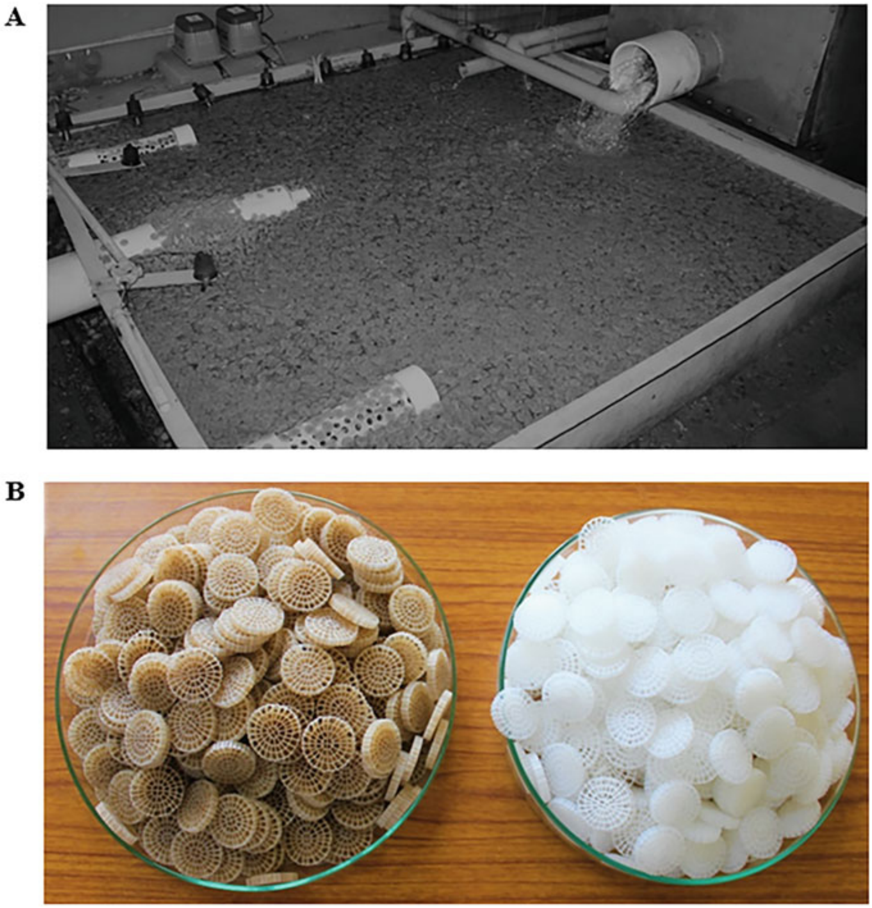

Fig. 11.6 MBBR biofilter in RAS unit at ICAR-DCFR, Bhimtal (**a**), and fresh (right) and matured K5 media (left) used in MBBR (**b**)

MBBR (Akhtar et al. 2018). The gravel bed biofilter consists of a gravel bed of 15–20 cm depth, made up of 5–10 mm crushed and washed gravel, and a plumbing design (with 1 mm slits) laid below the gravel (which acts as an inlet for the filtered water). The pump draws water from the bottom of the gravel, which enables the water to pass through the gravel. The nitrifying bacteria grown over the gravel surface converts ammonia to nitrate (Fig. 11.7). The authors have observed that 10–15 mm gravel has a decent VNR of 300–400 g TAN/m^3/day at 20 °C. The gravel bed biofilter also filters fine solids, which is a blessing in disguise, but this necessitates a regular periodic cleaning, which is laborious. Therefore, gravel-based biofilter is not suitable for commercial setups and only advised for lightly loaded and small RAS units.

Fig. 11.7 Submerged gravel bed filtration used for hatchery RAS system at ICAR-DCFR, Bhimtal, India

11.6.3.3 Fluidized Sand Filter

Another type of commonly used biological filter is a fluidized sand filter. Sand (0.1–0.2 mm) offers a very high specific surface area and VNR of 0.2–0.4 kg TAN/day/m^3 of expanded bed (Summerfelt 2006). The fluidized sand filter consists of a large cylindrical tank of 3–5 m height. Water is injected at the bottom of the cylinder, and this expands the silica sand bed. The significant advantage of a fluidized sand filter is the scalability and smaller footprint. However, a fluidized sand filter requires regular maintenance as the sand becomes lighter over the period of operation due to the growth of bacteria and eventually flows into the culture tank. Sand also forms channels due to biofouling and electrostatic charge in the sand particle, necessitating regular sand replacement (Davidson et al. 2008; Summerfelt et al. 2001).

11.6.4 Degassing Unit: For Removal of Carbon Dioxide

Carbon dioxide in the system is generated due to fish and bacterial respiration, and it must be removed to maintain the carbon dioxide levels in the water below permissible safe limits (<20 mg/L). Generally, carbon dioxide is not an issue when aeration is used for supplying oxygen (~ stocking density of 40 kg/m^3), as aeration also strips out carbon dioxide. However, when standing biomass goes above 40 kg/m^3 and when pure oxygen is used for maintaining the oxygen level, carbon dioxide can reach a very high level. In this case, a separate carbon dioxide stripper or degasser is required. Carbon dioxide can be easily stripped out of the water when the water is exposed to air as the carbon dioxide level is very less in the air. Using this principle, water is passed through packing media in a stripping column, which increases contact time with atmospheric air via cross-ventilation (air blew from the opposite side with the help of a blower) of the water with air, with a water-to-air ratio (G/L) of 5:1–20:1 (Summerfelt et al. 2000, 2001; Timmons et al. 2018). The CO_2 stripper can be mounted on top of low-head oxygenators to avoid extra pumping costs (Summerfelt et al. 2000).

11.6.5 Aeration and Oxygenation

Oxygen is the major limiting factor in any RAS as there is a direct relationship between oxygen intake, feeding and growth. Aeration is a commonly used dissolved oxygen-enhancing method that mixes atmospheric air into the water through the help of an air pump and air diffuser. There are at least three kinds of aerators used in RAS: they are diaphragm blower, regenerative blower or ring blowers and root blower. The diaphragm blower is less noisy, consumes much less energy and is suitable only for small systems as blowers above 0.2 kW capacity are not produced (Fig. 11.8). Root blowers are used for large-scale RAS as any capacity blower can be manufactured. Pressurized air is supplied to the fish tank through the help of air stone or air-oxy tubes as fine bubbles. But, the aeration efficiency of this kind of aeration is only 3–7% and thus supports a maximum fish density of 40 kg/m^3 (Timmons et al. 2018). Another way to mix air in the water is through Venturi, and this method has better aeration efficiency and requires high-pressure pumping. Though paddle wheel aerators have higher oxygenation efficiency (up to 4 kg/O_2/KWh), their use is limited in closed tank systems (Boyd 1998). Another major drawback of aeration is that it creates turbulence in the culture tank water, breaking the faecal matter, causing turbidity and thereby reducing the solid removal efficiency of settling basins and drum filters.

Fig. 11.8 Different types of air blowers used for aeration in a RAS (from left, diaphragm, ring or regenerative and root blowers)

Pure oxygen is inevitable to grow fishes at stocking densities above 40 kg/m^3. Pure oxygen can be obtained from at least three sources, namely, high-pressure oxygen gas, liquid oxygen and onsite oxygen generators. The choice of source, however, depends on the local availability and cost. Besides, oxygen can be generated onsite through two types of generators, namely, pressure swing adsorption (PSA) and vacuum swing adsorption (VSA) oxygen generators; the latter is expensive and reliable compared to PSA. Both generators purify the atmospheric oxygen from air with the help of molecular sieves, which filter out nitrogen. Since oxygen is expensive, wastage of oxygen is not desirable, so oxygen mixing devices should achieve nearly 100% oxygen transfer efficiency. Therefore, unlike air, oxygen is not supplied through the diffusers; instead, they are provided through special devices such as Speece cone/oxygen cone, low-head oxygenator, packed column oxygenators and U-tube oxygenators (Summerfelt et al. 2000, 2001). The oxygen cone provides a very high oxygen transfer efficiency of 95–99%, with the oxygen level in the outlet reaching 60–90 mg/L when properly operated, but this requires high-pressure water flow. The low-head oxygenators can achieve 50–90% oxygen transfer efficiency at different gas-to-water ratios and are very easy to operate, and it also strips out nitrogen and carbon dioxide to a certain extent. The U-tube oxygen transfer device provides 30–50% oxygen transfer efficiency depending on the depth of the tube and can also be operated without power if sufficient water head is available (Timmons et al. 2018).

11.6.6 Disinfection System

To reduce heterotrophic and pathogenic bacterial load in the recirculated water, ultraviolet (UV) light and ozone filters are used. Besides disinfection, these filters also improve the water quality and clarity, as ozone oxidizes organic matter and nitrite and reduces the brownish (recalcitrant) colour of the water. Moreover, a UV filter is effective only in water with higher clarity. Therefore, ozone and UV filter work complementarily, as O_3 converts into O_2 when passed through UV, reducing the toxic effect of ozone on fish. Moreover, UV filter is placed after the ozonation in the RAS loop. For RAS purposes, open-type UV bulbs are suitable as quartz sleeves can be checked and cleaned for biofouling or calcium deposits. Ozone is generated onsite through an ozone generator and is mixed in water along with oxygen transfer devices such as an oxygen cone or LHO. The ozone has a half-life of <15 min, which also depends on the organic matter of the water. The suggested ozone dosage in RAS varies between 13 and 24 g ozone/day/kg feed. ORP meters can be used to control ozone dosing. In any case, the ozone level in the fish culture tank should not cross 300 mV; the dosage is accordingly controlled, as ozone is also toxic to fish. Further, the ozone can be destroyed by passing it through UV illumination. Ozone exposure to people working in the RAS system can be dangerous. Therefore, proper ventilation and precaution should be in place when ozone is used in the RAS fish farming system (Summerfelt et al. 2009).

11.6.7 Water Pumps

The water pump is the heart of the RAS, as it moves filtered and oxygenated water from filtration systems to fish and flushes the wastewater from the culture tank into the filtration system. Pumping cost can be a major operational expenditure, as it contributes to the total electrical cost, next only to heating and cooling systems. Therefore, the selection of pumps has economic implications. Different types of pumps are used in RAS, namely, centrifugal pumps (Fig 11.9), axial pumps, airlift pumps, etc. Centrifugal pumps are designed to pump water to a very high head (> 30 m) and are often used in RAS, particularly when oxygen cones are used for oxygenation. The axial pumps are suitable for lower-head purposes (4–9 m) and are very useful in RAS when appropriately designed. The axial pump can pump large volumes of water at lower heads and consumes much less electricity than a centrifugal pump. However, axial pumps are not generally available for a small flow rate. Airlift pumps are suitable for lifting the water to a maximum of 15 cm head, and it does not contain any moving part; water is lifted with the help of an aeration manifold or diffusers. Though airlifts are cheaper and have very low operating costs, they are only useful in small systems and are not used in commercial RAS setups (Timmons et al. 2018). For the selection of an appropriate pump, the water flow requirement is calculated from the mass balance estimation, depending on the production target in the tank and the oxygen source used. The time required to exchange one tank volume of water is called hydraulic retention time (HRT) of the tank. For farming rainbow trout in RAS, generally, less than 30 min of HRT is

Fig. 11.9 Multiple centrifugal pumps used in RAS facility at ICAR-DCFR, Bhimtal

essential (standing biomass >40 kg/m^3) to supply sufficient oxygen and for flushing waste (TSS, CO_2, TAN) (Fig. 11.9).

11.6.8 Heating and Cooling System

Depending on the species and the local climatic conditions, heating and cooling systems may be required to maintain controlled temperature conditions in RAS. Heating can be done with the help of electric heaters (titanium heating elements), heat pumps or gas heaters. In terms of operating costs, heat pumps can cost-effectively heat the water, but they are expensive. Cooling of water can be done with the help of industrial chillers. Heating and cooling costs could account for most of the total electrical cost in RAS; therefore, heating and cooling requirements need to be ascertained with the economic benefits it provides. Utilizing geothermal energy is another potential option to maintain the required water temperature in the system.

11.6.9 Monitoring Equipment, Emergency Systems and Backups

One of the major challenges of intensive aquaculture (e.g. RAS) is the requirement for 24×7 monitoring of the system. Since fishes are reared at high density (up to 120 kg/m^3) in RAS, any component failure (pump, oxygen supply) or power cut even for 15 min could end up in a mass fish loss if the issue is not addressed immediately. Therefore, continuous system monitoring (Fig. 11.10) is crucial, and backups are essential. Backups for the pump, aeration, oxygen supply and an electricity generator are mandatory for RAS operation. Out of our own experience,

Fig. 11.10 Real-time DO monitor and alarming system (YSI 55000D) used at ICAR-DCFR, RAS facility at Bhimtal

we advise that it is better not to do RAS-based fish farming without adequate backups and risk avoidance measures. Dissolved oxygen is one crucial factor that can kill fishes in minutes when they are below the threshold level. In intensive rearing conditions, oxygen levels can quickly drop when pumping, oxygenation system or power failure occurs. Therefore, dissolved oxygen monitoring 24 × 7 is the first point of critical control. There are suppliers who provide real-time dissolved oxygen monitoring and control systems that can be connected to oxygenation devices and an alarming system that triggers an alarm when DO drops below a set threshold level. However, reliable and durable DO sensors are expensive and may be required for all rearing tanks. Another way to monitor water flow or the water level is through a water flow meter or water-level sensors which are cheaper and also reliable, but it is not a replacement for DO measurements. DO measurements and ozone levels (ORP) should be checked several (at least three to four) times a day. At the same time, other water quality parameters, such as ammonia, nitrite, nitrate, carbon dioxide, alkalinity, pH and TSS need to be checked regularly to ensure that all the RAS equipment is functioning to the expected operational efficiency. There could be many practical problems during the culture operation, if the system is not appropriately designed. For example, mortality of a few fishes (may be due to any reason) and failure to remove the dead fish can cause blockage in the central drain outlet, causing water to overflow, and the following day you might end up seeing all fish on the floor. Therefore, proper system design (e.g. dual drain, proper outlet) and system monitoring are extremely critical and essential.

11.7 Growing Fish in RAS

In RAS, fish should be grown near the system's carrying capacity at all times, to take maximum benefit of system design. Therefore, proper bio-planning is required while designing and operating the system. In the case of rainbow trout farming, fishes should be grown in different phases at least in four culture tanks, namely, hatchery system, nursery1, pre-grow-out and grow-out. This multiple tank rearing system is useful to reduce operational costs and save space. Moreover, this allows the farmer to harvest fish multiple times and regularly supply fish as per the market demand. It is always good to start from eyed ova, as it is easy to transport and also for biosecurity measures (eggs can be disinfected with povidone-iodine solution). Fish are then moved through the different tanks designated for the rearing phase (nursery and grow-out) during culture. This way, a new batch of eggs is brought as per the bio-plan, and fish are sold from grow-out tanks as per the market demand instead of dumping fish in the market all at once.

11.8 Feed and Feeding

Feed and feeding are one of the most critical factors (technically and economically) that determine the success of RAS operation, as it is integral to the equilibrium between fish growth, health and water quality maintenance. Advanced aquaculture systems such as the RAS require an equally advanced feed specific to the cultured species. Though the basic nutritional requirements for fish in RAS remain the same, due focus must be given to feed conversion efficiency into fish biomass as well as the efficiency of solid and dissolved waste removal. To improve the water filtration efficiency in RAS, research is being done on optimizing feed quality (physical and nutritional) and feeding strategies to improve feed palatability, digestibility, functionality and efficiency, as well as faecal stability and nutritional waste removal. In short, feeds for fish grown in RAS should be complete in nutrition, should elicit superior biological performance and must yield the desired faecal characteristics (high decantation rates) to maintain good water quality. The physical characteristics of faeces, such as dry matter, particle size distribution, viscosity, stability/disintegration and settling properties are quantified to aid the designing of filtration and waste removal systems in RAS (Tillner 2019). On the other hand, the quality of faeces and its recovery is decided by factors such as dietary ingredients, processing and the inclusion of additives. Some commercial feeds specifically designed for RAS production systems are already available in the global market. This includes Skretting's next-generation RCX feeds with high structural integrity for salmon production in RAS, BioMar's LARVIVA ORBIT feed concept to improve the efficiency of marine nurseries and Aller Aqua's PowerRAS concept to match RAS sophistication. In India, RAS-specific feeds are presently under research investigations and are not available commercially. Feeding management is another vital aspect of RAS, and continuous feeding throughout the day (every 2 h through auto feeders) is the main strategy to get faster fish growth. This also helps in the uniform excretion of ammonia (throughout the day) and does not put a sudden load on the biological filter due to a spike in ammonia or nitrite levels. The following feeding chart (Fig. 11.11) explains the feeding rate and feed amount in relation to fish size and

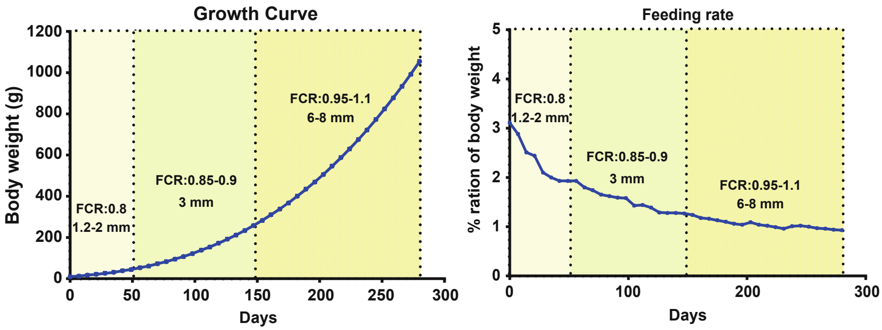

Fig. 11.11 Relation between feeding rate and growth rate of rainbow trout

growth rate. Feeding should be stopped whenever there is an issue with oxygen and water quality until the problems is resolved.

11.9 Depuration

Incidences of off-flavour or off-taste (muddy/musty odour) have often been reported in RAS-produced fish. The chemical compounds responsible for this muddy odour are geosmin and 2-methylisoborneol (MIB), which are produced as secondary metabolites by various microorganisms (Azaria and van Rijn 2018). Due to their hydrophobic nature, these compounds accumulate in the fish flesh (lipids) through simple diffusion (against the concentration gradient). The human nose can detect geosmin and MIB concentrations of less than 0.05 μg/L (50 parts per trillion) in the fish flesh, and thus off-flavour tainted fish flesh often causes consumer complaints and rejection. The accumulation of off-flavour compounds is prevalent mainly in RAS with low water exchange rates (Davidson et al. 2014).

Depuration or purging is a common method to reduce off-flavour in fish grown in RAS. Depuration involves rearing fish in a freshly disinfected tank, without any feeding for 7–12 days, with a slow exchange of freshwater (HRT of <1 day). This purging can be quickened with the addition of peracetic acid or hydrogen peroxide and ozone and UV filtration (Davidson et al. 2014; Lindholm-Lehto et al. 2022). During this process, the off-flavour compounds are passively depurated from the fish flesh into the water, which is later oxidized by ozone or flushed with freshwater. Recently, a novel advanced oxidation process (AOP) has also been developed to remove off-flavour through a multi-component action mechanism which can remove off-flavour in Atlantic salmon within 6 days, as compared to more than 10 days in other depuration methods (Kropp et al. 2022).

11.10 Waste Management

RAS generates concentrated effluents (i.e., solids, mostly from drum filter backwash and settling unit discharge) and nitrate-rich water, which need to be treated before releasing them into natural water bodies. One of the common effluent treatment methods is to discharge the effluent into a settling basin, followed by artificial wetlands, which eventually reduce nitrate and phosphorous levels in discharge (Martins et al. 2010). If the RAS is located near an agriculture field, the effluents can be directly used as fertilizer in the form of dilute slurry. Another way to remove sludge from the effluent is through sludge thickening using a belt filter, with or without flocculation. Geotextile bags can also be used to dewater the aquaculture solid waste, and dewatered solids could be used as organic fertilizer for agriculture (Guerdat et al. 2013). The use of RAS sludge for biogas is an exciting option, but unfortunately, biogas production is not efficient as that of cow dung due to effluent composition (minerals, protein and fibre). Therefore, currently, RAS sludge can only be used as a co-digestion mixture with ruminant manure, and further research are underway to improve the biogas production efficiency from aquaculture waste (Mirzoyan et al. 2010; Choudhury and Lepine 2020). Nitrate levels in the effluent water can be reduced through denitrification or by connecting it to de-looped hydroponics for integrated agricultural production and higher economic benefits.

11.11 Status of RAS in India

In India, RAS-based food fish production is still in its infancy, and the major bottlenecks are technical know-how and high initial investment. Commercial rainbow trout farming in RAS could be a reality soon, as rainbow trout is considered a premium high-value fish. In this direction, the ICAR-Directorate of Coldwater Fisheries Research has been working for the past 4 years. To overcome the challenges associated with conventional trout production systems, we have designed, established and successfully validated the feasibility of intensively farming rainbow trout in a pilot-scale cold-water RAS facility at Bhimtal, Uttarakhand. The production capacity of this pilot-scale RAS is nearly 2 tonnes per year and is mainly used for research, demonstration and training. Concurrently, ICAR-DCFR has also designed, developed and validated hatchery and nursery RAS systems for incubating trout eggs and rearing trout fry in multiple locations. Hatchery RAS under controlled conditions for rainbow trout could be a catalyst for increasing the production and productivity in remote high-altitude locations like Ladakh in India. Despite the extreme weather conditions in Ladakh, we have tested and validated that egg incubation and fingerling production can be successfully achieved in a shorter period under controlled RAS conditions. This allows sufficient time for fish to grow in the outdoor flow-through system when the water temperature is in a suitable range during summer (April–October), thus reducing the overall crop duration. Currently, only two commercial RAS-based rainbow trout farming facilities have been established or planned in India, namely, one at Awantipora, Kashmir, with a system volume of 500 m^3 (production capacity of 15 tonnes, operational from 2021) and another at Hyderabad, Telangana (initiated and expansion proposed), with a projected production capacity of 300 tonnes.

11.12 Challenges

The primary reasons for the slow adaption of RAS technology are high initial investment and a long payback period compared to other aquaculture systems (Martins et al. 2010; Badiola et al. 2012). RAS requires backups like emergency oxygenation, electricity generator, vital equipment and building, which increases the initial cost. Further, the production cost of fish in RAS is higher than in conventional aquaculture systems, but the same product from both systems has to compete for the same price in the open market (Ahmed and Turchini 2021). Another major challenge is the high energy requirement in RAS. Generally, energy requirement could vary from 5 to 20 kWh for every kg of fish produced in RAS depending on species, location and system design. With the addition of temperature control (heating and cooling), energy requirements can increase further (Martins et al. 2010; Badiola et al. 2017, 2018).

Other major causes for the failure of RAS are inadequate initial planning, poor system design, operational shortcomings and lack of technical expertise. Across the globe, losses in many commercial RAS facilities have been attributed to an initial poor design, wrong design calculations, use of inferior or cheap materials for RAS construction to cut down cost, improper management (lack of training), poor or wrong equipment selections and lack of proactive response to sudden equipment failures or water quality issues (Badiola et al. 2012). It is also reported that 50% of globally surveyed RAS-based aquaculture firms had rebuilt or redesigned their RAS due to failure resulting from the poor or inadequate initial design. Therefore, it is crucial to choose the right consultant or firm to design, construct and operate RAS. One must ensure that the firm has good prior experience in designing and building RAS facilities for the targeted species with a proven track record of successful fish production.

Current RAS treatment systems mainly address ammonia, nitrite, nitrate, carbon dioxide, alkalinity, pH and oxygen levels in the water. However, the removal of minerals, drug residues and metabolites is still poorly known or understood, and these may accumulate in the system causing chronic health issues and eventually affecting the quality and safety of the fish (Davidson et al. 2009; Martins et al. 2010). Some early studies have indicated that the chronic accumulation of metabolites and metals could cause deformities and abnormal swimming behaviour in rainbow trout reared in low exchange RAS (Davidson et al. 2011). Off-flavour in RAS-reared fish is another major issue affecting consumer acceptability, market price and farm economics due to additional depuration required in current RAS designs (Davidson et al. 2014; Badiola et al. 2012). Most of the publicly available knowledge on RAS is either from experimental scale units or semi-commercial operations carried out by research institutes. Knowledge gained on commercial RAS operations and management is closely safeguarded by private industries and is not publicly available due to business interests. Further, the firm seldom reports detailed information on the cause of failures due to fear of negative publicity and consumer scrutiny (Badiola et al. 2012).

11.13 Opportunities and Way Forward

Despite the above challenges, fish production from RAS has steadily increased in EU countries in the last 10 years (29,513 tonnes in 2018, Eurostat). In Asian countries, RAS is being slowly adopted due to rising land prices and competitive limitations of water resources (Ahmed and Turchini 2021). In India, RAS technology is promoted through various government schemes and initiatives, catering to different operational scales from small (mini) to entrepreneurial pilot systems. The driving force for adopting of RAS technology could be increasing consumer awareness of fresh, safe and sustainable fish and seafood. Since RAS can be located near the market, fresh and locally produced seafood can be supplied to consumers. The environmental advantage of RAS could be another driver, as RAS is considered as a climate-smart aquaculture practice (EUMOFA 2020). Another significant opportunity that RAS provides is the controlled and secure conditions for intensive farming, which allows the culture of high-value niche market species or exotic species (Atlantic salmon, rainbow trout, seabass and shrimps) near the market, which are otherwise not possible using conventional aquaculture practices.

Globally, the energy requirement and associated costs incurred are being reduced through RAS design optimization, utilizing low-head pumps, improving biofilter performance and utilization of renewable energy resources. Heating and cooling costs can be reduced by using geothermal energy, solar energy or other renewable sources and waste heat from other industries (Badiola et al. 2012). For example, low-temperature effluent water from a fish processing industry could be used for cooling purposes in RAS (in chiller condensers) to grow cold-water species in tropical areas. Likewise, waste heat generated from diesel generators or other industries can be used for heating purposes in RAS during winter. Furthermore, the development of simple and small-scale RAS with reduced investment can be a game-changer for quicker/wider adaptation of RAS for backyard fish production in rural and semi-urban areas of developing countries (Ahmed and Turchini 2021). New biofiltration methods such as the anaerobic ammonia-oxidizing (anammox) technology, which converts TAN directly into nitrogen gas, could be a significant step to make RAS more environment-friendly while reducing the operational cost (with lower energy usage, alkalinity requirement, oxygen requirement and depuration requirement) (Martins et al. 2010).

Additionally, inducing controlled anaerobic conditions within the RAS loop could be a possible solution to ameliorate the off-flavour issue in fish flesh (Guttman and van Rijn 2008). Using effluents as fertilizer or co-digestion mixture for biogas production, RAS technology can become a net energy producer than a consumer. This biogas, in turn, can be used for heating or as fuel for electricity generation. Integration with other agricultural practices such as aquaponics and algae production (macrophytes/aquatic weeds) could improve the water quality, reduce greenhouse gas emissions and generate additional products with economic benefits (Martins et al. 2010; Badiola et al. 2012). Future research should also aim to develop hybrid technologies such as RAS with bio-floc technology (BFT) to overcome the disadvantages of one system with the advantages of the other (Kuhn et al. 2009).

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Coldwater Fish Nutrition in the Indian Himalayas

12

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Abstract

In aquaculture, nutrition, feed and feeding are critical determinants of growth, physiological homeostasis, health, survival and flesh quality of the farmed organism. Optimum nutrition is even more important for cold-water fish species because of the shorter seasonal growth window in temperate regions. In the Indian Himalayas, rainbow trout, exotic carps, snow trout and golden mahseer are some of the most prominent fish species that are cultured or captive reared, either for livelihood and food security or conservation purposes. As rainbow trout and common carp have a worldwide presence and have been the subject of extensive research over many decades, we have a detailed understanding of their feeding habits, nutritional physiology, quantitative nutrient/energy requirements, diet formulations and practical feeding strategies. In contrast, our knowledge is very limited about the nutritional requirements and practical feeding of the endemic snow trout and golden mahseer, under captive conditions. There is a serious lack of consistent and systematic studies on the nutrient-energy needs, physiological capacities and feeding strategies for almost all the endemic cold-water fish species. In this chapter, we have consolidated the available information and our own research observations about the nutrition and feeding of the above four cold-water fish species, with the focus on the expansion and diversification of aquaculture in the Indian Himalayas.

Keywords

Rainbow trout · Compound feed · Feeding biology · Nutritional requirements · Feeding management · Micronutrients · High-energy trout feed

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12.1 Introduction

For all animals, including fish, food is a fundamental necessity for the very sustenance of life. The food preferences and feeding habits of fish species are greatly influenced by its size, life stage, habitat ecology, environmental conditions and food availability. Under aquaculture conditions, nutrition and feeding play a vital role in growth, physiological homeostasis, health, survival and flesh quality of the farmed organism. Moreover, the efficiency of feed conversion into fish biomass determines the unit productivity and culture dynamics of an aquaculture enterprise. As feed accounts for more than 50% of the operational cost and bulk of the waste generated in aquaculture farms, it has major economic and environmental implications, depending on the feed management strategies (NRC 2011).

Across the Indian Himalayan region, there is a vast expanse of water resources in the form of rivers, streams, reservoirs and lakes. The inhabitant aquatic living resources have unique biological characteristics, feeding habits and environmental preferences. Among them, rainbow trout, exotic carps, snow trouts and mahseer are the most prominent species that are presently considered for aquaculture, either for nutritional security or conservation purpose. Therefore, we have consolidated available information pertaining to their food habit, nutritional requirements and feeding practices in this chapter.

12.2 Nutrition and Feeding of Rainbow Trout

Rainbow trout (*Oncorhynchus mykiss*) is the most remunerative aquaculture species in the Indian Himalayas, and its contribution towards livelihood and food security in the cold-water regions is gradually expanding. It is primarily cultured in earthen or concrete flow-through raceways or ponds in a conventional manner. At present, the total annual production of rainbow trout in India is nearly 2500 tonnes, with an average unit productivity of 10–15 kg/m^3. Compound feed for the private and public trout farms comes from the state fisheries department-operated feed mills in Jammu and Kashmir and Himachal Pradesh, as well as few commercial feed manufacturers in recent times. As trout aquaculture is heavily dependent on the quality of the feed given, the composition and physical properties of the feed, mode of preparation and application strategy are keys to success (Kamalam et al. 2020).

12.2.1 Feeding Biology

As it is a popular and widely cultured fish across the globe, there is a large number of scientific literature on the feeding habit, food preferences and nutrition of rainbow trout. By nature, rainbow trout is a high trophic-level fish, and their diet consists of zooplankton during fry stage, followed by insects, crustaceans and smaller fish as they grow older (Hardy 2002). Being carnivorous, they consume a high-protein diet and are prone to use amino acids for energy supply. Accordingly, the digestive

Fig. 12.1 Gastrointestinal tract of rainbow trout

system of rainbow trout consists of an acid-secreting stomach (J-shaped), pyloric caeca and shorter intestine that is better suited to process protein-rich animal matter (Buddington et al. 1997; Fig. 12.1). Reflecting their feeding habit, feed formulations for trout contain higher levels of protein and lipid and less carbohydrates.

12.2.2 Nutritional Requirements

The requirements for many of the dietary essential nutrients for rainbow trout have been studied and reported. A complete diet must supply all the essential amino acids, fatty acids, minerals and vitamins at required levels, to meet the physiological needs. With respect to protein, the recommended dietary levels for the ten amino acids that are commonly essential for optimum growth and nitrogen utilisation in rainbow trout are known (NRC 2011; Table 12.1). For effective utilisation of dietary protein, an optimal ratio of 57% indispensable to 43% dispensable amino acids has been reported. The dietary protein to energy (DP/DE) levels can be optimised by increasing the supply of non-protein digestible energy (DE) while reducing dietary protein levels (Bureau et al. 2002). Irrespective of dietary DP/DE ratios, the dietary energy requirement for optimal growth of rainbow trout varies from 14 to 17 MJ of DE/kg feed, depending on the body mass, rearing temperature and physiological conditions. It is well known that the energy supply from lipid is higher than that of proteins or carbohydrates. Further, dietary lipids have a proven protein-sparing effect in rainbow trout, which has led to the application of extrusion and oil-coating technologies for producing nutrient-dense trout feeds with 16–24% dietary lipid levels (Hardy 2002). Dietary lipids must importantly meet the requirement of essential fatty acids,

Table 12.1 Comparative information on the macronutrient requirements of rainbow trout, common carp, snow trout and mahseer

Macronutrients	Rainbow trout	Common carp	Snow trout	Mahseer
Digestible energy (kcal/kg)	4200	3200	NT	NT
Amino acids (%)				
Arginine	1.5	1.7	NT	NT
Histidine	0.8	0.5	NT	NT
Isoleucine	1.1	1.0	NT	NT
Leucine	1.5	1.4	NT	NT
Lysine	2.4	2.2	NT	NT
Methionine + cystine	1.1	1.0	NT	NT
Phenylalanine + tyrosine	1.8	2.0	NT	NT
Threonine	1.1	1.5	NT	NT
Tryptophan	0.3	0.3	NT	NT
Valine	1.2	1.4	NT	NT
Digestible total protein (%)	38	32	36–38	36–38
Fatty acids (%)				
18:3 *n*-3	0.7–1.0	0.5–1.0	NT	NT
n-3 LC-PUFA	0.4–0.5	R	NT	NT
18:2 *n*-6	1.0	1.0	NT	NT
Cholesterol (%)	NT	NT	NT	NT
Phospholipids (%)	NT (4–14)[a]	NT (2)[a]	NT	NT
Digestible total lipids (%)	16–24	5–15	R[b]	<5
Carbohydrates (%)	NR (15–25)	NR (30–40)	NR	NR (20–25)

NT not tested, *NR* not required, *R* required in diet but quantity not determined
[a]Values in parentheses represent requirements reported for early stages
[b]To be ascertained

phospholipids and other lipid-soluble compounds of nutritional interest (Tocher 2003). There is no dietary requirement for carbohydrates per se, but the inclusion of digestible carbohydrate sources in trout feeds can support protein-sparing and improve energy supply. The recommended inclusion level of digestible carbohydrate sources for rainbow trout is around 15–25% (Kamalam et al. 2017).

Among the micronutrients, the quantitative requirements for most of the vitamins have been ascertained for rainbow trout (NRC 2011; Table 12.2). However, there are possible interrelationships between diet composition and nutritional factors that can influence the vitamin requirements. For instance, the dietary pyridoxine requirement depends on dietary protein level, and vitamin E requirement depends on the dietary PUFA level and the peroxidation status of the lipid source (Halver 2002). With respect to targeted nutritional interventions, higher inclusion levels of different vitamins (A, C, D and E) in brooder and functional feeds could play an important role in improving reproductive competence, stress tolerance and normal skeletal development. On the other hand, information on mineral nutrition of fishes is relatively less because of the complex diet and environment interactions (Kaushik 2002). Nevertheless, the dietary requirements of trout for important macro-minerals

Table 12.2 Comparative information on the micronutrient requirements of rainbow trout, common carp, snow trout and mahseer

Micronutrients	Rainbow trout	Common carp	Snow trout	Mahseer
Fat-soluble vitamins				
A (mg/kg)	0.75	1.2	NT	NT
D (μg/kg)	40	NT	NT	NT
E (mg/kg)	50	100	NT	NT
K (mg/kg)	R	NT	NT	NT
Water soluble vitamins (mg/kg)				
Thiamine	1	0.5	21.5	NT
Riboflavin	4	7	NT	NT
Vitamin B_6	3	6	NT	NT
Pantothenic acid	20	30	NT	NT
Niacin	10	28	NT	NT
Biotin	0.15	1	NT	NT
Vitamin B_{12}	R	NR	NT	NT
Folic acid	1	NR	NT	NT
Choline	800	1500	NT	NT
Myoinositol	300	440	NT	NT
Vitamin C	20	45	NT	NT
Minerals (%)				
Calcium	NR	0.34	NT	NT
Phosphorus	0.7	0.7	NT	NT
Magnesium	0.05	0.05	NT	NT
Sodium	NR	NT	NT	NT
Potassium	NT	NT	NT	NT
Trace elements (mg/kg)				
Copper	3	3	NT	NT
Iodine	1.1	NT	NT	NT
Iron	NT	150	NT	NT
Manganese	12	12	NT	NT
Selenium	0.15	NT	NT	NT
Zinc	15	15	NT	40

NT not tested, *NR* not required, *R* required in diet but quantity not determined

(P and Mg) and trace elements (Cu, Zn, Mn, I and Se) are known. Like vitamins, additional provision of certain minerals (P and Se) maybe required according to the diet composition and husbandry conditions. With the gradual reduction of fish meal in commercial fish feeds, the dietary inclusion of minerals has assumed greater significance (Antony Jesu Prabhu et al. 2016). For example, in feeds containing high levels of plant proteins, the bioavailability of phosphorus may be limiting due to high levels of phytic phosphorus, and this should be taken into account while deciding the dietary mineral supplementation levels.

12.2.3 Practical Diets and Feeding Practices

As the nutritional requirements of rainbow trout are well defined, formulating a balanced practical feed is relatively easy. Nevertheless, feed formulations depend on the availability and supply of quality ingredients at competitive prices. At present, rainbow trout feeds in the Indian Himalayan region are generally based on fish meal and fish oil as the primary source of protein and lipid, along with selected oilseed meals, rendered animal products and cereal by-products (Table 12.3). But, in the context of sustainability and cost-effectiveness, there is a clear emphasis on reducing the amount of marine ingredients with locally derived agro-industry by-products and non-conventional feedstuffs (e.g. single-cell proteins). ICAR-Directorate of Coldwater Fisheries Research (ICAR-DCFR) is at the forefront of developing highly efficient rainbow trout feeds for different life stages, with a feed conversion ratio of 0.9–1.1, under optimum rearing conditions and feed management.

At present, feed ingredients for rainbow trout feed are selected based on their proximate nutrient and energy content, pricing and availability. Their dietary inclusion levels are further decided based on the stage of production, palatability, digestibility, biological utilisation potential and the presence of anti-nutritional factors. Globally, research efforts are in progress to evaluate alternate proteins and also to substitute fish meal with a blend of plant-derived proteins and other marine ingredients (Gatlin et al. 2007). Likewise, fish oil (the preferred source of lipid) is increasingly being substituted with vegetable oils (e.g. linseed and rice bran oil), during the grow-out phase of trout production (Turchini et al. 2009). Wheat- or rice-based carbohydrate sources are also included in trout feed formulations to help in pellet binding, stability and floatability, besides their nutritional role. To meet the micronutrient requirements, vitamin and mineral premixes are added in adequate quantities, with due consideration of losses during feed manufacturing. Also, micro-quantities of carotenoid pigments such as astaxanthin are included in trout feeds to augment flesh quality and consumer acceptance. With respect to feed production, extrusion and vacuum coating technology has aided the production of high-energy (lipid) feed with different buoyancy and physical properties (Fig. 12.2).

Feed is the single major operating cost (60–90%) in rainbow trout farming in the Indian Himalayan region. Appropriate feed management and feeding strategies are therefore critical determinants of profitability and environment impact in a trout

Table 12.3 Generalised rainbow trout feed formulation used in India

Ingredients	Inclusion level (g kg^{-1} feed)
Fish meal	400–600
Oilseed (soybean) meal	100–200
Rendered animal protein	50–100
Cereal flour/by-product	150–250
Fish/vegetable oil	100–120
Vitamin premix	2–5
Mineral premix	5–10
Binder	5–10

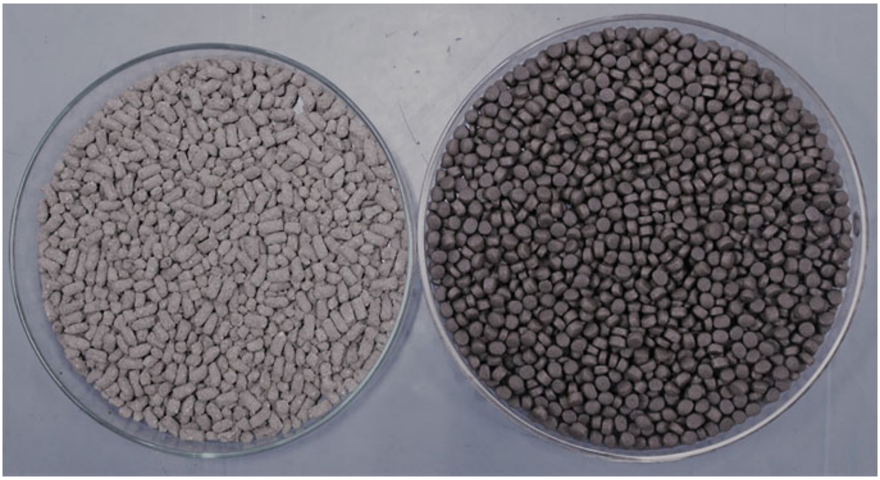

Fig. 12.2 Pelleted (left) and extruded high-energy (right) rainbow trout feeds

production unit. For example, feeding aspects such as ration size, meal frequency, feed size and method of delivery have a direct influence on growth, feed utilisation, uniformity of fish size, cost of fish production and amount of feed wastage (Kamalam et al. 2020). Moreover, feed management strategies should be planned according to the fish size and water temperature. At higher water temperature, the feed requirement is more, and at lower temperature, feeding rate decreases. Likewise, smaller (young) trout requires higher feed ration and frequent feeding than that of larger trout. Further as the trout grows, the feed particle or pellet size should be increased to suit its mouth size, in order to allow the fish to comfortably grab and swallow them (Fig. 12.3). ICAR-DCFR has developed indicative rainbow trout feeding charts to guide trout farmers in deciding the appropriate feed size, feeding rates and frequencies (Table 12.4). However, it should be noted that the feeding schedule must be adjusted as per the varying environmental and husbandry conditions in different farms. Feed delivery is presently done by manual broadcasting or hand feeding. As the scale of operation increases, the use of automatic feeders can be beneficial.

12.3 Nutrition and Feeding of Common Carp

Cyprinids, mainly carps, are the most important group of farmed fishes, which contribute the bulk of freshwater aquaculture production globally, including India. Common carp (*Cyprinus carpio*) is one of the most popular and widely cultured cyprinid fish, along with grass carp and silver carp in traditional polyculture ponds (Woynarovich et al. 2010). The combined annual production of these Chinese carps in India is nearly 0.5 million tonnes. As they tolerate a wide range of temperature (3–35 °C) and grow well at relatively low temperatures (20–25 °C), they are also

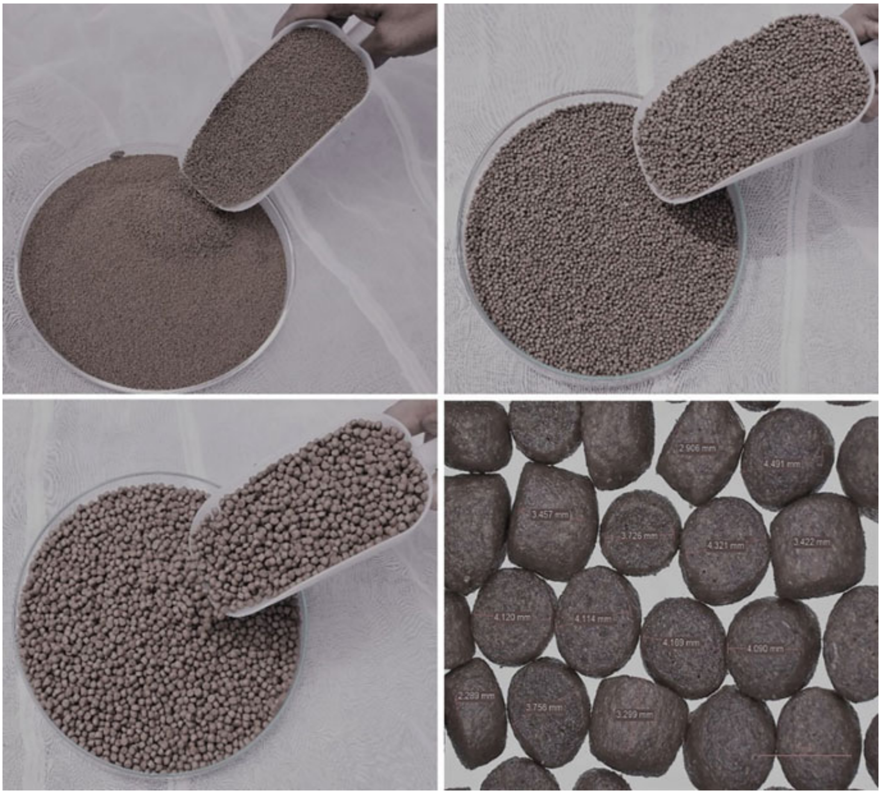

Fig. 12.3 Feed pellets of different sizes for specific life stages

farmed in the Indian Himalayan region. Though the sector is not well-organised, carp farming is taken up as monoculture, polyculture or integrated culture in irrigation ponds and tanks in the foot hills and mid-altitudes. In terms of nutrition and feeding, farm-made feed mashes (cereal bran and oil cakes) and low-cost commercial feeds are used as a supplementary feed, in addition to the natural food available in the ponds.

12.3.1 Feeding Biology

Common carp is an omnivorous fish that consumes a variety of natural foods such as zooplankton (copepods and rotifers), insects (larvae and adults), worms, fish eggs, smaller fish and aquatic macrophytes. It is an opportunistic feeder that can flexibly adapt to the available food. The food spectrum and feeding habit change with life stage. For example, as it grows, bottom feeding becomes more pronounced, and they become benthic feeders (Takeuchi et al. 2002). The common carp has a relatively large accordion-like mouth that enables their benthic feeding, two pairs of barbels

Table 12.4 Indicative feeding chart developed by ICAR-DCFR for Indian trout farmers

Fish size (g)	Pellet size (in mm)	Feed type	Feed specification (protein/lipid)	Feeding frequency (times/day)	Feeding rate (% of biomass at 16 °C)
0.1–0.2	0.3	Crumble	52/12	8–12	4.8
0.2–0.5	0.5	Slow-sinking pellet	52/12	6–8	4.2
0.5–1.5	0.8	Slow-sinking pellet	52/12	4–6	3.5
1.5–8	1.2	Floating pellet	48/16	3–4	2.8
8–35	1.8	Floating pellet	48/16	2–3	2.3
35–150	3	Floating pellet	45/18	1–2	1.9
150–500	6	Floating pellet	45/18	1–2	1.6

that help in searching for food, molar-like pharyngeal teeth to grind the consumed food and an agastric digestive tract that is completely developed only at the advanced fry stage. When water temperature is above 20 °C, common carp feeds actively; at temperatures below 15 °C, the feeding rate decreases; and below 8 °C, feeding stops and the fishes starts to hibernate in groups (FAO AFFRIS).

12.3.2 Nutritional Requirements

Similar to rainbow trout, the nutritional requirements of common carp have been relatively well investigated, and recommended values have been reported (NRC 2011). Dietary protein levels of 30–35% were found to be optimal, when digestible energy is adequately supplied. In other terms, a daily protein intake of 7 and 12 g/kg of body weight is required for efficient nitrogen utilisation and maximum protein retention, respectively (Jauncey 1982). The quantitative requirement for the ten essential amino acids has been reported through various studies (Table 12.1). Depending on the life stages, the requirements of some amino acids may change (e.g. lysine requirement decreases from 2.25 to 1.75% of the diet, as the fish grows). As in other fishes, a part of methionine and phenylalanine requirements can be spared by cystine and tyrosine, respectively. Dietary variations do not alter the whole-body amino acid composition of carp. The digestible energy content of the diet decides the overall protein and lipid requirements. Though there is not much information on the energy requirements of carp, the optimum digestible energy-to-protein ratio for maximum growth was found to be 97–116 (Takeuchi et al. 2002). As carps are omnivorous, both dietary lipids and carbohydrates can be effective energy sources. Increasing dietary lipid levels (from 5 to 15%) does not improve growth and protein utilisation, but results in higher deposition of visceral fat. With respect to essential fatty acids, carps require 0.5–1% of *n*-6 and *n*-3 polyunsaturated fatty acids for optimal growth and feed efficiency. For larval stages, the dietary supply of phospholipids and medium-chain triglycerides is important for normal development and rapid growth (Tocher 2003; NRC 2011). Compared to carnivorous fish like rainbow trout, common carp has better physiological ability (e.g. higher intestinal amylase activity) to use dietary carbohydrates as an energy source. Studies have pointed that an inclusion of 30–40% of digestible carbohydrates could be optimal in carp diets (Kamalam et al. 2017).

The quantitative requirements for vitamins and minerals have been relatively well investigated in carps and are summarised in Table 12.2. Carps do not require vitamin B_{12} and folic acid, as these vitamins can be synthesised by their intestinal microbiota. Whereas, the requirements of vitamin D and K have not been tested yet (NRC 2011). Generally, the vitamin requirements of carp could be influenced by diet composition, water temperature and fish size. For instance, carp fry requires dietary supplementation of vitamin C, but as they grow into juveniles, they begin to synthesise ascorbic acid from glucose. As in trout, the requirement of vitamin E corresponds to the dietary level of polyunsaturated fatty acids (Halver 2002). With respect to mineral requirements, as carp does not have an acid-secreting stomach, the bioavailability of minerals depends on the solubility of the supplemented form of mineral salt and other ingredients. For instance, in the case of phosphorus, mono- and dicalcium phosphates are more soluble than tricalcium phosphate. Dietary supply of other minerals such as magnesium, copper, zinc, manganese and iron is also essential for carp (Antony Jesu Prabhu et al. 2016).

12.3.3 Practical Diets and Feeding Practices

Even as there is a gradual transition from the traditional use of farm-made feed mashes to commercially prepared feeds, not much attention is given to prepare a nutritionally balanced carp feed from judiciously selected ingredients, for economic reasons. Especially in low water temperature zones like in the Indian Himalayan region, special efforts are necessary to develop and use a nutritionally adequate feed to make the best use of the suitable growing season. Carp feeds are presently prepared using oilseed meals, cereal by-products, slaughterhouse wastes and other low-cost ingredients, with very less or no fish meal and fish oil inclusion. The biological efficiency of the feed is dependent on the nutrient and energy digestibility of the ingredients used (Takeuchi et al. 2002). With the wide use of feed extrusion technology, the contribution of dietary carbohydrates (wheat, rice and maize starch sources) to energy supply has greatly increased in carps, due to higher gelatinisation levels (Kamalam et al. 2017). The reduction of anti-nutritional factors in plant ingredients, through various processes such as fermentation, thermal treatment and solvent extraction, has led to more efficient carp feeds. Distillery waste and protein concentrates from conventional/non-conventional feed resources are also increasingly being evaluated and used in commercial carp feeds. In addition to the development of nutritionally adequate feed formulations, appropriate feeding strategies are also essential to support the expansion of carp culture and enhancement of overall production in the Indian Himalayan region. Location-specific and diet-specific feeding schedule has to be developed, as feeding rates and frequencies strongly depend on fish size, water temperature and diet composition. Moreover, it is important to determine and consider the variations in natural productivity-derived nutrient input and turnover (Takeuchi et al. 2002).

12.4 Nutrition and Feeding of Snow Trout

Snow trouts are a group of cold-water cyprinid, belonging to the genus *Schizothorax*. They are widely distributed across the freshwater riverine stretches and hill streams of the Trans-Himalayan region. By nature, they are rheophilic, demersal and slow-growing. Their occurrence and distribution are determined by current velocity, water discharge, substratum, temperature and food availability. They contribute substantially to the subsistence fishery in the Indian Himalayan region and are considered to be a potential endemic candidate for species diversification in cold-water aquaculture due to their flesh quality and consumer preference (Kamalam et al. 2019; Rajesh et al. 2019). As supply from wild capture is becoming limited, there is a growing demand to develop the aquaculture of snow trout.

12.4.1 Feeding Biology

Snow trout is agastric like other cyprinids and has an inferior mouth and fleshy lips. Their feeding habit is omnivorous, and they reportedly feed on epiphytic algae, periphyton and detritus. Both vegetable and animal matters have been found in the intestine of wild-collected snow trout, with seasonal pattern of abundance. As they grow, they are said to get herbivorous tendencies, and their feeding intensity is inversely related to breeding and low temperature. Depending on the fish size and habitat, the relative gut length ranged from 1.6 to 3, and entero-somatic index ranged from 5 to 10% (Fig. 12.4; Shekhar et al. 1993; Koundal et al. 2013). The intestinal length increases with age, and the intestinal wall consists of the serosa, muscularis, submucosa and mucosa with varying thickness. The goblet cell number, intestinal diameter and height of villi decrease towards the rectum (Gargya et al. 2014). The ultrastructure of the digestive tract, liver and olfactory organs of snow trout has also been described (Mir and Channa 2010; Mir et al. 2011). With respect to the digestive tract ontogeny, mouth opening was found to occur on the third day post-hatch, and exogenous feeding commenced on the fifth day post-hatch after the morphological differentiation of the digestive tract in *S. plagiostomus* (Gargya et al. 2014). Similarly, several studies have investigated the neuropeptides, intestinal peptides and hormones (such as proglucagon, leptin, cholecystokinin, ghrelin and agouti-related protein) involved in appetite regulation and energy balance in *S. prenanti*.

Fig. 12.4 Digestive tract of snow trout (*S. richardsonii*)

12.4.2 Nutritional Requirements

Scientific studies and information on the quantitative nutritional requirements of snow trout are scanty (Tables 12.1 and 12.2). For different life stages, a dietary crude protein level of 45% was found to be optimal for growth and protein utilisation in *S. richardsonii* (Wagle et al. 2016; Rajesh et al. 2019). Through another experiment, we attempted to evaluate the optimal lipid requirement of *S. richardsonii* with graded levels of dietary lipid (3–13% with 50:50 ratio of fish oil and soy oil), but there was no significant difference in growth due to high variation between replicate tanks (Rajesh et al. 2019). Therefore, the dietary requirement of lipid for snow trout has to be ascertained in subsequent studies. With respect to micronutrients, only thiamine requirement has been reported, on the higher side, to be 21.5 mg/kg diet for juvenile *S. prenanti*, based on growth, feed utilisation, hepatic concentration of thiamine and serum transketolase activity (Xiang et al. 2016). There are no other studies or information on the macronutrient (amino acid and fatty acid), energy, vitamins and mineral requirements.

12.4.3 Practical Diets and Feeding Practices

Soybean meal was found to have the potential to replace fish meal to a variable extent (40–80%) in the practical diets for juvenile *S. prenanti*, without compromising growth, feed utilisation and immunity (Xiang et al. 2012). Similarly, soybean oil, groundnut oil and sesame oil were found to be good sources of lipid for *S. prenanti*, while sunflower oil and rapeseed oil had a negative effect on lipid metabolism (Xiang et al. 2010). The supplementation of bile acid at 75–150 mg/kg diet was found to improve the digestion, metabolism and utilisation of dietary lipids and also protected the intestinal structure and integrity in *S. prenanti* (Zeng et al. 2016). Another study showed that the inclusion of 8–18 g of oxidised konjac glucomannan per kg diet enhanced growth, feed utilisation and intestinal morphology (mucosal fold height and epithelial thickness) and modulated the intestinal microflora in *S. prenanti* (Zheng et al. 2015). Dietary supplementation of the seeds of *Achyranthes aspera* (5 g/kg diet) either alone or in combination with vitamin C (800 mg/kg diet) was found to improve growth, digestive enzyme activities, *n*-3 polyunsaturated fatty acid content, fatty acid bioconversion potential (*fads2* and *elovl5* mRNA expression) and immune system capacity (myeloperoxidase and nitric oxide synthase) and reduce lipid peroxidation in snow trout, *S. richardsonii* larvae (Ngasainao et al. 2017; Kumar et al. 2021). Similarly, the dietary supplementation of chitin at 20 g/kg diet was reported to improve growth and feed conversion efficiency in *S. richardsonii* (Mohan et al. 2009). As compared to their inorganic counterparts, the dietary addition of nanoparticulate iron and copper was found to improve growth, feed use, antioxidant enzyme activities and blood immunological indices in *S. zarudnyi* (Afshari et al. 2021). There is no substantial information on feeding practices and strategies in snow trout. We comparatively evaluated two feed ration sizes (1% and 2% of fish biomass) and alternate-day feeding and observed that growth and feed use were higher at 2% ration, while alternate-day feeding slightly improved the feed conversion efficiency in *S. richardsonii* (Kamalam et al. unpublished data).

12.5 Nutrition and Feeding of Golden Mahseer

The golden mahseer (*Tor putitora*) is an important fish species of the Indian sub-continent that inhabits the rivers, streams and lakes in the foot hills and mid-altitudes of the Trans-Himalayan region. Their attractive appearance with golden-coloured scales, large size and fierce fighting nature makes them an excellent candidate for sport fishing, and they have attracted the attention of anglers worldwide. Besides the recreational ecosystem services, they also have cultural and food value for the local Himalayan communities. However, their natural population has declined at an alarming rate due to indiscriminate human activities such as overfishing, habitat destruction/degradation, fragmentation of migration routes and introduction of invasive species. Thus, they are presently classified as an endangered fish in many Asian countries. ICAR-Directorate of Coldwater Fisheries Research has taken the lead to conserve, rehabilitate and restore the population of this fish species in the Himalayan region by developing captive maturation, breeding and rearing strategies through environmental manipulations and dietary interventions (Akhtar et al. 2018; Ciji et al. 2021).

12.5.1 Feeding Biology

Golden mahseer has an omnivorous feeding habit, and their natural food comprises microalgae, zooplankton (rotifers), insects, crustaceans, small fish and macrophytes. The food habits of this species apparently change with the seasonal food availability in the habitat and life stages. For instance, they are known to feed on diatoms at fry stage, and as they grow, there is an increase in the proportion of animal and plant matter in the diet of juveniles and adults. The dietary fraction of algae and plant matter was found to be higher during the monsoon season (Bhatt and Pandit 2016). The ontogeny and developmental kinetics of various digestive enzyme activities such as total protease, trypsin, amylase, lipase and alkaline phosphatase have been studied in 0–45 days of post-hatch golden mahseer. Mahseer larvae were reported to have the potential to digest exogenous macronutrients from early larval stages (Akhtar et al. 2013). Similarly, the histomorphological changes in the digestive tract of golden mahseer have been elaborated in larval developmental stages and also in juveniles and adults. Mouth opening and the appearance of liver and pancreas (associated digestive organs) were observed at the second day post-hatch. The appearance of anal opening, goblet cells, taste buds and epithelial stratification was observed from 3 to 5 days post-hatch. Changes in intestinal folding and the complexity of the extra-mucosal layer were found to occur continuously from larval to adult stages, indicating the progressive changes in the digestive physiology throughout the life of golden mahseer (Sharma et al. 2016). Until 35 days post-hatch, the growth, intestinal nutrient absorption and hepatic nutrient accumulation efficiency of captive-origin larvae was found to be relatively low when compared to wild-brooder progeny (Ciji et al. 2022). These observations indicate the various challenges in captive propagation and culture of golden mahseer.

12.5.2 Nutritional Requirements

As in the case of snow trout, our knowledge of the quantitative nutritional requirements of golden mahseer is very limited (Tables 12.1 and 12.2). The dietary protein requirement for the juvenile life stages (fry and fingerlings) of golden mahseer for optimal growth and feed utilisation was found to be 40–45%, based on laboratory and field studies (Hossain et al. 2002; Islam and Tanaka 2004; Sawhney and Gandotra 2010). But hitherto, no studies have been carried out on the requirements of essential amino acid and other macronutrients for golden mahseer. Information from a congeneric species (*T. tambroides*) suggests that the dietary lipid content need not be more than 5%. High lipid levels did not have any positive effect on growth, feed use efficiency and protein-sparing, but may result in visceral fat deposition in the peritoneal cavity. With respect to carbohydrates, 20–25% of dietary inclusion was found to yield good growth, beyond which hypertrophy and mild steatosis were observed in the liver (Lau et al. 2021). Among the micronutrients, only the quantitative requirement for zinc has been studied and reported to be 40 mg/kg diet for golden mahseer fry, based on growth, feed utilisation, whole body zinc retention and RNA/DNA ratio (Bhagawati et al. 2015). The requirement of all the other minerals and vitamins is yet to be studied and quantified.

12.5.3 Practical Diets and Feeding Practices

Very limited studies have been carried out on the practical diets and feeding practices to be adopted for the culture of golden mahseer. In a study that evaluated the effect of supplementary feeding of golden mahseer with a 20 and 30% protein diet in a monoculture system, the feed with the higher protein content yielded the best growth and fish yield after 150 days of culture. Interestingly, higher growth, lower feed conversion ratio (5.3–5.4 versus 7.1–9.6) and total fish production were observed during the outdoor phase of rearing, in comparison to the indoor rearing period. Irrespective of the culture conditions, growth performance (specific growth rate of 0.3–0.8%) was not promising (Islam 2002). Dietary inclusion of phospholipids (soy lecithin) at 10–20 g/kg feed was found to enhance the antioxidative enzyme activities and critical thermal tolerance limits at the upper and lower end of the temperature spectrum, but did not affect growth, survival and immune status of golden mahseer fry (Ciji et al. 2021). Similarly, feeding moderate levels of β-glucan (5–10 g/kg diet) significantly improved the survival, antioxidant status, critical thermal tolerance limits, non-specific immune responses and disease resistance of golden mahseer fry (Akhtar et al. 2021a). Moreover, dietary provisioning of β-glucan to golden mahseer brooders (5 g/kg diet) yielded progeny with improved growth, body condition, thermal tolerance and immunity, besides enhancing the sperm characteristics and antioxidative status in males (Akhtar et al. 2021b, c). When exposed to a hypoxia stressor, dietary supplementation of 300 mg of vitamin C (ascorbyl polyphosphate)/kg diet was found to enhance the activity level of antioxidative enzymes and lysozyme (immune status) in juvenile golden mahseer (Khan et al. 2019). Supplementation of vitamin C in combination with nano-selenium (0.7 mg/kg diet) synergistically improved the growth, feed efficiency, immune status and blood oxygen-carrying capacity of golden mahseer (Khan et al. 2017). In the congeneric Malaysian mahseer, palm oil was reported to be a good lipid source. Starch derived from corn and taro was found to be good sources of carbohydrates. Dietary supplementation of host-associated gut microbes (autochthonous probiotics belonging to the genera *Alcaligenes* and *Bacillus*) improved growth and intestinal structure and function (Lau et al. 2021). Till date, feeding strategies for different life stages of golden mahseer have not been evaluated and needs to be explored.

12.6 Conclusion

While we have an extensive knowledge on the nutrition and feeding of the exotic fishes (rainbow trout and common carp) that are cultured in the Indian Himalayan region, there is a serious lack of information on the nutritional requirements and feeding strategies for our endemic snow trout and golden mahseer. At present, aquaculture expansion and augmentation of fish production is dependent on the farming of rainbow trout and exotic carps, and there is a good amount of work done on the development of efficient feeds and feeding strategies. But for future species diversification and conservation of the other endemic species such as snow trout and golden mahseer, focused and meticulous research on the practical aspects of nutrition and feeding is essential for the development of their aquaculture.

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Molecular Characterization and Population Structure of the Important Himalayan Fish Species

13

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Abstract

The biodiversity hotspot, the Himalayas, is home to diverse endemic and valuable cold-water fishes that provide subsistence fisheries to the local inhabitants. In recent decades, the Himalayan fishery has been threatened directly or indirectly by several anthropogenic stressors and climate change. As a result, several economically important fish species have become endangered in the Himalayan rivers and been experiencing a reduction of genetic variability among existing stocks. Genetic diversity is directly linked to a species' ability to adapt to a changing environment and its evolutionary potential. Understanding genetic diversity is a prerequisite for its efficient utilization and the implementation of appropriate conservation measures. However, limited information is available on the current genetic diversity and population structure of the Himalayan fish species. In the present chapter, we provide insight into several molecular markers developed for the genetic characterization of important Himalayan fish species. Besides, we have also discussed the population structure of a few indigenous and exotic Himalayan species. The information has consequences for researchers attempting to study the genetic diversity and population structure of the Himalayan fish species and fisheries managers, involved in conservation measures and restoration activities.

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Genetic diversity · Population structure · Molecular markers · Mahseer · Trout · Himalayas · Conservation

13.1 Introduction

The biodiversity hotspot, Himalaya, is one of the world's richest biodiversity regions, with diversified flora and fauna (Wambulwa et al. 2021). It stretches across 595,000 square kilometres and covers a wide span of countries, including Afghanistan, Pakistan, India, Nepal, Bhutan and China. Major rivers, like the Ganges, Indus, Yarlung, Yangtze, Yellow, Mekong and Nujiang, have their origins in the Himalayas (Bandyopadhyay and Gyawali 1994). The Himalayan waters have about 203 cold-water fish species. Among these, snow trout, mahseer, minor carps, minnows, loaches and *Barilius* species are the important native species, whereas rainbow trout, brown trout, common carp and silver carp are the major non-native species (Regions and Pradesh 2016). These species form an important source of livelihood for the people of the Himalayan region. Alfthan et al. (2018) acknowledged that around 2.5 million fishers in India depend on fisheries from the Brahmaputra River for their livelihood. Recently, Gupta et al. (2020) reported that among the five Indian Himalayan states, communities or tribes such as Balti and Arghons from Jammu and Kashmir; Kinnaur, Lahules and Pangwal from Himachal Pradesh; Tharu, Bhotia, Jaunsari and Raji from Uttarakhand; Bhutia and Lepcha from Sikkim; and Apatani and Nyishi from Arunachal Pradesh are involved in various fisheries-related activities.

Despite its importance, fisheries in the Himalayan region are threatened either directly or indirectly by several anthropogenic stressors, such as overexploitation of natural resources, destruction of riverine habitat and breeding grounds, construction of dams, barrages and hydropower projects and introduction of non-native species (Gupta and Everard 2019). These pressures are further compounded by climate change (Comte et al. 2013) that poses a serious threat to the survival of many species and serves as the main factor for biodiversity changes at both gene and species levels (Cui and Graf 2009; Emel et al. 2021; Woodbridge et al. 2021). It was estimated that the pace of warming in the Himalayas is three times the world average, making the area more susceptible to the threat to biodiversity (Shrestha et al. 2012).

Accordingly, several economically important fish species have vanished from the Himalayan Rivers' downstream reaches (Gupta et al. 2020). This eventually led to a decline in genetic diversity among existing populations. These serious threats have drawn the attention of the scientific community to the urgent need to prevent further loss of fish genetic resources and to sustain the biodiversity of the Himalayan waters. For effective implementation of any conservation management program, it is not only vital to study the species richness and assemblage patterns but also the genetic diversity and population structure (Ali and Siva 2022). Of late, it has been emphasized by the Convention on Biological Diversity to recognize biodiversity conservation at all levels, from genes, population, species and ecosystems.

Diversity in genetic resources increases the opportunity of a population to adapt and survive environmental changes and increases its chances of long-term persistence. Pattern of genetic diversity across populations can deliver indications to the populations' life histories, evolutionary isolation and the presence of any desirable traits (Okumu and Çiftci 2003). Therefore, investigation of genetic diversity and population structure of the Himalayan fish species is crucial ultimately for the establishment of effective and efficient conservation practices. In this chapter, we provide an overview of the diverse, predominantly molecular approaches used in molecular characterization and population structure assessment of the important Himalayan fish species. Besides, we discuss the population structure of a few indigenous and exotic Himalayan species.

13.2 Genetic Diversity

Genetic diversity refers to the difference between the alleles of a gene, and it can be studied at the nucleotide level in the deoxyribonucleic acid (DNA) sequence. It is the result of accumulation of traits and abilities through millions of years of evolutionary processes. Estimation and documentation of these genetic variations help in understanding the forces that change their genetic composition over time (Burden 2019). The genetic blueprint, present in all organisms, is the source of genetic diversity and polymorphism, which is due to the difference in their nucleotide sequences. However, there are certain evolutionary forces like 'mutation' and 'genetic drift' which are responsible for the genetic variations in the population. Mutation is the base pair substitution in the nucleotide sequences that contribute towards the genetic variation among individuals at the species or population level, while genetic drift, i.e. a random change in gene frequencies, causes loss of alleles in the population. To measure the genetic variability and population structure at the individual or population level, a number of important population genetic parameters need to be assessed (Gillespie 2004). There are a number of morphological, biochemical and DNA-based markers that can be utilized to find out the genetic difference at the morphological and molecular levels and can be expressed as a dendrogram, a percentage of polymorphic loci and genetic distance (Lewontin and Hubby 1966). Among these, morphological and biochemical markers were used as the traditional step in determining the genetic diversity of a particular germplasm. Morphological marker measures the genetic diversity indirectly and inferentially via controlled breeding and performances records or by standard systematic inspection of phenotypic traits (Okumu and Çiftci 2003). However, DNA-based markers are preferred over the traditional approaches as molecular markers are not affected by ecological influences or the developmental stage of the fish species (Kumar et al. 2022; Kumawat et al. 2015). Availability of different DNA-based markers like randomly amplified polymorphic DNA (RAPD), restriction fragment length polymorphism (RFLP), amplified fragment length polymorphism (AFLP), mitochondrial DNA (mtDNA), microsatellite, single nucleotide polymorphism (SNP) and expressed sequence tags (EST) provides valuable information in the areas of fisheries in particular, stock structure analysis, taxonomy and systematic as well as phylogenetic relationship (Liu and Cordes 2004; Schulman 2007). Among the Himalayan fish species, the widely used molecular markers to assess genetic diversity include RAPDs, AFLPs, mitochondrial DNA and microsatellite markers (Singh et al. 2011; Sharma et al. 2019b; Vasave et al. 2014).

13.2.1 Golden Mahseer (*Tor putitora*)

The golden mahseer, *Tor putitora*, is a principal sport fish as well as food fish in the family Cyprinidae (Akhtar et al. 2018). The species is endemic to Asia region with a distribution range extending from Hindukush-Kabul-Kohistan to Sadiya (Brahmaputra) river in the Himalayas (Nguyen et al. 2008). The species inhabits the natural running waters and semi-lacustrine waters in the Himalayan region and migrates upstream in rivers with rocky bottoms for breeding (Jaafar et al. 2021). *T. putitora* reaches a maximum length of 275 centimetres and a maximum body mass of 54 kilogrammes; it is sexually dimorphic, with females being larger than males (Bhatt and Pandit 2016). There is great demand for the fish in the Himalayan region because of its culinary quality, nutritional value and fighting trait (Khare et al. 2014). In recent years, the golden mahseer populations have been under considerable pressures due to overexploitation, loss of habitat and climate change. As a result, the species has been categorized as an 'endangered' species in the IUCN Red List (Pinder et al. 2019; Akhtar et al. 2017).

Although the phased migration pattern observed in the golden mahseer is expected to contribute in panmixia, the recent modification of mahseer habitats, development of dams/barrages and other anthropogenic events in Himalayan rivers, leading to inadequate dispersal ability, unidirectional migration and isolation of habitats, act on mahseer natural populations and shaped the population's genetic structure (Yadav et al. 2020). Therefore, it is crucial to understand the stock structure and genetic diversity of *T. putitora* throughout its natural range (Singh et al. 2011). Nevertheless, this may not be practical until the present taxonomic uncertainties are resolved and adequate polymorphic markers for the generation of genetic data are identified (Sahoo et al. 2013).

The taxonomic uncertainties in mahseer are mainly due to the absence of morphometric information in the original description, the existence of insufficient holotypes, indiscernible morphological variations in them and disputes in identifying particular morphological features (Laskar et al. 2013). In this context, genomic approaches play an indispensable role in complementing conventional taxonomy and eliminating taxonomic ambiguities. Recently, mitochondrial DNA sequences have been proposed to be adequate to distinguish closely related species due to their faster rate of evolution. In mahseer, the commonly used mtDNA genes include cytochrome c oxidase subunit I (COI), cytochrome b (Cytb), D-loop, ATPase6/8 gene and large subunit ribosomal RNA (16 S rRNA) (Jaafar et al.

2021). The majority of the studies employing these markers focused on resolving the species dilemma, understanding phylogenetic relationship and assessing the genetic variations, population structure, gene flow and demography of the geographically isolated mahseer species and populations (Jaafar et al. 2021; Khare et al. 2014; Laskar et al. 2013, 2018; Nguyen et al. 2008; Sati et al. 2015; Yadav et al. 2020). For example, using Cytb and ATPase6/8 gene sequences, Sati et al. (2015) have analysed the genetic differences among seven geographically isolated golden mahseer population, namely, River JiaBhoreli (Assam), River Satluj (Himachal Pradesh), River Beas (Himachal Pradesh), River Kosi (Uttarakhand), Walwhan dam (Maharashtra), River Chenab (Jammu & Kashmir) and River Ravi (Jammu & Kashmir), and found that River JiaBhoreli population was genetically different from other six populations.

In addition to the mitochondrial genes, genetic diversity and population structure of mahseer have also been studied using microsatellites (Bhatt and Pandit 2016). Microsatellites are the most extensively utilized markers for conservation genetics, molecular ecology and population genetics research in non-model species. They are codominant, extremely polymorphic and apparently neutral markers in wild populations (Okumu and Çiftci 2003). Nevertheless, developing species-specific microsatellite markers is often costly and time-consuming. Thus, utilizing cross-species microsatellite markers between closely related species is a general approach for mitigating these expenses. Accordingly, Mohindra et al. (2004) studied cross-species amplification of 32 primer pairs developed for three cyprinids (*Catla catla*, *Cyprinus carpio* and *Barbus barbus*) and identified seven polymorphic microsatellite DNA loci suitable for *T. putitora*. Later, Singh et al. (2011) have characterized 26 polymorphic single-locus microsatellite loci-specific for *T. putitora* with the fast isolation by AFLP of sequences containing repeats (FIASCO) procedure. Subsequently, Sahoo et al. (2013) identified 12 highly polymorphic microsatellite loci from a partial genomic library of *T. putitora*. However, limited studies have utilized these highly polymorphic microsatellite loci to study the genetic structure of different mahseer populations in the Himalayan region. Recently, Yadav et al. (2020) documented a structuring pattern in the golden mahseer populations at the microsatellite level and identified that there are close genetic linkages among the Bhagirathi and Ganga mahseer populations, while Alaknanda and Yamuna populations are genetically distinct. Likewise, Sahoo et al. (2013) have assessed *T. putitora* from two different populations of the River Ravi and the River Kosi, Ramnagar, using 12 microsatellite markers. Later, Kumar et al. (2014) have assessed the genetic variation among three riverine populations (River Beas, Satluj and JiaBhoreli) using eight microsatellite makers.

Overall, these studies showed that there is a considerable gene pool mixing in populations with unrestricted dispersion and open migration routes; yet, there were significant genetic relationships among certain studied populations owing to the absence of active migration. Hence, a recent study recommended the development of microscale protected areas near golden mahseer breeding grounds and constructing fish passages to ensure migration and sustain gene flow (Yadav et al. 2020).

13.2.2 Chocolate Mahseer (*Neolissochilus hexagonolepis*)

The chocolate mahseer *Neolissochilus hexagonolepis*, a member of the family Cyprinidae, is a promising candidate species for the aquaculture. It is a common species in India's Northeast area and has been recorded extensively in Southeast Asia (Sharma et al. 2019a). It usually prefers rivers and streams of upland regions of the Himalayas. The natural population of this fish has fallen substantially over the previous few decades, and it is now classified as a near-threatened species (Sharma et al. 2019b). Nevertheless, conservation and management measures are yet to be implemented in the Himalayan region. The severe loss of this species may be attributable to the destruction of natural habitat, hydrodevelopment projects and fishing pressure. However, the hatchery raised *N. hexagonolepis* has not been stocked to improve stock production. Additionally, the degrees of genetic diversity, population divergence and changes in the abundance of wild populations are mostly unexplored.

Neutral molecular markers often employed in conservation genetic investigations have been developed for *N. hexagonolepis*, such as the mitochondrial genome (Sahoo et al. 2015) and microsatellites (Sharma et al. 2019b). The mitochondrial genome of the chocolate mahseer is 16,563 base pairs in length and composed of 13 protein-coding genes (PCG), 22 transfer RNAs (tRNA), 2 ribosomal RNAs (rRNA) and 1 regulatory region. Using the mitogenome, Sahoo et al. (2015) analysed the phylogenetic relationship among the other cyprinids and found that the chocolate mahseer belonged to the same clade of mahseer group of fishes but then distinct from the genera *Barbus* and *Acrossocheilus*. Using mitochondrial genes (CoxI, Cytb and ATPase 6/8), Sharma et al. (2019a) have surveyed the genetic diversity and population structure of nine populations from different drainages of Northeast India. The study identified six genetically different chocolate mahseer populations in the Northeast regions of India and advised considering these six groups as different evolutionary significant units while applying any conservation measures. In particular, the research suggests using the populations from the Dikrong, Sankosh and Umiam rivers as founder populations for a hatchery to retain sizeable genetic diversity in the descendent populations of chocolate mahseer.

Later, applying next-generation sequencing, Sharma et al. (2019b) have developed 25 species-specific microsatellite markers and analysed the genetic diversity among seven wild chocolate mahseer populations in Northeastern India. Here, the research found five main groups that may be regarded distinct conservation units while forming any management measures. Additionally, the migration study determined that there is no active movement between these populations. Finally, the research showed that two populations from the rivers Dikrong (Arunachal Pradesh) and Umiam (Meghalaya) had a significant level of genetic diversity. These populations may be used in the breeding programme to produce descendant populations with significant genetic diversity.

13.2.3 Snow Trout (*Schizothorax richardsonii*)

Snow trouts which belong to the subfamily Schizothoracinae are the abundant and diversified ichthyofauna in the Himalayan region. They inhabit fast-flowing snow-fed streams and lakes and have high ability to different Himalayan environments with high altitude and low water temperature (Ma et al. 2020). Almost 28 species of snow trouts have been listed in the Himalayan and sub-Himalayan regions (Rehman et al. 2020b). Among these, *S. richardsonii* is an important part of the local subsistence fisheries in the Central Himalayan region and is slowly getting more attention as a possible candidate for aquaculture (Kamalam et al. 2019; Tandel et al. 2021). In recent years, natural populations of the species have been under considerable fishing pressure. River valley modifications, destructive fishing practices and exotic salmonid introductions have likely led to a decline in population size of the species. Furthermore, studies have estimated that the fish would lose its habitat by 16% in the next 30 years (Sharma et al. 2021). In spite of the great commercial and recreational value of the species, levels of genetic diversity, population differentiation and trends in abundance of wild populations remain largely unexplored.

In recent decades, various molecular markers such as complete mitochondrial genome (Goel et al. 2015a, b, 2016; Sahoo et al. 2015a, b), 12S and 16S ribosomal RNA (Rehman et al. 2020a, b), cytochrome b (Barat et al. 2012; Chen et al. 2017), ATPase 6/8 and COI gene sequences (Ali et al. 2014; Chandra et al. 2012; Wang et al. 2019), RAPD (Vasave et al. 2014) and microsatellite loci (Barat et al. 2011) markers have been utilized to unravel taxonomic ambiguity and the extent of genetic variation and phylogenetic relationship among *Schizothorax* species. However, studies that focus on the population structure and genetic variability of snow trout (*S. richardsonii*) are limited. To date, only a single genetic study describing a very close genetic relationship among five geographically isolated populations of *S. richardsonii* based on ATPase 6/8 and COI gene sequences is available (Ali et al. 2014). Besides, eight EST-derived microsatellite markers (Barat et al. 2010) and five heterologous microsatellite loci derived from closely related species (Barat et al. 2011) are available for future population genetic studies of the Indian snow trout. In the future, further studies utilizing these markers are required to know the genetic diversity and population structure of *S. richardsonii*.

13.2.4 Rainbow Trout (*Oncorhynchus mykiss*)

The rainbow trout (*Oncorhynchus mykiss*) is a member of salmonid family and native to Pacific coasts of North America and west to the Kamchatka Peninsula and Okhotsk Basin of Russia (Ward et al. 2003). The species have been widely introduced all over the world and is most successful in terms of establishing self-sustaining populations outside its native range (Crawford and Muir 2008). The global introduction of trout was basically aimed for hatchery stocking programme and seed stocking in natural environment for recreational purposes (Gall and Crandell 1992). In Indian Himalayas, rainbow trouts were transplanted from Europe primarily to develop sports fishing or recreational angling (Mitchell 1918; Jhingran and Sehgal 1978; Gopalakrishnan et al. 1999). The rainbow trout was successfully established in Kashmir, and from here the species was transplanted to different regions of the Western and Central Himalayas (Jhingran and Sehgal 1978). Rainbow trout also remained an important species for aquaculture production in almost all regions of the world (Fornshell 2002; Woynarovich et al. 2011).

Different types of improved strains of rainbow trout, targeting economically important traits (e.g. growth rates, disease resistance, age at maturity, flesh quality, time of spawning, etc.) have been developed through selective breeding programmes in different countries (Gjedrem 2000). These strains are under cultivation at different farms in Europe, and therefore, microsatellite markers have been used to assess levels of genetic variability and differentiation among the 12 rainbow trout strains reared in Northern and Eastern Europe (Gross et al. 2007). The study using ten microsatellite loci indicated that genetic diversity present in the Northern European strains was comparable with North American domesticated strains and wild populations, while the Eastern European strains have significantly lost their genetic variability (Gross et al. 2007). It also emphasized the potential of microsatellite markers in assessing the genetic structure of different populations as well as its utility in identifications of origins of strains. Since the species have been introduced in most of the countries more than 100 years back and further transplanted in different regions passing through different farms, it was essential to assess the genetic structure of the different stocks present in respective countries. For example, Australian rainbow trout largely originated from New Zealand and that itself introduced from California, USA (MacCrimmon 1971; Clements 1988), further there were minor introductions that took place in different farms originating from freshwater river and lake strains of rainbow trout (Ward et al. 2003). Therefore, West Australian stocks of rainbow trout were assessed for levels of genetic variation using ten microsatellite loci. The study clearly reflected the high level of genetic differentiation among the four populations of West Australia. Further the study also compared the stocks with the original stocks of California, USA, and found that some of the West Australian populations were considerably less variable than North American populations and reduction in variation has been attributed to about 100 years of isolation and genetic drift (Ward et al. 2003). Iran is presently the leading producer of rainbow trout in the world (FAO 2020), and the trout was introduced in 1960 from various European sources, including Denmark (MacCrimmon 1971; Crawford and Muir 2008). Genetic variation of rainbow trout strains introduced into Iran from different countries was assessed using microsatellite (Yousefian et al. 2012).

In India, rainbow trout is the prime species for commercial cold-water aquaculture and widely cultured in western Himalayan regions (Singh 2020). The genetic variability among the different stocks of rainbow trout in India was assessed with 15 microsatellite markers that revealed the genetic status of different stocks (Barat et al. 2015). Interestingly, the study revealed that the stock located in the Peninsular India was quite distinct from other stocks present in the central and western Himalayan regions of India. The peninsular stock of rainbow trout being the oldest and remaining isolated since its introduction had a low level of genetic variation compared to the other Himalayan stocks (Barat et al. 2015). Molecular markers have also been used to investigate the hybridization and introgression between the different trout species (Young et al. 2001). However, studies related to genetic variability between wild and farmed populations in Himalayan regions are still lacking. Further, there are probabilities that hybridization might have occurred between rainbow and brown trouts, since both the species have been introduced into the natural streams of Himalayan region for angling and sports. The introgressive hybridization between native and introduced species of trout has been widely examined in other parts of the world (Young et al. 2001; Al-Chokhachy et al. 2014; McKelvey et al. 2016); however, no such endeavour has been made to examine the probable hybrids of trout in the Himalayan waters that is essentially required for setting the conservation guidelines (Allendorf et al. 2001).

13.2.5 Brown Trout (*Salmo trutta fario*)

Brown trout *Salmo trutta fario*, which belongs to Salmonid family, is recognized as a single polytypic species with a facultative migratory character and flexible life history, making the species highly adaptable to different environments (Hoar 1976). The genus *Salmo* is composed of only two species *Salmo trutta*, the brown trout, and *Salmo salar*, the Atlantic salmon (Smith and Stearley 1989). The brown trout is native of Iceland and the northern coasts of Europe and further extended to the countries fronting the Mediterranean Sea up to Northern Africa and eastward from the Atlantic drainages towards the northern slopes of the Himalayas (MacCrimmon and Marshall 1968). Brown trout has been introduced in different parts of Europe (Thibault 1983), Australia (Frost and Brown 1967), New Zealand (Hobbs 1948), Canada, USA, Japan and other Asian countries including India (MacCrimmon et al. 1970). The primary interest of such introduction remained angling, and the species established successfully in 24 countries; however these introductions also had certain repercussions on the native fish fauna (MacCrimmon and Marshall 1968; Jackson and Williams 1980; McIntosh and Townsend 1995). Earlier attempt to introduce European brown trout in Nilgiris, India, which was made in 1863, remained unsuccessful. Later, the successful introduction of brown trout ova of European origin was made in 1889 in the state of Kashmir, India (MacCrimmon and Marshall 1968) and from here the species was further introduced to other western Himalayan regions of Himachal Pradesh and Uttar Pradesh (Jones and Sarojini 1952). Presently, the brown trout is mainly confined in the western Himalayan Rivers of Himachal Pradesh and Kashmir and parts of Central Himalayan rivers of Uttarakhand and a few streams of Northeastern Himalayas in India. Around the world, there are diverse populations of brown trout that exists having extensive inter-population genetic variability, and estimation of this genetic heterogeneity is a fundamental requirement for correct interpretation of ecological importance, rational management and conservation of this and other salmonid species (Ferguson 1989). Brown trout also remained a favourable species for aquaculture and sports and therefore historically occupied different watersheds that generated intricate genetic structure (Krieg et al. 1992; Quillet et al. 1991; Bernatchez 2001).

In France, the species was widely introduced for angling and sports into the natural ecosystems with captive-reared fish. Bohling et al. (2016) studied genetic diversity and population structure of domestic brown trout (*S. trutta*) in France, using microsatellite markers and measured relative fitness of different strains from various aquaculture farms. Recently, genetic diversity of domestic brown trout stocks in Europe was assessed using microsatellite markers which revealed the origin of different stocks across Europe as well as the level of high genetic polymorphism of most hatchery strains (Berrebi et al. 2021). The complete mitochondrial genome of brown trout from Indian Himalayan region was characterized, and its phylogeny was studied which is useful for its identification and conservation (Sahoo et al. 2016). The size of the mitochondrial genome was 16,677 bp and was composed of 13 PCG, 22 tRNAs, 2 rRNA genes and 1 putative control region (Sahoo et al. 2016). However, there is a further need to study the genetic structure of different populations of brown trout in Indian Himalayan regions using different molecular markers for quantifying the genetic variations in wild and hatchery stocks.

13.2.6 Hill Trouts (*Barilius* spp.) and Other Himalayan Species

In addition to the above-mentioned species, few indigenous hill stream Himalayan fishes, including *Barilius bendelisis*, *B. vagra*, *Cyprinion semiplotum* and *Garra* species, have been studied at the population level (Kalita et al. 2020; Kumar et al. 2021; Sharma et al. 2020). The species of the genus *Barilius* are usually referred as hill trout. These minnows occupy both shallow lentic and lotic waters in the Himalayas. Recent truss-based morphometric analysis performed on six different populations of Alakanda (Ganga River basin) and Chenab River (Indus River basin) drainages of Himalaya found phenotypic plasticity among them. The observed evident separation of *B. vagra* populations across two physically distinct river basins in the Indian Himalaya emphasizes the need for distinct conservation and management techniques to guarantee the future sustainability of the stock (Kumar et al. 2021).

Similarly, there are a few studies available on the population structure of *B. bendelisis* (Kumar and Singh 2019; Mir et al. 2015; Sah et al. 2011). These studies have used both truss morphometric and molecular data (cytochrome b) to find the level of genetic differentiation among different *B. bendelisis* populations from geographically isolated rivers including Saryu, Kalsa, Kosi, Alaknanda, Chenab Gaula and Mandakini. Overall these studies found significant phenotypic heterogeneity between the geographically isolated regions of Central Indian Himalaya (Mir et al. 2015). Apart from this, the evolutionary divergence and molecular phylogeny of *Barilius* spp. have also been studied using neutral mitochondrial 16S rRNA gene and established adequate information to differentiate the five *Barilius* species, *Barilius bakeri*, *B. gatensis*, *B. vagra*, *B. bendelisis* and *B. tileo* (Singh et al. 2015).

The Assamese kingfish (*Cyprinion semiplotum*), belonging to the family Cyprinidae, is native to Southern Asia and has a restricted range in the Eastern Himalayan region. It is a significant source of food as well as ornamental industry, thus livelihood to the local people. The species has a complex taxonomic history; hence Sharma et al. (2020) characterized 16,671 base pairs of long complete mitogenome of *C. semiplotum* and identified its taxonomic position by reconstructing the most comprehensive phylogenetic trees of Cyprinidae using the entire mitogenome. Moreover, the study also identified a distinctive 90 bp insertion in 3′ periphery of the control region, which can be used for the identification of the species at the population level. Recently, Kalita et al. (2020) studied the genetic diversity of this vulnerable fish from three distinct rivers, namely, Siang, Lohit and Tirap, in Arunachal Pradesh, India, using mitochondrial DNA and inferred that *C. semiplotum* stocks in Northeast Indian region have minimal genetic differentiation. Further, the research also proposed to view these groups as a single panmictic population.

13.3 Conclusion

The Himalayan region is experiencing rapid environmental change, but impacts on aquatic biodiversity are yet to be assessed on different scales. A variety of forces act on its natural fish populations to shape complex patterns of genetic structure. Although few genetic studies have been reported in the Himalayas, they mainly focused on the characterization of molecular markers, resolving taxonomic ambiguities and understanding the phylogenetic relationships. Also, most of these studies were performed a decade ago. The Himalayan fish's genetic diversity and population structure might have changed over the past 10 years. Therefore, genetic diversity and population structure assessment is necessary to elucidate the present genetic level, patterns of dispersal (connectivity) and demographics (past and present). Hence, to ensure the long-term sustainability of the endangered Himalayan fishes, we recommend that special immediate attention may be given to the rapid development of additional novel molecular markers and the incorporation of conservation genetics in future recovery programmes of the endangered Himalayan species. Finally, we also recommend the establishment of microscale protected areas near the breeding grounds of endangered species and construction of fish pass wherever necessary to ensure migration to maintain gene flow. Information consolidated in this chapter will serve as a ready reference for researchers, policy makers, managers and other stakeholders attempting to study the genetic diversity and population structure of the Himalayan fish species for devising conservation measures and restoration activities at various levels of governance/management.

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14

Prospects and Challenges of Molecular Interventions for Enhancing Aquaculture Production in the Temperate Himalayas

Neetu Shahi and Sumanta Kumar Mallik

Abstract

Global harvest of aquatic biota which includes flora and fauna both, through capture fisheries has already reached its maximum potential, or has shown offshoot in some cases. Capture fisheries is now stagnant, and therefore, in order to fulfil the need for growing worldwide population, culture fisheries have come up with a promising way. To further increase the production and sustainability of culture fisheries, various tools and techniques of biotechnology can be used. Aquatic biotechnology, which has both basic and spin-off applications, can help aquaculture producers increase output, efficiency, profitability, and sustainability. Genomic and proteomic research such as whole genome sequence (WGS) and marker-assisted selection (MAS) of economically important cultured fish could have an impact on fish genetic resource development and management as well. In genetically modified (GM) and gene knockout (GKO) fishes, economically important features such as improved growth, enhanced muscle mass, cold tolerance and disease resistance can be further improved. Cryopreservation of gametes (sperms and eggs) and embryos could open up new commercial possibilities for endless seed and fry production, as well as healthier and better-conditioned fish and brood stock management. It could also help with ex situ genome conservation in threatened and endangered species. Biotechnological interventions in intensive aquaculture have shown a considerable potential in using bioremediation and probiotics to regulate effluents, toxicants, and pathogens in the environment. Therefore, molecular tools can be used to minimize the impact of intensive aquaculture in environmental pollution.

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14.1 Introduction

Aquaculture is a growing industry globally, as a source of income and easily digestible protein-rich food. But over the last few decades, due to growing global population, aquaculture has shifted from extensive farming to intensive farming. In intensive farming the fishes are stocked at higher density, and therefore, the production enhances tremendously. However, intensive farming also leads to several serious issues such as disease outbreak and effluent generation, which leads to environmental pollution.

Aquaculture in India, Nepal, and Bhutan is practiced based on many fish species such as common carp (*Cyprinus carpio*), brown trout (*Salmo trutta*), rainbow trout (*Oncorhynchus mykiss*), chocolate mahseer (*Neolissochilus hexagonolepis*), and minor carps (*Labeo* spp.). The type of fish, cultured in this region, depends upon the availability of water, topography, availability of seed and the climatic conditions. In India, rainbow trout is the most widely cultured fish species in temperate Himalayan region, followed by common carp and chocolate mahseer. The temperate Himalayan region of India stretches over 2500 km from Arunachal Pradesh to Jammu and Kashmir and 200–400 km from north to south. The principal sources of cold water include upland streams, rivers, high and low altitude lakes, and reservoirs in various hill states. In these regions, rainbow trout and common carp are the most widely cultured food fish species, depending upon the altitude, climatic condition, geography, infrastructure, and resource availability.

Molecular biology provides tremendous tools for developing sustainable, environment-friendly, economically viable, and feasible global aquaculture output. Increased public demand for fish as a protein-rich food and declining capture fisheries have prompted scientists to investigate how biotechnology can boost aquaculture productivity, making aquaculture a topic of great interest. To increase productivity and improve quality, scientists can use biotechnology tools to detect and combine economically important features in fish and shellfish. One example of the economically important trait is enhanced growth rate and disease resistance in fish species, used in aquaculture. Therefore, looking into the genes that promote the synthesis of natural fish growth hormones and natural defensive chemicals is always desirable. In case of aquaculture, enhanced coloration and unique-looking fish are desirable. Therefore, fluorescent fish or glow fish has high market demand than the normal-looking fish. However, it should always be kept in mind that current biotechnology should be utilized in conjunction with traditional technologies rather than as a replacement and that their use should be guided by need rather than the greed.

The need for aquaculture produce is high, and biotechnology can help meet that demand. Aquaculture, like other biotech-based products, will be rigorously vetted before being released to the public. The benefits, promised by developing technologies, would not be realized without a consistent investment to basic research. Synthetic hormones in induced reproduction are one of the biotechnology applications in cold-water aquaculture.

14.2 Biotechnology in Fish Breeding

Several fish species reach maturity but do not breed when kept in confined water bodies such as ponds and tanks. As a result, induced breeding techniques for producing high-quality and abundant cultured fish seed have been developed. It is one of the most reliable methods of producing pure seed of desired fish species. As a result of their efficacy and convenience, synthetic spawning hormones are increasingly being used. Pituitary gonadotropic hormone was purified from murrel and catla for the first time. When administered alone or with carp pituitary, antuitrin-s, leutocyclin, and LH-RH were ineffective. The Central Inland Fisheries Research Institute in Barrackpore, India, conducted extensive research using LH-RH alone or in conjunction with progesterone; breeding success rates ranged from 25 to 49% in carps to 100% in catfishes. The most extensively utilized biotechnological technology for induced breeding in fish is gonadotropin-releasing hormone (GnRH). In all vertebrates, the fundamental regulator and central initiator of the reproductive cascade is GnRH (Battacharya et al. 2002). It is a decapeptide, discovered in the hypothalamus regions of pigs and ships. One type of GnRH has been identified as the sole neuropeptide responsible for LH and FSH synthesis in the most placental mammals, including humans. It should be noted that LH-RH alone is ineffective in inducing fish spawning. The Linpe technique is a highly successful approach that induces ovulation and spawning in farmed fish by combining LH-RH-a (GnRH-a) with a dopamine antagonist. Syndel Laboratories, Inc. of Vancouver, British Columbia, Canada, has marketed this technique, under the trade name Ovaprim. There have been reports of rohu, mrigal, and catla successfully spawning with LH-RH analogues and 100% ovulation with pimozide at 10 mg/kg body weight.

In non-mammalian animals (excluding the guinea pig), 12 GnRH variants have been physically described, with seven or eight distinct forms separated from species of fish (Halder et al. 1991). The same advancement of GnRH technology has now enabled the successfully induced breeding in fish. There are several synthetic hormones, which are currently being widely used in induced breeding. Examples are HCG (human chorionic gonadotropin) hormone; Ovaprim, ovatide, synahorin (CG and mammalian pituitary gland mixture), and ovapel are the most widely used inducing agents. Among all these, Ovaprim is the most widely used synthetic agent in India for induced spawning of fish, including carps. These synthetic hormones are superior to pituitary extract in its performance and are easily available with fish vendors. The dose depends upon the species and sex of the fish. For carps single dose is given for induced spawning. Similarly, indigenous preparations such as Ovatide

(M/s. Hemmopharma Ltd., Mumbai) and WOVA-FH (M/s. WOCKHARDT Ltd., Mumbai) are widely utilized in India for carp and other fish spawning.

The following is the dose of various spawning agents (Ovaprim, Ovatide, WOVA), which can be used in fishes:

Females:

- Catla: 0.4–0.5 mL/kg body weight.
- Rohu: 0.3–0.4 mL/kg body weight.
- Mrigal: 0.25–0.3 mL/kg body weight.
- Fringe-lipped carp: 0.3–0.4 mL/kg body weight.
- Catfishes: 0.6–0.8 mL/kg body weight.
- Males (all carp species): 0.1–0.3 mL/kg body weight.
- Male (catfish): 0.15–0.4 mL/kg body weight.
- Silver carp: 0.4–0.7 mL/kg body weight.
- Grass carp: 0.4–0.8 mL/kg body weight.
- Bighead carp: 0.4–0.5 mL/kg body weight.
- Mahseer: 0.6–0.7 mL/kg body weight.

14.3 Genetically Engineered Fish/Transgenic Fish

Transgenesis or transgenics is the process of introducing a foreign gene or DNA into the host genome, resulting in its stable integration, transmission, and expression. For the first time, transgenic mice were generated by introducing the metallothionein human growth hormone fusion gene (MT-hGH) into mouse eggs, resulting in considerable growth. This generated a flurry of gene transfer research in commercially important fish species.

China created the first transgenic fish (Zhu et al. 1985). The method has now been used to successfully treat a variety of fish species. This method has resulted in dramatic growth enhancement, particularly in salmonids.

Currently, around 35 species of cultured fish species including trout, catfish, salmons, striped bass, tilapia, and flounder are genetically modified. These fish species are being genetically modified to have traits that make them more suitable for large-scale intensive farming, such as better growth, disease resistance, more muscle, and tolerance to extreme temperatures. The genes, used in these genetically modified fish, come from a range of organisms, including other fish, bacteria, coral, mice, and humans. FDA has approved the transgenic salmon, AquAdvantage salmon, produced by AquaBounty Technologies in year 2015. The same company is also developing transgenic tilapia and trout for commercial aquaculture. In other parts of the globe, researchers are also working on transgenic salmon and tilapia. GMO technique can be used to enhance the growth of several slow-growing cold-water fishes such as snow trout and mahseers.

The introduction of transgenic technology has also increased the requirement for sterile offspring production. This would clearly be beneficial, allowing for optimal transgenic stock growth and controlled reproduction while assuring that any escaping fish would be unable to reproduce. For some years, fish transgenics researchers have been studying how to improve fish resilience to freezing temperatures (Fletcher et al. 2001). Cold-water temperatures stress many fish, and only a few can tolerate below 0 °C. This is a major issue in fisheries especially in cold climates. Some marine teleosts have high levels of serum antifreeze proteins (AFP) or glycoproteins (AFGP), which effectively lower the freezing temperature by preventing the formation of ice crystals. The winter flounder hepatic AFP gene was effectively transplanted into the genome of Atlantic salmon, where it was taken into the germ line and subsequently passed on to the offspring F3, where it was largely expressed in the liver. Developing stocks, expressing this gene, might be tremendously advantageous in commercial aquaculture in places where winter temperatures consistently approach these species' physiological limitations.

These can be used for common carp, allowing them to be farmed in the extreme cold of the Himalayas. Developing embryonic stem cell (ESC) technology is without a doubt the most potential technique for future transgenic fish production. This would make it simple to add and remove genes on a regular basis. Despite tremendous progress in a number of laboratories around the world, a number of challenges remain before transgenic brood stock for aquaculture can be commercialized.

14.4 Production of Sterile Offspring

Transgenic technology has also increased the importance of producing sterilized offspring to reduce the risk of genetically modified stocks combining in wild species. Technology advancements have increased the possibility of producing sterilized fish or fish whose breeding action could be particularly transformed on or off, using transcriptional promoters. It would have also been extremely valuable, allowing for optimal development and limited reproduction of transgenic stocks while ensuring that any escaping fish could not reproduce. For some years, researchers in fish transgenics have been exploring enhanced tolerance to low temperatures (Fletcher et al. 2001).

14.5 Taping Potential Role of Kisspeptin in Sexual Maturity and Reproduction of Reproductive Dysfunctional Fish in Temperate Aquaculture

Reproductive dysfunction in *Tor putitora* is a major issue in temperate aquaculture. Because of its widespread distribution in several South and Southeast Asian countries, as well as its high consumer acceptance, this fish is currently being considered as a candidate species for temperate aquaculture. The primary constraint to golden mahseer seedlings is its fertility disorder and the lack of control throughout its reproductive cycle in captivity (Shahi et al. 2015). The reproduction event in vertebrates, including teleost, is controlled by a series of synchronized actions along the brain-pituitary-gonad (BPG) axis, where kisspeptins, as RF-amide neuropeptide key upstream signaling molecules, elicits the release of hormone called gonadotropin-releasing hormone (GnRH) from the hypothalamus via GnRH neurons via its receptors (kiss1 and kiss2 receptor). GnRH stimulates the release of gonadotropins (GtHs) in the pituitary gland, as well as follicle-stimulating hormone (FSH) and luteinizing hormone (LH), which regulates the secretion of gonad sex steroids.

Kisspeptins are thought to regulate early development, gonadal sex differentiation, puberty onset, and seasonal reproduction in teleosts (Selvaraj et al. 2010, 2015; Zohar et al. 2009; Taranger et al. 2010; Migaud et al. 2012). Attempts have also been made to clone kisspeptin genes from various fish species in order to better understand their role in sexual maturity and reproduction. Similarly, the transcript level of kiss1 and kiss1r mRNA in the brain, pituitary, and gonad of golden mahseer was investigated during different gonadal development stages (Shahi et al. 2016). Kisspeptins' potential role in temperate aquaculture sexual maturity and reproduction can thus be investigated.

14.6 Fish Health Management

Disease is a significant barrier to aquaculture growth. Biotechnological technologies such as molecular diagnostic methods, vaccinations, and immunostimulants are gaining popularity for enhancing viral disease resistance in fish and shellfish species across the world. In this scenario, infection avoidance is crucial, and a quick pathogen detection approach is necessary. In this arena, biotechnological tools such as polymerase chain reaction (PCR) and gene probes have a tremendous promise. A range of illnesses affecting fish and shrimp have been found using PCR-based diagnostic and gene probe techniques (Karunasagar and Karunasagar 1999). In the case of finfish aquaculture, vaccines against bacteria and viruses have been developed. Traditional vaccinations based on dead microorganisms have been used in some cases, but a new generation of vaccines based on protein subunit vaccines, genetically edited organisms, and DNA vaccines is now being developed.

In the vertebrate system, illness immunity is a typical technique. Despite the fact that the shrimp immune system is still undeveloped, biotechnological technologies can be utilized to create compounds that trigger the shrimp immune response. Recent studies have revealed that microbial compounds such lipopolysaccharides, peptidoglycans, and glucans may be employed to increase the non-specific defensive response in fish (Itami et al. 1998). Glucan and levamisole are two immunostimulants that have been shown to improve phagocytic activity and specific antibody responses in fish (Sakai 1999).

14.7 Transgenes' Pleiotropic Impact on Disease Resistance

The incorporation of a transgene may have pleiotropic effects (Dunham 2011). Pleiotropic effects arise when a transgene impacts many traits, either positively or negatively. Unintentional genotypic or phenotypic alterations may have pleiotropic effects. Overexpression of a transgene can affect other traits, as seen in the case of growth hormone-transgenic salmon, where the hormone's overexpression resulted in a variety of pleiotropic effects other than growth, such as skeletal morphological changes and behavioral changes in feeding and swimming behavior (Devlin et al. 1995). If random transgenic integration occurs into fish functional genes, the insertion might be mutagenic (Gong et al. 2003). The changed phenotype may potentially result in pleiotropic consequences. Lysozyme activity, serum bactericidal activity, leucocratic activity, and the fraction of phagocytic macrophages in the head kidney were all significantly enhanced in transgenic carp. Phagocytic indices and relative spleen weight, on the other hand, did not differ across genotypes (Wang et al. 2006).

14.8 Chromosome Engineering

In farmed fish species, chromosomal sex modification techniques have been widely used to induce uniparental chromosome inheritance (gynogenesis and androgenesis) and polyploidy (triploid and tetraploid) (Lakra and Das 1998). Because they allow for fast gonadal sterilization, sex control, hybrid viability enhancement, and cloning, these treatments are important for enhancing fish breeding. Most vertebrates are diploid, which implies that their somatic cells have two complete sets of chromosomes. Polyploids have one or more extra chromosomal sets, bringing the total number of chromosomal sets to three in triploids, four in tetraploids, and so on. Triploids can be produced by crossing tetraploids with diploids. In fish species with female homogametic, gynogenesis can be used to produce completely female populations and reveal the sex determination processes. For a variety of aquaculture species, methods combining induced gynogenesis and hormonal sex inversion have been developed (Gomelsky et al. 2000). Androgenesis is a method that can be used commercially in aquaculture. It can also be used to create homozygous fish lines and to recover lost genotypes from cryopreserved sperm. A similar approach can be utilized for cold-water fishes such as golden mahseer, which have bigger females than males.

14.9 Gamete Cryopreservation or Gene Banking

Cryopreservation is a technique for preserving and storing biological material for lengthy periods of time at extremely low temperatures, generally −196 °C (liquid nitrogen temperature). Cryogenic preservation of fish spermatozoa (milt) technology has been applied in animal husbandry. Blaxter (1953) claimed to be the first to maintain fish sperm at low temperatures by fertilizing herring (*Clupea harengus*) eggs, using frozen thawed sperm. Cryopreserved spermatozoa are currently available for almost all cultivable fish species (Lakra 1993). Cryopreservation eliminates the issue of male development occurring before female maturation, allowing for selective breeding, stock augmentation, and conservation. Breeders can develop new strains by utilizing one of the growth criteria. Gene banks are the source of the great majority of plant types. The aquatic gene bank, however, is limited since only male finfish gametes can presently be cryopreserved, with no feasible approach for finfish eggs and embryos. However, new findings on the freezing of shrimp embryos by Subramonium and Newton (1993) and Diwan and Kandasami (1997) sound promising. As a result, gene banking of cultivated and cultivable aquatic species must be completed as soon as feasible.

14.10 Genome Editing in Fish

Genome editing is a relatively new method of genetic engineering in which a sequence of DNA in any organism may be changed, replaced, inserted, deleted, or edited. Unlike prior genetic engineering techniques that randomly insert genetic materials into a host genome, the gene is added to particular regions of the genome in this case. As a result, this is more exact. The genome may be modified via zinc finger nuclease (ZFN), transcription activator-like effector nuclease (TALEN), and clustered regularly interspaced short palindromic repeats (CRISPR/Cas9). Because of the multiple biological benefits of fish models, fish species, particularly model species like zebrafish and medaka, have played an important role in testing novel genome editing approaches in recent years. Many more genes have been disrupted or altered in several fish species, including common carp, Atlantic salmon, tilapia, rainbow trout, rohu, and others, for functional studies, notably those linked to reproduction, disease resistance, and growth (Shahi et al. 2022). Gene knockout approach by microinjection (Fig. 14.1) can be utilized in cold-water fishes to increase muscle mass in commercially significant fish species such as common carp (Fig. 14.2).

14.11 Techniques for Genome Editing (GE)

GE-owned techniques include:

- CRISPR/Cas [including all variants under development, the most advanced of which is the CRISPR/Cas9 variant].
- Meganucleases.
- Zinc finger nucleases (ZFN).
- Transcription activator-like effector nucleases (TALEN).
- Oligonucleotide-directed mutagenesis (ODM).

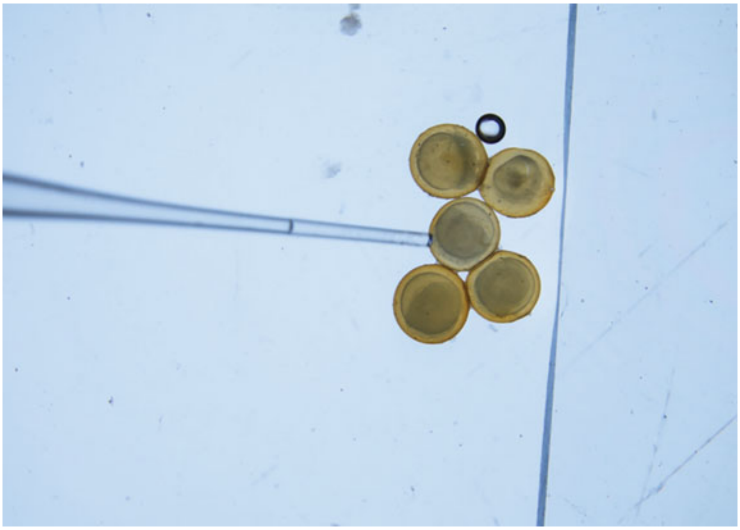

Fig. 14.1 Microinjection in fertilized eggs of common carp

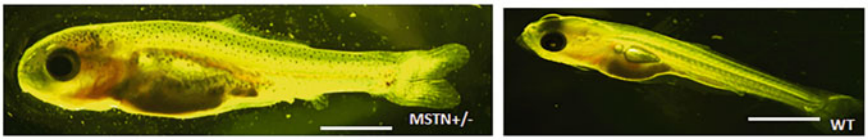

Fig. 14.2 Mstn knockout and wild-type common carp

Site-directed nucleases (SDNs) are used in these GE procedures because, unlike standard genetically modified techniques, SDN techniques are directed to a specific area of the genome and generate precise and targeted alterations (EFSA 2012). According to the EFSA, SDNs are classified into three types. Only this is rapidly transported into SDN-1 with the intention of generating random mutations at the target site, resulting in endogenous nucleotide repair of the damaged DNA of the host cell. SDN-2 uses HDR to produce specific nucleotide sequence alterations by using small non-protein-coding homologous repair DNA (donor DNA). SDN-3 uses HDR to route a lengthy length of protein-coding donor DNA (up to several kilobases) to a specific genomic location for insertion (EFSA 2012).

CRISPR/Cas is the most widely used SDN due to its ease of use, low cost, and high efficiency (Wang et al. 2016). CRISPR/Cas9, the most complex CRISPR/Cas variant, causes double-strand breaks at specific target places on the DNA, causing the cut sites to be repaired by the cell's endogenous DNA repair mechanisms: HDR and non-homologous end joining (NHEJ) (Jiang and Doudna 2017). Because the NHEJ is prone to mistakes, the repair process usually leads in nucleotide deletion, insertion, or substitution modifications to the DNA sequence (Jiang and Doudna 2017). Such modifications can make the target gene dormant or knockout (KO), which is useful in gene knockout applications. The HDR repair process can employ exogenous DNA sequences as templates to insert donor nucleotide sequences at target locations via substitution and insertions (Jiang and Doudna 2017).

14.11.1 Limitations of CRISPR/Cas Use in Aquaculture

1. Despite the benefits of CRISPR/Cas, attaining the technique's full potential in fish aquaculture is limited by a number of technical hurdles, which are outlined from both a genetic and an application standpoint:
2. *Genetic perspective.*
   (a) The most significant aquatic species have been sequenced, and the aquatic genetic resource is still restricted (Wargelius 2019). A good grasp of genetic background is required for genome editing.
   (b) Trait-related genes need to be identified. Because the genetic dissection of aquatic species lags behind that of humans and plants, trait-related genes must be found.
3. There is fish duplication. In terms of species diversity, fish are the most abundant aquatic creatures. In contrast, teleosts experienced teleost-specific whole genome duplication (TS-WGD) (Glasauer and Neuhauss 2014).
4. *Application perspective.*
   (a) In oviparous fish, the egg membrane decreases the success rate of microinjection. There is no known gene editing platform for ovoviviparous fishes at the moment.
   (b) Off-target effect identification in model organisms focuses on knockout efficiency to optimize CRISPR/Cas design (through the NHEJ/SDN-1 technique). While considered a food resource, off-target effects in aquatic creatures should also take into account the impact of introducing new genes via transgenesis or cisgenesis (i.e., the HDR/SDN-3 strategy).
   (c) Because aquatic creatures have distinct traits that demand species-specific design, such as needle type, injection dose, and so on, there is no standard technique. Because of the rarity of known cell lines and the tiny size of the egg and embryo in crustaceans and mollusks, only *Crepidula fornicata*, *Exopalaemon carinicauda*, and Crassostrea gigas have had successful GE (Gui et al. 2016; Perry and Henry 2015; Yu et al. 2019).
5. *Possible solutions to these issues.*
   (a) As the cost of sequencing decreases (less than $10/sample), more aquatic genomes will be decoded in the future, establishing the genetic groundwork for future GE events.
   (b) As QTL and genetic and molecular biology tools (e.g., QTL mapping, comparative genomics, and pooled CRISPR screens) improve, more trait-related genes will be found (Houston et al. 2020).

(c) For traits involving many genes (quantitative traits), concurrently creating multi-gene knockout mutants using CRISPR/Cas will allow for the production of the desired phenotype.

14.12 Conclusion and Perspective of Genome Editing Tool

Because of the rapid advancement of genome sequencing technology and the completion of whole genome sequencing in multiple fish species, fish breeding has entered the post-genomic age. Not only will genome editing make identifying gene functions at the individual gene level easier, but it will also allow for the insertion of different forms of nucleotide polymorphism or modifications in the fish genome at single-base resolutions. However, before genome editing techniques are widely deployed, it is necessary to address the phenomena of genetic compensation, which can disguise genome-edited phenotypes (Balciunas 2018). As a result, large-scale screening in the zebrafish model with genome editing technologies is necessary, resulting in a comprehensive understanding of the link between sequence changes and gene function dynamics. Furthermore, using genome editing methods, it may be feasible to develop farmed fish with a variety of advantageous qualities, including growth acceleration, high nutrition, disease resistance, stress tolerance, and high fertility, in the future.

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An Overview of Cold-Water Fish Diseases and Their Control Measures

15

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Abstract

World aquaculture is shifting from extensive to intensive practices, and the degree of microbial incidences has increased considerably with the intensification. The trout culture is exposed to stress in intensive aquaculture systems, which often leads to immune impairment and increased susceptibility to disease. Different stresses, such as poor physico-chemical parameters of water, poor nutrition and excessive stocking density, can lead to infection by opportunistic pathogens. Additionally, the spread of the disease has emerged as a major barrier to the trade and production of sustainable aquaculture products, affecting the socio-economic status of the people. Several pathogens of bacterial, viral, fungal and parasitic origin are reported from cold-water aquaculture, known to cause substantial economic loss. This chapter briefly discusses the common viral, bacterial and parasitic diseases reported from salmonids and other cultured cold-water fishes worldwide. Moreover, prevention and control measures are mentioned, which may help combat these microbial infections in aquaculture.

Keywords

Temperate aquaculture · Bacteria · Disease · Parasite · Virus

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15.1 Introduction

Aquaculture is the fastest-growing animal food sector and will continue to expand to meet the global food demands. Along with this growth, aquaculture industry is increasingly threatened by diseases, caused by bacteria, viruses, fungi, oomycetes and parasites (Table 15.1). Moreover, intensification in aquaculture systems has led to the emergence of new pathogens and more dependence on antibiotics and other supplements and poses a threat to the overall well-being of fish, humans and the environment (Watts et al. 2017). The disease is a significant constraint to the expansion of aquaculture and causes substantial losses in aquaculture production. Annual losses of more than six billion USD are reported from the diseases in aquaculture (Shinn et al. 2015). It is estimated that the management of disease in aquaculture accounts for 10–50% of the production cost (Sahoo et al. 2017). This book chapter briefly describes some common bacterial, viral and parasitic diseases, reported from temperate/cold-water aquaculture.

15.2 Bacterial Diseases in Temperate Aquaculture

Fishes are susceptible to a vast number of bacterial pathogens that cause severe diseases with economic repercussions (Pandey et al. 2021). Most bacterial pathogens are believed to be a part of the normal component of the aquatic microflora, but under stressful conditions, they are assumed to function as opportunistic pathogens. The following section briefly discusses some common bacterial diseases reported in salmonids and other cold-water fishes.

15.2.1 Lactococcosis

Lactococcus garvieae is an emerging zoonotic bacterial pathogen that causes deadly haemorrhagic septicaemia in humans and cultured fish. The disease was first reported in Japan around the end of the 1950s (Hoshina et al. 1958). Its initial epidemic happened in Spanish rainbow trout farms in 1988 (Palacios et al. 1993). In addition, it was first isolated by Shahi et al. (Shahi et al. 2018a, b) from the lower intestine of the farm-raised rainbow trout in the northwest Himalayan region of India (Shahi and Mallik 2020). Their study proved that Indian farmed rainbow trout are susceptible to 'warm-water lactococcosis'.

15.2.1.1 Aetiology

L. garvieae, previously known as *Streptococcus garvieae*, isolated from the United Kingdom, is designated as the reference strain (ATCC 43921) for this species (Collins et al. 1983). It is a gram-positive, chain-forming and haemolytic cocci linked to meningoencephalitis and deadly haemorrhagic septicaemia in humans, animals and commercially important fish species, such as rainbow trout, salmonids, tilapia, sea bream, Japanese eel and olive flounder (Kusuda et al. 1991; Eldar et al.

Table 15.1 Diseases in cold-water aquaculture

S. no.	Disease	Aetiological agent	Susceptible age group	Signs
Bacterial diseases				
01	Lactococcosis	*Lactococcus garvieae*	All age groups	Hyperacute haemorrhagic septicaemia
02	Motile *Aeromonas* septicaemia (MAS)	*Aeromonas hydrophila*	All age groups	Haemorrhagic septicaemia
03	Rainbow trout fry syndrome (RTFS)	*Flavobacterium psychrophilum*	Fry	Loss of balance, spiralling swimming, drowsiness, hyperexcitability, bleeding and death
04	Columnaris disease/ Saddle-back disease	*Flavobacterium columnare*	All age groups	Lesions at the base resembling a 'saddle-back'. Cottony wool appearance around mouth or mouth fungus
05	Cold-water disease (CWD)	*Flavobacterium psychrophilum*	All age groups	Loss of fin tip integrity In the peduncle region, there may be a darkening of the skin colour
06	Bacterial gill disease	*Flavobacterium* sp.	Mostly fry and fingerling	Lethargy gasping for air, fish aggregation near the inlet of the tank
Viral diseases				
01	Infectious hematopoietic necrosis (IHN)	Infectious hematopoietic necrosis virus (IHNV)—Fish *Rhabdovirus*	Fish under 2 months old tend to be the most vulnerable to the virus in both natural and artificial infections	Characterised by the necrosis of eosinophilic granular cells in the submucosal layer of the intestinal wall, which leads to trailing faecal casts
02	Viral haemorrhagic septicaemia (VHS)	Fish *Rhabdovirus*—Viral haemorrhagic septicaemia virus (VHSV)	Younger fish are more vulnerable, and fish older than 6 months appear to be resistant	Necrosis in the kidney and spleen regions
03	Infectious pancreatic necrosis (IPN)	Aquabirnavirus – Infectious pancreatic necrosis virus (IPNV)	Fry and post-smolt	Milky mucous substance in the digestive tract and presence of McKnight cells

(continued)

Table 15.1 (continued)

S. no.	Disease	Aetiological agent	Susceptible age group	Signs
Parasitic diseases				
01	White spot disease	*Ichthyophthirius multifiliis*	Fry and fingerlings	White pinhead-sized patches appear in the epidermis and gills
02	Costiasis	*Costia necatrix*	All age groups	The skin of the fish develops a light grey-blue film, and more severely affected body sections display red patches
03	Trichodiniasis	*Trichodina*, *Trichodinella* and *Tripartiella*	Common in young fish	Appearance of tiny red dots on gills
04	Gyrodactylosis	*Gyrodactylus salaris*	All age groups	Excess mucus secretion, gill filament breakage and haemorrhagic lesions in the gills
05	Black spot disease	*Diplostomum* sp.	Fry and fingerling commonly affected	Each fish has a unique pattern of spots, ranging in size from 1 to 2 mm, depending on the species
06	Eye disease of rainbow trout	Digenetic trematode (metacercaria)	Adult trout	Cataracts, lens displacement and degeneration, cortical fibre liquefaction and eventually blindness
07	Argulosis	*Argulus* sp.	All age groups	Localised reddish patches on the external body surface
08	Whirling diseases	*Myxobolus cerebralis*	Small fry and fingerlings	Imbalance and loss of homeostasis leading to erratic swimming

1999; Lee et al. 2001; Aguado-Urda et al. 2014; Tsur et al. 2015; Gibello et al. 2016; Vendrell et al. 2006). These non-motile, non-spore-forming, facultatively anaerobics produce α-haemolysis on blood agar (Vendrell et al. 2006). The bacteria is one of the emerging fish pathogens in temperate regions (Meyburgh et al. 2017), affecting a diverse range of fishes (Vendrell et al. 2006). Additionally, it is regarded as an emerging zoonotic pathogen, as human infection reports are on the rise (Meyburgh et al. 2017).

15.2.1.2 Clinical Signs

The disease condition is classified as hyperacute haemorrhagic septicaemia (Bercovier et al. 1997). The infected fish shows irregular swimming, discolouration, exophthalmia and malnutrition (Muzquiz et al. 1999; Chang et al. 2002). In addition, bilateral exophthalmos with periocular bleeding is also reported (Muzquiz et al. 1999; Chang et al. 2002; Vendrell et al. 2004). Internal symptoms included a pale liver, spleen and renal congestion and pericardial whiting. Ascites in the peritoneal cavity are occasionally observed (Chang et al. 2002).

15.2.1.3 Histopathological Lesions

L. garvieae infection leads to a hyperacute systemic disease, hyperplasia of the haematopoietic tissue, erosion of the mucosal layer with pseudomembrane-like formation, severe peritonitis with fat necrosis in the celomic cavity and acute meningitis (Eldar and Ghittino 1999).

15.2.1.4 Control

Sanitary procedures are the initial line of defence against the prevention of pathogens into a fish farm (Vendrell et al. 2006). This infection has been effectively controlled with antibiotics; however, this has led to drug resistance (Katae 1982). Strains of formalin-inactivated strains of *L. garvieae* recovered from the fish farm have also been used to develop autovaccines, and they have shown good potential to tackle lactococcosis (Robinson and Meyer 1966; Eldar et al. 1997).

15.2.2 Motile *Aeromonas* Septicaemia (MAS)

Motile *Aeromonas* septicaemia is an emerging disease in salmonids (Cao et al. 2020) and catfishes (Zhang et al. 2016), and *Aeromonas hydrophila* is the most commonly responsible candidate bacterium for it (Bhat et al. 2021). It is an opportunistic infection that causes infections in stressed fish. The haemolysin and aerolysin are the two most significant pathogenic virulence factors that the bacterium secrets for causing the disease (Stratev and Odeyemi 2017). The bacterium is usually found in the aquatic environment, particularly in warm and rich in organic matter freshwater.

15.2.2.1 Etiological Agent

Aeromonas hydrophila is the most frequent etiological agent for motile *Aeromonas* septicaemia (MAS). It is a gram-negative, pleomorphic bacillus with a monotrichous flagellum that does not produce spores. Both freshwater and saltwater fish species can contract this illness (Stratev and Odeyemi 2017). It is a facultative anaerobe frequently present in freshwater and sewage. Shahi et al. (2013) reported aeromonosis in the caudal region of the rainbow trout, *Oncorhynchus mykiss* (Walbaum), reared in the raceways. The fish displayed haemorrhagic skin ulcers and frayed haemorrhagic fins.

15.2.2.2 Clinical Signs

The symptoms of *A. hydrophila* infection usually vary among different fish species. The symptoms include skin ulcerations, lack of appetite, abnormal swimming patterns, pale gills and unexpected death in apparently healthy fish (Swann and White 1991). Skin ulcers can appear anywhere on the fish, and they frequently have a vivid border of red tissue around them. The kidneys, spleen, gills, liver and skeletal muscle are other organs, often impacted by this disease (Austin and Austin 2007). The severity of the symptoms varies depending on the virulence of the microorganism, the susceptibility of fish to infection and stress and the presence or absence of bacteraemia or septicaemia (Swann and White 1991).

15.2.2.3 Histopathological Lesions

Histopathological analyses have revealed a haemocyte aggregation with cell necrosis in the gills, a significant aggregation of haemocytes with pyknotic nuclei in the hepatopancreas and a reduced rate of haemocyte aggregation in the fish digestive tract (AlYahya et al. 2018). When bacteria infect exophthalmic eyes, they heavily colonise the conjunctiva, causing epithelial detachment, necrosis, oedema and haemorrhage (Miyazaki and Jo 1985). Additionally, haemorrhages in the visceral organs, interstitial tissues and some skin haemorrhages on the ventral surface and anal areas have been discovered in fishes, affected with MAS. Typical pathological damage comprises vacuolation in the functional epithelium of the affected organs, granular and/or hyaline droplet degeneration or hazy swelling (Stratev et al. 2015).

15.2.2.4 Control

The vaccine formulation is difficult because of the variability of the *Aeromonas* genus, which makes bacteriosis in aquaculture challenging to prevent (Plant and LaPatra 2011). Therefore, biosecurity and sound management practices stand out as cost-efficient, simple-to-implement, and highly successful techniques. These methods and disinfectants are an excellent substitute to lessen the effects of bacteriosis in aquaculture (Muniesa et al. 2019).

15.2.3 Rainbow Trout Fry Syndrome (RTFS)

Large disease outbreaks in fish farms around the world are caused by *Flavobacterium psychrophilum*. The bacterium is responsible for cold-water disease in salmonids as well as rainbow trout fry syndrome (RTFS) (Madetoja et al. 2003). The bacterial pathogen is ubiquitous in many countries and causes economic losses. In most cases, when water temperatures are still below 10 °C in the spring, the illness becomes evident (Faruk 2002).

15.2.3.1 Aetiology

Flavobacterium psychrophilum, the causing agent, is a gliding bacterium (Garcia et al. 2000), a gram-negative, filamentous, chromogenic rod-shaped and furthermore linked to salmonid fish outbreaks of the bacterial cold-water disease (BCWD)

(Wood and Yasutake 1956). In salmonids, it is isolated from skin mucus and connective tissue of their fins, gills and operculum. The presence of *F. psychrophilum* in the lumen and mucosa/submucosa of the stomach of naturally infected rainbow trout fry indicates the gastrointestinal tract as an entry site (Boyacioglu and Akar 2012).

15.2.3.2 Clinical Signs

Major clinical signs include the loss of balance, spiralling swimming, drowsiness, hyperexcitability, bleeding and death (Marcquenski and Brown 1997). The Lethargy, skin discolouration, bilateral exophthalmia, stomach distension, and periocular bleeding. Internally, ascites, spleen enlargement, liver pallor and anorexia are commonly reported signs (Faruk 2002).

15.2.3.3 Histopathology

Histopathological alterations, induced by *F. psychrophilum*, include peritonitis, which extends from the outer surface of the spleen; spleen alterations include significant hypertrophy and loss of organ border definition. In the spleen, splenic pulp loses its thick look, and oedematous alterations in the red and white pulp result in the formation of stromal voids. In advanced cases, cell degeneration, haemorrhages, karyorrhexis and pyknosis were also observed. In experimental infections, anaemia predominates, and splenic squashes lack the bacteria of interest (Rangdale et al. 1999). Histologically, the most consistent and notable alterations are characterised by peripheral layering due to fibrous infiltration, loss of boundary definition and widespread intracellular oedema in the spleen (Faruk 2002).

15.2.3.4 Control

Currently, no antibiotic or drug warrants 100% control against RTFS. Antibiotics, such as oxytetracycline and amoxicillin, play a significant role in controlling RTFS (Faruk 2002).

15.2.4 Columnaris Disease/Saddle-Back Disease

Davis was the first to identify columnaris disease in warm-water fishes from the Mississippi River (Davis 1922). Numerous cold- and warm-water fish species are affected by the columnaris infections, which commonly occurs in warm temperatures of 15 to 25 °C and above. Various farmed and wild fish species are believed to be prone to disease. The columnaris disease affects a variety of aquaculture and aquarium fish species, particularly catfish species.

15.2.4.1 Etiological Agent

F. columnar is the causative agent of columnaris disease and belongs to the family Flavobacteriaceae (Bernardet and Bowman 2006). Both domesticated and wild freshwater fishes are susceptible, including several species of commercially important fishes. The origin of *F. columnare* strains in fish farms has been hypothesised to be the surrounding water, and the farm practices may favour virulent strains to cause outbreaks (Pulkkinen et al. 2010). Infections with *F. columnare* can cause skin lesions, fin erosion and gill necrosis, which have a high mortality rate and cause significant economic losses (Declercq et al. 2013). Under laboratory conditions, the bacterium can maintain its virulence in water for at least 5 months. *F. columnare* can transform from a virulent to a less virulent form while living outside the host, most likely to conserve energy (Kunttu et al. 2012). *F. columnare* fails to penetrate fish in the presence of competing bacteria such as *Citrobacter freundii* when its CFU/mL is about a hundred times lower than those of the competitors (Declercq et al. 2013).

15.2.4.2 Clinical Signs

F. columnare commonly affects the gills, skin and fins and can cause acute to chronic infections. The virulence of the strain that causes the disease determines its clinical appearance (Declercq et al. 2013). Juveniles of salmon (*Salmo salar*) can be killed by strains of high virulence in 12 to 24 h at 20 °C, while strains of low virulence produce slow infection rates at water temperatures above 21 °C and cause severe tissue damage before death (Rucker et al. 1954). In chronic situations, gill damage takes longer to manifest and may form skin sores (Decostere 2002). Small lesions on the body typically begin as regions of light skin discolourations that are bordered by a clear crimson hue (Pacha and Ordal 1967). This mainly starts at the dorsal fin base. After that, fin degeneration occurs, which is the opposite of typical finrot, commencing with the lesion starting at the fin's base and progressing outward. The lesions then begin to extend laterally from their usual spot at the base of the dorsal fin, encircling the fish in a manner resembling a 'saddle-back' (Morrison et al. 1981). As a result, the disease is known as 'saddle-back disease'. Finrot is also frequently seen (Declercq et al. 2013). The region around the adipose fin in rainbow trout may get black and exhibit erosions. The term 'peduncle disease' was coined because these lesions spread to the peduncle (Bernardet and Bowman 2006).

15.2.4.3 Histopathology

In trout, epithelial lifting, fusion and necrosis of secondary gill lamellae, lamellar hyperplasia and infiltration of erythrocytes are visible in the gill histology. The other organs show melanomacrophage aggregation in the spleen, renal corpuscle dilatation and tubular necrosis in the kidney, cellular hypertrophy, congestion and vacuolation in the liver (Singh et al. 2021).

15.2.5 Cold-Water Disease (CWD)

Fish that live in cold waters are susceptible to the bacterial illness known as cold-water disease (CWD). The condition is most widespread and severe at water temperatures of 10 °C or lower, where it typically occurs at 16 °C or lower. Both captive and wild populations can get cold-water disease, although hatchery-raised salmon and trout are particularly susceptible to infections.

15.2.5.1 Etiological Agent

F. psychrophilum, formerly known as *Cytophaga psychrophila* and *Flexibacter psychrophilus*, is the causative agent of CWD. This gram-negative bacterium can be isolated from infected host tissues. Serious illness and mortality are reported by cold-water disease in cold-water fish species, particularly in some populations of trout and salmon. All fish species are impacted; however, young fish (fry and fingerling size) are more prone to infections.

15.2.5.2 Clinical Signs

Loss of appetite and widespread restlessness are frequently the first signs of the disease (CWD). The disease affects both exterior surface and interior organs. Loss of fin tip integrity may signal the onset of external disease. In the peduncle region, there may be a darkening of the skins. Bacterial colonisation may cause further fin erosion, especially to the caudal fin; in some fish, colonisation manifests as a whitish substance on the fins and a separation of the fin rays. In severe situations, the caudal vertebra may finally become exposed at the peduncle area due to necrosis. The development of an internal and systemic infection occurs concurrently with or after the external pathology. It is mostly noticed that a physical injury to the skin serves as a portal of entry to the infection.

15.2.6 Bacterial Gill Disease

The bacterial gill disease is most prevalent in spring, which also happens when fish hatcheries produce small-sized fish (fry and fingerling size) after spawning. Salmonids raised in hatcheries are frequently infected with the bacterial gill disease (BGD), which can also infect warm-water species grown under harsh conditions. As defined by Wood and Yasutake (1956), the disease name refers to the clinical symptoms in gills during infection. According to Wakabayashi et al. (1989), filamentous bacteria, such as *Flavobacterium* branchiophila are thought to represent the etiological agent. Large amounts of filamentous bacteria on the gills and fusing and clubbing of the gill filaments are symptoms of BGD. There might be acute or chronic manifestations of the disease, and acute epidemics might have daily fatality rates close to 20%. Bacterial gill illness typically follows when environmental circumstances worsen due to overcrowding and an increase in harmful metabolic waste products. Aquaculture bacterial gill disease outbreaks are common in endemic regions and frequently coincide with elevated host stresses. Although healthy fish of different ages have been experimentally induced with bacterial gill disease, many researchers have noted that overcrowding, low dissolved oxygen, higher ammonia and particulate matter in the water are some predisposing variables that frequently occur in conjunction with this condition. Therefore, it has often been demonstrated that reducing these host stresses can lessen the intensity of ongoing epidemics and stop them from spreading. If the conditions in the culture are not rectified, or treatment is not adequately administered, mortality might increase quickly and significantly.

15.2.6.1 Clinical Signs

Infected fish usually exhibit signs of exhaustion such as lethargy, piping and gasping for air at the water surface and assemble near the inlet of the tanks and ponds.

15.2.7 Miscellaneous Bacterial Diseases in Cool and Cold-Water Aquaculture

Some strains of *Vibrio* have been discovered to produce haemorrhagic septicaemia in cultured golden mahseer, *Tor putitora*. Mallik et al. (2020) also isolated and characterised *Aeromonas* strains from moribund grass carp fry cultured in cages in the central Indian Himalayan region and identified *A. veronii* as the causal agent. *Chryseobacterium scophthalmum* was isolated from the gill lesions of the diseased golden mahseer in India, displaying the clinical signs of bacterial gill disease. Shahi and Mallik (2014) isolated *Pseudomonas koreensis* from the eye of *T. putitora* and reported that the isolated strain was virulent and could cause histopathological alterations in fingerlings of golden mahseer.

15.3 Viral Diseases

The culture of fish under an intensive system has led to the emergence of new diseases/pathogens (Table 15.1). Among them, viruses probably cause a wide spectrum of fish diseases where the mortality rate can reach to 100%. These viruses are the primary pathogens affecting salmonids, and their spread is a serious threat to aquaculture (Kibenge et al. 2012). This section provides an overview of some of the major viral infections affecting rainbow trout.

15.3.1 Infectious Hematopoietic Necrosis Virus

Infectious haematopoietic necrosis (IHN) is a viral infection that affects most salmonid fish raised in fresh or salt water (St-Hilaire et al. 2002; Crane and Hyatt 2011). Although adult fish may get IHNV without showing any symptoms, fishes under 2 months of age are typically the most susceptible to the virus in both natural and artificial infections (Lapatra 1998). A bullet-shaped virion with a non-segmented, negative-sense, single-stranded RNA genome of roughly 11,000 nucleotides that encodes six genes (Bergmann and Fichtner 2008; Mulei et al. 2019): the nucleocapsid (N), phosphoprotein (P), matrix protein (M), envelope glycoprotein (G), non-virion protein (NV) and polymerase or large protein (L) is the aetiological agent of the disease (Nita-Lazar et al. 2016). Five of these genes encode structural proteins, while the sixth encodes NV which is a non-structural protein (Biacchesi et al. 2017). Due to the presence of NV gene, IHNV has been placed under genus *Novirhabdovirus* of the family Rhabdoviridae (Dixon et al. 2016).

15.3.1.1 Gross Pathology

Affected fishes have darkened skin, pale gills and mucoid ascites, a swollen abdomen, trailing faecal casts, exophthalmia and pinpoint haemorrhages on their fins (Ahmadivand et al. 2017; Woo and Cipriano 2017). In some cases, fish, primarily rainbow trout, may develop eye haemorrhages and skin petechiae (Huo et al. 2022). In addition, the fishes exhibit atypical swimming patterns such as occasional whirling, spiral swimming and flashing (Yong et al. 2019). The clinical indications are caused by virus multiplication in endothelial cells of capillaries, haematopoietic tissues and kidney cells. The blood of the impacted fry has a low haematocrit, leukopenia, leucocyte and thrombocyte degeneration and high levels of cellular debris. Blood chemistry is altered in extreme cases, as with other haemorrhagic viraemias of fish (2019 OIE Manual).

15.3.1.2 Histopathology

Histopathological examination reveals degenerative necrosis in haematopoietic tissues, liver and the digestive tract. IHNV infection is characterised by the necrosis of eosinophilic granular cells in the submucosal layer of the intestinal wall (Bruno and Poppe 1996).

15.3.2 Viral Haemorrhagic Septicaemia Virus

Viral haemorrhagic septicaemia virus (VHS) is the causative agent of one of the most important salmonid viral diseases, affecting farmed rainbow trout, turbot, Japanese flounder and various wild freshwater and marine species (Smail and Snow 2011; Kim et al. 2014). Fry and juvenile fish may experience 100% mortality, whereas older fish may experience 25–75% mortality (Kim and Faisal 2011). ‘Egtved illness’ is another name for viral haemorrhagic septicaemia. Different VHSV isolates are currently classified into one of four genotypes based on a genetic study. Genotype IV was discovered recently in North America, Japan and Korea. Genotypes I, II and III are more commonly found in Europe and Japan (Frattini et al. 2011).

15.3.2.1 Aetiological Agent

The virus is a member of the family Rhabdoviridae and the genus *Novirhabdovirus* (Walker et al. 2000). The negatively sensed single-stranded RNA genome of the VHSV virion is enveloped and bullet-shaped and contains six genes. The total genome size is around 11 to 12 kb (Zhang et al. 2019) and encodes nucleoprotein (N), phosphoprotein (P), matrix protein (M), glycoprotein (G), non-virion protein (NV) and polymerase (L) (Snow et al. 2004).

15.3.2.2 Clinical Signs

The disease is manifested in three forms and progresses with significant deterioration in hematopoietic tissues (Kim and Kim 2011). The three forms are acute, chronic and nervous forms. High death rate, sluggish swimming, being separated from the shoal, loss of appetite and crowding at the pond edge are the signs in the acute infection. Acute infection shows skin ulceration, bloated belly with ascites and pale gills with petechial haemorrhages in the fatty tissues, intestine, gonads, liver and muscle. There is also a minor darkening of the body colour with deep red colour in the kidneys (Department of Agriculture 2014). In chronic infections, the signs are considerable cumulative mortality (long-term), ataxic swimming and spinning motion around the body axis (OIE Manual 2021). The viral titres in the brain may arise during the chronic stages (Smail and Snow 2011; Wolf 1988a). Chronic infection is frequently accompanied by no visible symptoms: exophthalmia (pop eye), a severe darkening of the skin, pale gills (anaemic), pale abdominal organs, a mottled and pale liver (with surface haemorrhages) and a pale, empty gastrointestinal tract (Department of Agriculture 2014). The neurological form is manifested with low mortality and severe aberrant swimming behaviour. Also, flashing and spiralling movements and motor disorders are common. The general gross pathological signs are exophthalmia (pop eye), bloated abdomen, pale gills with or without petechial (pinpoint) haemorrhages, bleeding under the skin, bleeding around the base of the pectoral and pelvic fins and bleeding in the eyes (CABI 2019).

15.3.2.3 Histopathology

Most tissue alterations can be characterised as significant or moderate necrosis in the liver, kidney, spleen and skeletal muscles. The infection first manifests in necrotic regions of the kidneys and spleen hematopoietic regions. Degeneration can also be seen in the kidney, liver and spleen, with cytoplasmic vacuoles, pyknosis, karyolysis and lymphocytic invasion (OIE 2021). Although the skeletal muscles do not appear to be the primary location of the infection, erythrocyte build-up can occur in the skeletal muscle bundles and fibres (Evensen et al. 1994).

15.3.3 Infectious Pancreatic Necrosis Virus (IPNV)

A disease of significant concern in aquaculture is infectious pancreatic necrosis (IPN), especially amid fry and post-smolt, with mortality of more than 80–90%. At least 32 distinct families of fish, 11 species of molluscs and 4 species of crustaceans are susceptible to IPNV (Hill and Way 1995). M'Gonigle first referred to this condition as acute catarrhal enteritis in 1951 (M'Gonigle 1941). IPN susceptibility typically decreases with age, except for Atlantic salmon smolts, which are frequently vulnerable during the transition from freshwater to seawater (Jarp 1999; Smail et al. 2006; Johansen et al. 2011).

15.3.3.1 Aetiological Agent

IPNV is a non-enveloped, icosahedral-shaped containing a bi-segmented RNA (designated segments A and B) belonging to the genus *Aquabirnavirus* of the family Birnaviridae (Crane and Hyatt 2011) with an average size of approximately 65 nm (Delmas et al. 2019). Segment B of the genome encodes the RNA-dependent RNA polymerase (RdRp) (Skjesol et al. 2009). Segment A encodes five viral proteins, namely, VP1 to VP5, three of them (VP1, VP2 and VP3) are structural, and two (VP4 and VP5) are believed to be non-structural proteins (Dopazo 2020).

15.3.3.2 Clinical Signs

Anorexia and fast whirling swimming motion are among the behavioural indicators (Wood et al. 1955). The IPNV infection is characterised by abdominal enlargement, bilateral exophthalmos, pale gills, skin darkening and petechial haemorrhages on the ventral surface, including the fins (Palchak et al. 2018). Several fishes also leave behind white or yellow casts from their anal opening (Wolf 1988b). In addition, there is a shortage of food in the digestive tract, which may contain a pathognomonic milky mucous substance and is frequently accompanied by petechial bleeding and visceral ascites (Munro and Midtlyng 2011; Pérez-Prieto 2003).

15.3.3.3 Histopathology

Histopathological lesions include necrosis of the intestinal mucosa, increased pancreatic acinar cell death and damage to the hepatic tissue, but not all of these diseases are always visible (Dopazo 2020). Histological alterations also include necrosis of the exocrine pancreas, shedding of the intestinal epithelium, degeneration of the inner heart and degeneration of the skeletal muscles (Poppe et al. 1989). The presence of McKnight cells (epithelial cells of the pyloric ceca) that inflate and develop fractured nuclei and subsequently spill eosinophilic cytoplasm into the lumen is another diagnostic hallmark of this condition (McKnight and Roberts 1976).

15.4 Transmission of IHNV, VHSV and IPNV

Salmonid fish can get IHNV both horizontally (from fish to fish) and vertically (from generation to generation) (Mulcahy and Pascho 1984). Also for VHS, direct contact with infected fish and oral consumption of contaminated material are the two major portals of VHSV transmission that spread virus particles horizontally through the water (Kurath and Winton 2011; Schönherz et al. 2012). Nevertheless, the virus must establish complete infection cycles in many host species, involving host entry, genome translation, replication, assembly of new functioning viral particles and release into the environment, in order for inter-species transmission to take place (Schönherz et al. 2013). The horizontal transmission of IPNV is very efficient, and its vertical transmission is also well known (Munro and Midtlyng 2011).

15.5 Control Measures of Viral Diseases

Current IHN control strategies focus on preventing viral exposure by establishing strict control policies and sound hygiene practices. To avoid the emergence of IHNV at a specific fish production site, it is essential to thoroughly disinfect fertilised eggs, incubate eggs and raise fry and alevins in virus-free water sources (Winton 2001).

Also to control IHN in enzootic areas, it is necessary to stop the vertical transmission of the virus from brooders to fry and the horizontal transmission of the virus by preventing exposure of susceptible fry to virus shed by infected fish residing in the water supply (Winton 1991). Strict biosecurity measures should be adopted in the farming system (Opiyo et al. 2020). Viral haemorrhagic septicaemia (VHS) is highly contagious, and quarantine is the best method to limit its outbreak (Faheem et al. 2021). Fish health monitoring systems and eradication are nowadays used as control methods (Faheem et al. 2021). Despite the ability of the virus to survive, a variety of chlorine (5-min treatment at a concentration of 30 ppm) and iodine-based disinfectants, as well as oxygen compounds (10-min treatment with NaOH pH 12.5 or 5-min treatment with 3% formalin), have been shown to be beneficial against viral infection. Both autogenous, killed vaccinations and a DNA vaccine are licenced for commercial use in Atlantic salmon in North America (Hølvold et al. 2014; Salgado-Miranda et al. 2013). Several studies have reported NV gene disruption within VHSV and IHNV as a potential strategy to combat these pathogens (Kim and Kim 2011). Steps for the diagnosis of viral diseases should be the following:

- Typical clinical signs.
- Isolation and identification of virus in cell lines.
- Antigen-antibody-based diagnostic tests like indirect fluorescent antibody test and enzyme-linked immunosorbent assay.
- Polymerase chain reaction.
- LAMP and qRT-qPCR.

15.6 Parasitic Diseases

Parasitic diseases cause significant economic losses in commercial aquaculture. They provide predisposing sites for the invasion of bacterial and viral pathogens. The following section briefly discusses some common parasitic diseases reported in salmonids and other cold-water fishes.

15.6.1 White Spot Disease

White spot disease, often known as ich disease, is a parasite infection frequently recorded in native and exotic cold- and warm-water freshwater fishes (Abowei et al. 2011). The parasite feeds on the red blood cells of the fish by invading their skin and gills. It is caused by the holotrichous ciliate protozoan *Ichthyophthirius multifiliis* (Dickerson et al. 2011; Mallik et al. 2015). Within the fish, it grows and multiplies in both the host and the tank or pond water (Matthews 2005). The adult parasite measures 1 mm in diameter and has circular cilia (Buchmann et al. 2001; Buchmann 2020). The parasite is oval, having ‘C’ or horseshoe-shaped nucleus (Shuter et al. 1983). Tomites are pear-shaped and contagious and invade the fish body (Mallik et al. 2015). Infected gills, skin or fin epithelium develop white spot or nodule where parasite encysts (Dickerson and Dawe 2006). Histological sections of the infected area show an increase in the number of epidermal cells (Ghosh et al. 2021). Each *Ichthyophthirius* can produce about 250 to 1000 young parasites in just 12 to 18 h. They can grow to a size of 0.03–0.04 mm in just 36 h under ideal conditions and can swim freely in search of a new host. Warmer temperatures encourage the spread and severity of outbreaks (Mallik et al. 2015). In the majority of cases, this parasite affects fry and fingerlings. Fish exhibiting erratic swimming patterns, rubbing their bodies against the hard surfaces of the pond and congregating at the inlet are warning signs (Mallik et al. 2015). White pinhead-sized patches appear in the epidermis and gills as the parasite penetrates these organs (Mallik et al. 2015). Additionally, inflammation and epithelial deterioration may be visible. White spot disease is more prevalent in summer as the temperature increases.

15.6.1.1 Treatment

Treatments include the following:

- Dip the fish for 1 to 2 min in a solution of salt that is 2–3% (Mallik et al. 2015).
- In pond, lime can be applied through lime at 30–50 mg/L (Mallik et al. 2015).
- Frequent water change and a combination of copper and formalin treatment can effectively control the parasite (Ghosh et al. 2021).
- Dip treatment with KMnO4 at 1 ppm (Mallik et al. 2015).

15.6.2 Costiasis

Another prevalent disease that affects salmonid fry and fingerlings is costiasis (Mitchell and Rodger 2011). The disease manifests in the spring when the hatchery starts to warm up. The epidermis, fins and gills provide the invasion sites for *Costia necatrix* (Ellis and Wootten 1978). The infected fish exhibits a variety of symptoms, including browning of the gills and, in some instances, partial destruction of the gills. The skin of the fish develops a light grey-blue film, and more severely affected body sections display red patches (Faruk 2018). The sick fish becomes weak, loses appetite and eventually perishes (Robertson 1985; Woo and Poynton 1995).

15.6.2.1 Treatment

Costiasis can be treated with a 30-min formalin bath in a concentration of 1:4000 or a 15-min formalin bath at a concentration of 1:2000 (Fish 1940; Mitchell and Rodger 2011). A 20-min bath in a 10 g/L solution of table salt is an alternative treatment method (Mallik et al. 2015).

15.6.3 Trichodiniasis

Trichodina, *Trichodinella* and *Tripartiella* ciliate protozoans are the etiological agents of this disease (Saha et al. 2017). The parasites, which measure 30–40 micrometres in diameter, are found in the gills as well as the external surface of the fish. They cause a lot of irritation and discomfort at the point of attachment. High stocking density, malnutrition, a larger organic load with poor water quality and a rise in water temperature are a few factors that increase the risk of disease outbreaks. Skin, fins and gills are common targets for parasites. Trichodiniasis is most common in young fish with a high mortality rate (Noga 2000; Uribe et al. 2011). This parasite thrives in intensive fry rearing facilities with a high organic load and rising temperatures. Tiny red dots appear on the gills of the infected fish. The parasite is most commonly found in the skin, fins and anal fins. Fish show unpredictable behaviour and try to scratch their bodies on hard surfaces to alleviate itching as these parasites scrape the mucus in their bodies. The skin and gills produce a lot of mucus, which leads to the discolouration of the fish skin.

15.6.3.1 Treatment

- Dip treatment in 2–3% salt solution for 2–3 min every alternate day. The treatment should be given for a week (Mallik et al. 2015).
- Dip treatment in 1:1000 acetic acid for 2–3 min (Mallik et al. 2015).
- Dip treatment with $KMnO_4$ at 1 ppm (Mallik et al. 2015).

15.6.4 Trematode

There are two main types of trematodes: monogenic and digenic (Abdel-Fattah and El-Sayed 2020). Monogenic trematodes can complete their life cycle on a single host. These are a few typical parasites that affect fish species found in cold waters. Larvae and fry of salmonids and carp are more prone to this disease. Widespread mortality caused by monogenic trematode infection in 30–40-day-old fry of fast-growing Hungarian common carp is reported. In cold-water aquaculture, there are two major issues, dactylogyrosis and gyrodactylosis, linked to trematode infection (Mallik et al. 2015). In the case of dactylogyrosis, the parasite invades the gills of the fish, which are crucial for oxygen exchange and life. The main symptoms are excessive production of light bluish mucus, changes in body colour, haemorrhages, light yellow lining in the gill filaments and fading of gill colour. In extreme situations, growth between the gill filaments resembles cotton wool and is studded with dirt particles. Fishes with the infection become feeble and malnourished and eventually die. In both cold-water and warm-water fishes, this gill parasite has been found to cause significant fry deaths. It is regarded as one of the worst cold-water parasites that occurs in grow-out ponds and during seed production.

The parasite has two eye spots, seven pairs of marginal hooks and two big hooks that help it adhere to the host. High organic loads, dense stocking, decreased dissolved oxygen/pH and increased free ammonia levels are some of the crucial elements that encourage parasite growth in the environment. Another frequent occurrence in infested facilities is pH reduction brought on by the build-up of leftover feed. The danger of disease outbreaks is further increased by the development of filamentous algae growth in cemented nursery tanks during larval rearing and a rise in temperature. The presence of a parasite in the gills can be used to gauge the severity of infection (El-Sayed 2020).

15.6.4.1 Preventive and Control Measures

Immersion in 2–3% salt solution for 2–3 min on alternate days, followed by immersion in 1–4 ppm $KMnO_4$ solution takes care. Improving water quality parameters and transferring juvenile fishes to freshwater also reduced infestation (Woo and Cipriano 2017).

15.6.5 Gyrodactylosis

It is a trematode infection that causes little red spots to appear all over the body, including the fins and the gills of the fish. Mucus is excessively secreted in contaminated fish, resulting in emaciation, restlessness, gill filament breakage and haemorrhagic lesions in the gills. Gills are also infected by the parasite, although fins and skin are more severely affected. Osmoregulation and infection are the primary causes of large-scale fish death (OIE 2009). *Gyrodactylus salaris* is the etiological agent of the disease (OIE 2009). The absence of an eye spot and the presence of eight pairs of marginal hooks and two large hooks in the centre region distinguish this from *Dactylogyrus* sp. (Peatow et al. 2009).

15.6.6 Black Spot Disease

Infected fishes have circular black nodules or cyst-like outgrowths all over their bodies, making the disease easy to spot. Fry and fingerlings of all sizes are most commonly affected. Each fish has a unique pattern of spots, ranging in size from 1–2 to 50–60, depending on the species. There is also a reduction in growth and weight loss. Despite the low mortality and morbidity rates, fishes still have an unsightly appearance, and the potential for various secondary infections is increased. The infestation causes the disease due to the digenic trematode *Diplostomum* sp. The parasite completes its life cycle in three hosts, namely, a fish-eating bird that eats snails and a fish. Metacercaria attaches themselves to the fish skin, and the fish body reacts by secreting melanin pigment and covers the parasite due to this reaction. Management measures include:

- Getting rid of aquatic weeds can help limit the snail population surrounding ponds, which in turn helps control the snail life cycle and prevent the parasite from completing the life cycle.
- Fish-eating birds should be kept out of the fish ponds and out of the surrounding area if we want to stop the life cycle of the parasite.
- Controlling the infection using picric acid.
- The use of bleaching powder at 60 ppm, while preparing the nurseries can help control snails in and around the facility.

15.6.7 Eye Disease of Rainbow Trout

A white opacity in the lens of fish is the first sign of the sickness. Adult trout are more susceptible to the disease, which causes cataracts, lens displacement and degeneration, cortical fibre liquefaction and eventually blindness. Blind fishes have significantly reduced feed intake, resulting in weaker fish. A healthy rainbow trout is more likely to injure a blinded trout. The eye disease outbreaks have been linked to the arrival of monsoon, rising water temperatures and the deposition of the forest organic load-enriched in water supplies. Its preventive and control measures include:

- The use of Praziquantel at 300 mg/kg body weight of fish.
- Bath treatment in Praziquantel at 10 mg/L for 1 h.
- Breaking the life cycle of the parasite by removing the secondary host present in the fish environment (Fish Diseases, Volume II).

15.6.8 Argulosis

Salmon, trout and carp are particularly vulnerable to argulosis in cold-water environments (Tandel et al. 2021a, b). More than 100 different species of *Argulus* have been identified and characterised. Localised reddish patches appear at the base of the ventral and pectoral fins in the early stages of infestation, and this spreads to other parts of the body as time goes on (Hoffman and O'Grodnick 1977). The typical indications that can be noted include excessive mucus secretion, unpredictable behaviour, scratching against the hard substrate, surfacing, reduced feed intake and emaciation. Rainbow and brown trout become more vulnerable in the summer when water temperatures rise above 16–17 °C. In the spring and summer, when pond biomass grows with rising temperatures, argulosis is more common.

Preventive and control measures include:

- Installing nets to filter incoming water.
- Removal of aquatic weeds and floating hard substrate from the pond lessens the level of infestation.
- Manual removal of deposited eggs is possible by placing wooden, bamboo or FRP plates in tanks or ponds and removing them after 2 to 3 days.
- Chitin inhibitors, such as dimilin, can be used to prevent parasite moulting.
- Diflubenzuron and lufenuron, which impede the production of chitin.
- Butox at 70–75 mL/ha m (Woo and Leatherland 2006).

15.6.9 Myxosporadian Parasites

Cold-water fish are infested by three primary genera of myxosporadian: *Thelohanellus*, *Henneguya* and *Myxobolus* (Mallik et al. 2015). Fishes raised in the foothills and the mid-Himalayan region are commonly infected with these genera. One of the distinguishing characteristics of these parasites is the presence of spores with polar capsules and eye spots (Bruno et al. 2006; Mallik et al. 2015). The spores are protected by a thick wall, making them resistant to many therapeutic treatments. Parasitic gill obstruction occurs during attachment, and after detachment of cysts, the location serves as a gateway for secondary diseases to enter the host. Myxosporidian and microsporidian spores are divided into two broad types based on their spore size, which attach or penetrate various exterior and internal organs of the fish. Myxozoans go through three stages in their life cycles: schizogamy, gametogamy and sporogamy (Mallik et al. 2015). Several types of myxosporidians infect salmonids and cyprinids. Mucoid cysts on the body, fins and gills have been observed in the fish species. Ovaries, kidneys, liver and spleen are all impacted by microsporidian infection (Bruno et al. 2006). Unpredictable swimming patterns, haemorrhages at infected sites, reduced eating and lethargy are all signs of this disease. The fishes that have a lot of cream-coloured cysts on their skin sell for a low price (Das and Das 2015). In addition, it leads to decreased egg production and breeding response due to gonadal regression, and infection can damage renal tubules and hepatic cells. Cysts of cream colour contain thousands of spores that adhere to the fish skin or gills. There are also histopathological alterations seen in the skin and gill epithelial and cause lamellar fusion, cellular necrosis, hyperplasia necrosis and dystrophic alterations (Mallik et al. 2015).

Preventive and control measures include:

- Good husbandry and management contribute to the control of the disease to some extent.
- Fresh bleaching powder can be used at 40–60 ppm during pond preparation.
- The use of anti-coccidial drugs toltrazuril prevents the growth of developmental stages of *Myxobolus* sp. (Mallik et al. 2015).

15.6.10 Whirling Diseases

Myxobolus cerebralis is the causative agent of the disease and an oligochaete that lives in fish ponds called *Tubifex*. *Tubifex* serves as the parasite carrier (Gilbert 2002; Gilbert and Granath 2003). As a result of imbalance and loss of homeostasis, this disease causes infected fish to swim erratically, darken the area around their tails, develop skeletal deformities and eventually die. Small fry and fingerlings are highly susceptible to the disease. Numerous species, including trout, exotic carp and native fish of hill stream, are infected by the parasite (Wolf 1985; Mallik et al. 2015). Even though the infection is difficult to eliminate, its severity can be controlled if fishes are raised in routinely cleaned and disinfected ponds. In concrete raceways with strong water flows or in spore-free waters, the fish can be easily prevented from the spores (Hoffman 1990). The same preventative and control methods apply to other myxosporidians (Mallik et al. 2015).

15.7 Control Measures for Cold-Water Fish Diseases

Several researchers are currently working on finding a suitable and environmentally friendly alternative for combating microbial infections in aquaculture without developing antibiotic-resistant bacteria. Various alternatives, namely, antimicrobial peptides (Bhat et al. 2020, 2022; Chaturvedi et al. 2020), phytotherapy (Bhat et al. 2021; Tandel et al. 2021a, b), probiotics and vaccines, have been suggested in the recent past. Here we briefly mention the chemicals/drugs currently used in controlling fish disease (Table 15.2) (Hoffman and O'Grodnick 1977). Depending upon the affected population (fish) and type of disease, medicine could be added to the water and through the feed.

15.7.1 Methods of Treatment

The following methods could be used to administer the required therapeutic dose in order to control diseases effectively:

15.7.1.1 Flush Treatment

At the inlet or location where incoming water enters, a chemical is added and allowed to circulate through the tank. It is feasible for raceway units with a high flow rate to flush out the drug completely within the predetermined time (Noga 2010).

15.7.1.2 Dip Treatment

A higher concentration of chemicals/disinfectants is used, and the process is adopted to treat small-sized fishes under controlled conditions. The duration of exposure is very less than 1–2 min (Nayak and Mogalekar 2022). The main advantage of this method is that a large population can be treated with small doses of medicines.

15.7.1.3 Bath Treatment

This is used in small experimental tanks with strict oversight, and after introducing chemicals or medications, it is left for a predetermined amount of time. When a fish exhibits stress symptoms, freshwater is either supplied to the tank, or the fishes are removed from the tank and released in freshwater.

15.7.1.4 Oral Route

Medication used in feeds must be applied correctly; otherwise, the medicine may leach into the water and never reach its intended target. The chemotherapeutant can be fed to the fish by mixing it with the right amount of feed and feeding it to them. However, this treatment technique of treatment should be used in the early stages of the sickness, as fishes in severe stages of the disease are unable to eat. Antibiotics such as sulfa medicines, oxytetracycline and nitrofurans are commonly combined with feed to treat bacterial infections. The feed can be kept suspended in perforated

Table 15.2 Fish disinfectants/chemicals/drugs used in aquaculture

Name	Type if treatment	Total quantity required	Use
Potassium Permanganate	Pond treatment at 2–3 ppm Bath treatment at 500–1000 ppm for 1–2 min	20–30 kg/ha-m 25–50 g in 50 L	General bactericide against external parasites and fungal infections
Acriflavin	Bath treatment at 500 ppm for 20 min	10 g in 20 L	Fish egg disinfectant and acts against bacterial infection
Sodium chloride	Bath treatment at 2–3% for 1–2 min	2–3 kg in 100 L	Bactericide, fungicide and ectoparasiticide
Formalin	Pond treatment at 15–25 ppm Dip treatment at 250 ppm for 10 min	150–250 L/ha-m 5 mL in 20 L	Parasiticide and against protozoan infections
Malathion 50%	Pond treatment at 0.25 ppm (three doses)	5 L/ha-m	Against *Argulus*, *Ergasilus* and other parasites
Butox	Pond treatment	70–75 mL/ha-m	Against *Argulus* and *Ergasilus*
Oxytetracycline	With feed at 70 mg/kg body weight for 10 days	70 g for 1000 kg	Bactericidal used against common bacterial diseases, particularly against gram-negative bacteria
Chloramphenicol	With feed at 50 mg/kg body weight for 10 days	55 g for 1000 kg	Bactericide against *Aeromonas* disease
Chlortetracycline	With feed at 55 mg/kg body weight for 10 days	55 g for 1000 kg	Against diseases caused by *Aeromonas* and *pseudomonas*
Sulfadimethoxine/ ormetoprim	Feed at 50 mg/kg of body weight/day for 5 days	23 mg sulfadimethoxine-ormetoprim/lb	Against *Aeromonas* and *Edwardsiella* infections
Erythromycin thiocyanate	Feed at 100 mg/kg of body weight/day for 21 days	45 mg/lb	Mainly effective against gram-positive bacteria and is primarily used for controlling bacterial kidney disease in salmonids
Nifurpirinol	Add 10–20 mg nifurpirinol/L, and treat for 2 h Feed 0.45–0.90 mg/kg of body weight/day for 5 days	Immersion method: 3.8–7.2 mg/gallon Through feed: 1–2 mg/lb	These are effective groups of synthetic, broad-spectrum antimicrobials that are usually bacteriostatic but can be bactericidal at high concentrations

(continued)

Table 15.2 (continued)

Name	Type if treatment	Total quantity required	Use
Florfenicol	Feed at 10 mg/kg (= 4.5 mg/lb) of body weight/day for 10 days for treatment of furunculosis or rainbow trout fry syndrome Feed at 6–25 mg florfenicol/kg (= 2.7–11 mg/lb) of body weight/day for treatment of pasteurellosis	10 grams for 1 tonne of fish	It is chemically modified chloramphenicol so that it apparently does not induce aplastic anaemia like chloramphenicol
Enrofloxacin	Feed at 10 mg/kg of body weight/day for 10 days Inject at 5–10 mg/body weight IM as preoperative treatment to prevent infection	Feed at 4.5 mg/lb. Inject 2.2–4.5 mg/lb	Enrofloxacin is a fluorinated quinolone that is active against *Aeromonas salmonicida* and is also useful for treating aquarium fish
Bithionol (syva)	Add 25 mg/l for 3 h on 2 consecutive days to treat ichthyobodosis Add 1 mg bithionol/l (= 3.8 mg/gallon), and treat for 60 min in seawater to treat amoebic gill disease	95 mL/gallon for ichthyobodosis 3.8 mg/gallon for amoebic gill disease	Anthelmintic that can prevent the ichthyobodosis in rainbow trout and amoebic gill disease in Atlantic salmon
Bronopol (Pyceze)	Add 1 mL Pyceze/25 L and treat for 30 min Add 0.1 mL Pyceze™/L and treat for 30 min daily, as necessary, beginning at 24 h after fertilisation for treating water mould infection on eggs	20 mg bronopol/l = 0.15 mL Pyceze™/gallon 50 mg bronopol/L = 0.38 mL Pyceze™/gallon for treating water mould infection on eggs	Against fungal and oomycete infections of salmonids

bags linked to bamboo poles for less waste and decreased antibiotic leaching, unlike the traditional approach of disseminating the feed over the pond.

15.8 Conclusion

The intensification of aquaculture systems has led to the emergence of new pathogens and diseases in aquaculture. Thus strict husbandry management measures should be adopted to prevent the entry and the emergence of enzootic pathogens in aquaculture. The biosecurity protocols provide an excellent approach to avoiding disease incidences in fish farms. Further, several sustainable and environmentally friendly alternatives should be used to prevent the development of antibiotic-resistant bacteria in the culture systems. Disease surveillance and monitoring systems should be employed to check the disease outbreaks and the emergence of new pathogens closely.

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Oomycetes: Fungal-Like Menace in Cold-Water Aquaculture

16

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Abstract

One of the emerging oomycete pathogens of rainbow trout and other salmonids is designated as *Saprolegnia* spp. Rainbow trout and other cold-water fish are most susceptible to *Saprolegnia* infections in early and advanced life stages. *Saprolegnia* has a complicated and well-characterized life cycle that includes both sexual and asexual stages. It has been traditionally identified and distinguished, using patterns of asexual and sexual characteristics, while the sexual characteristics, oospore and lipid droplet position in the oospore, and the asexual characteristics, such as mycelium and germinating cyst, have been most frequently used in identifications. This chapter highlights the morphological and molecular identification of *Saprolegnia* spp., symptoms of *Saprolegnia* infections and control measures, including biocontrol methods.

Keywords

Saprolegniasis · Morphological identification · Molecular characterization · Control measures

16.1 Introduction

Since the 1990s, the main species captured and cultured in the Indian Himalayan regions have been *Oncorhynchus mykiss*, *Schizothorax richardsonii*, *Tor putitora*, *Labeo dero* and *Labeo dyocheilus* (Sarma et al. 2018). Rainbow trout (*O. mykiss*) is

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the most cultured cold-water exotic species in more than 100 countries, including India (FAO 2020). The primary producers of rainbow trout are Iran, Turkey, Chile, Norway, Peru and other European Union countries. In India, trout farming has advanced steadily, and the cold-water aquaculture industry in Himalayan states and union territories has grown exponentially over the past 15 years. Due to intensification, improved feed, infrastructure facilities and trout production in upland states have attained increasing attention (Sarma et al. 2018). Significant impediments to the development of intensive trout aquaculture in India are various health disorders, climate change, old rainbow trout stocks and effluent discharges (Singh 2020; Barat et al. 2015).

Rainbow trout and other salmonids are most susceptible to *Saprolegnia* infections in early and advanced life stages (Mehrabi et al. 2020). *Saprolegnia* is generally considered a secondary infectious agent that causes severe economic losses in cultured freshwater fish, affecting skin, gills and other organs (Van West 2006). Saprolegniasis in fish is mainly caused by *Saprolegnia parasitica* and *S. australis* (Sandoval-Sierra and Diéguez-Uribeondo 2015). *S. parasitica* can cause devastating impacts, leading to 'winter kill' in catfish and accounting for losses up to £24 million, representing 10–50% of farmed fish (Bruno et al. 2011). The losses can even exceed 30–50% annually because of *S. parasitica* infection in coho salmon farming in Japan (Hatai et al. 1990; Bruno et al. 2011). Saprolegniales are responsible for the weakening of fish immune mechanism by haemodilution and production of effector proteins (Van West 2006; Walker and van West 2007; Romansic et al. 2009; Rezinciuc et al. 2014; Van Den Berg et al. 2013; Masigol et al. 2019, 2020).

In India, major bottleneck in rainbow trout farming in flow-through system is the saprolegniasis infection by oomycetes. The fluctuations in water temperature, water currents and poor management practices in farms and hatcheries are the key risk factors for the saprolegniasis. Changes in temperature regime weaken the fish's immune system and provide an environment for developing infections in culture conditions (Sarowar et al. 2014). Further, prolonged incubation period in hatcheries produces oomycetes spores from the dead to healthy eggs, causing significant economic loss at the early stages of fish production.

16.2 Oomycetes: Fungal-Like Organism

Oomycetes or water moulds or fungal-like organisms are eukaryotic microbes different from true fungi with distinct phylogenetic, physiology and biochemical properties (Judelson and Blanco 2005). They have evolved either pathogenic or saprophytic lifestyles and have fungal-like characters such as filamentous hyphae (Kamoun 2003). It causes the most destructive disease in animals, plants and fishes, which results in significant economic losses (Derevnina et al. 2016). They are stramenopile and superficially resemble true fungi with their appearance, ecological niches and physical characters (Verret et al. 2010).

Although fungi and the animal kingdom share a common evolutionary ancestor, oomycetes are more closely connected to golden-brown algae (Table 16.1). The

Table 16.1 Major Oomycetes (*Saprolegnia* sp.) abstracted from India and abroad affecting rainbow trout and other important fish

Species	Host	Region/ country	References
S. parasitica	*Schizothorax richardsonii*	Bhimtal, India	Tandel et al. (2021)
S. parasitica and *S. australis*	Rainbow trout (*Oncorhynchus mykiss*)	Bhimtal, India	Tandel et al. (2021)
S. parasitica	Golden mahseer (*Tor putitora*)	Bhimtal, India	Shah et al. (2021)
Saprolegnia diclina	Tilapia (*Oreochromis niloticus*)	Riyadh, Saudi Arabia	Mostafa et al. (2020)
Saprolegnia parasitica	Stripped catfish (*Pangasianodon hypophthalmus)*	UP, India	Kumar et al. (2022)
S. parasitica	Atlantic salmon (*Salmo salar* L.), ova, fry or brood stock	Canada	Elameen et al. (2021)
S. parasitica, *S. diclina*, *S. salmonis*	Sockeye salmon (*Oncorhynchus nerka*) and Coho salmon (*Oncorhynchus kisutch*)	Japan	
S. parasitica, *S. ferax*, *S. diclina*	Brown trout (*Salmo trutta*) and one strain from common whitefish (*Coregonus lavaretus*)	Norway	
S. diclina *S. ferax* *S. Hypogyana* *S. parasitica* *Achlya americana*	*Channa gachua*, *C. striatus* *C. batrachus* *C. gachua* *H. fossilis*, *Mystus* sp., *C. punctatus* *H. fossilis*, *Labeo rohita*	Andhra Pradesh, India	Mastan (2015)
Saprolegnia parasitica	Rainbow trout (*Oncorhynchus mykiss*)	Iran	Mehrabi et al. (2019)
Saprolegnia parasitica	Pike (*Esox lucius*)	Netherlands	Minor et al. (2014)
Saprolegnia species	Rainbow trout, *Oncorhynchus mykiss*	Tehran, Iran	Johari et al. (2014)
Saprolegnia diclina, *S. ferax* and *S. parasitica*	*C. catla*, *C. mrigala* and *L. rohita*	Bhopal, India	Chauhan et al. (2012)
Saprolegnia diclina	*Clarias batrachus*	Bhopal, India	Chauhan et al. (2012)
S. parasitica	*Tor putitora*	Bhimtal, India	Singh et al. (2013)
Saprolegnia spp.	Nile tilapia (*O. niloticus*)	Egypt	Mahboub and Shaheen (2021)
Saprolegnia australis	Salmonid eggs, *Salmo trutta*	Spain	Rezinciuc et al. (2014)
Aphanomyces invadans	*Labeo rohita*, Tilapia (*Oreochromis niloticus*)	Bangladesh	Sarowar et al. (2019)

(continued)

Table 16.1 (continued)

Species	Host	Region/ country	References
Saprolegnia parasitica	Gilt-head seabream (*Sparus aurata*)	Turkey	Dinçtürk et al. (2019)
Saprolegnia spp.	Rainbow trout	Iran	Tour Savad Kouhi et al. (2021)
Saprolegnia parasitica and *S. australis*	Female crayfish, *Pacifastacus leniusculus*	Sweden	Edsman et al. (2015)
Saprolegnia parasitica and *Saprolegnia ferax*	*Cyprinus carpio var. communis* and *specularis*	India	Magray et al. (2021)
S. delica, *S. ferax*	Rainbow trout (*Oncorhynchus mykiss*)	India	Magray et al. (2021)
Saprolegnia spp.	African catfish (*Clarias gariepinus*) eggs and adults	Ethiopia	Melaku et al. (2017)
Saprolegnia parasitica	White fish (*Rutilus frisii kutum*) eggs	Iran	Kalatehjari et al. (2015)
Saprolegnia spp.	Common carp, *Cyprinus carpio* L.	Iraq	Salih and Mustafa (2017)
Saprolegnia parasitica	Rainbow trout (*Oncorhynchus mykiss*) eggs	Iran	Salehi et al. (2015)
Saprolegnia parasitica	*O. niloticus* and *C. gariepinus*	Egypt	Younis et al. (2020)
S. diclina	*Salmo salar* *Salvelinus alpinus* *Salmo trutta* *Coregonus lavaretus* *Lampetra fluviatilis* *Esox lucius* *Perca fluviatilis*	England	Pickering et al. (1979)
S. parasitica (CBS 223.6) *S. parasitica (ITT 320/15/20)* *Saprolegnia delica (ITT 290/15/15)*	*Esox lucius* *Salmo trutta fario* *Oncorhynchus mykiss*	Italy	Tedesco et al. (2019)
Saprolegnia parasitica	*Oncorhynchus mykiss*	Iran	Khosravi et al. (2012)
Saprolegnia parasitica	*Oncorhynchus mykiss*	Korea	Shin et al. (2017)
Saprolegnia diclina *S. parasitica* *S. hypogyna* *S. ferax*	*Salmo salar*	Norway	Thoen et al. (2015)
Saprolegnia sp.	*Oncorhynchus mykiss* eggs	Finland	Hoskonen et al. (2015)

(continued)

Table 16.1 (continued)

Species	Host	Region/ country	References
Saprolegnia parasitica	*A. leptodactylus*	Sweden	Diéguez-Uribeondo et al. (1994a, b)
Saprolegnia diclina	Pejerrey, *Odontesthes bonariensis*	Japan	Kitancharoen et al. (1995)
Saprolegnia parasitica	*Salmo trutta*	Sweden	Diéguez-Uribeondo et al. (1996)
Saprolegnia parasitica	*Oncorhynchus mykiss*	UK	Pottinger and Day (1999)
Saprolegnia parasitica, *S. diclina*, *S. salmonis*	Rainbow trout, all freshwater species, incubator eggs	Egypt	Hussein and Hatai (2002)
Saprolegnia parasitica, *S. diclina*, *S. salmonis*	Rainbow trout, all freshwater species, incubator eggs	USA	Torto-Alalibo et al. (2005)
Saprolegnia parasitica	*Oncorhynchus mykiss*	Iran	Mirmazloomi et al. (2022)
Saprolegnia parasitica, *S. australis* and *S. ferax*	*Oncorhynchus mykiss*, *Salmo trutta*	Italy	Pavić et al. (2021)
Saprolegnia spp.		Japan	Hatai et al. (1990)
Saprolegnia parasitica	Brown trout, *Salmo trutta fario*	Spain	Diéguez-Uribeondo et al. (1994a, b)

composition of the cell wall, genome size, ploidy structure, many cytoplasmic gene sequences and mitochondrial morphology can all be used to distinguish between biflagellated water moulds and true fungi (Bruno et al. 2011). Plant pathogenic oomycetes, *Phytophthora infestans*, cause late potato blight, which losses UK £3 billion annually (Phillips et al. 2008). Sudden oak death caused by *P. ramorum* and the soybean pathogen *P. sojae* continues to cause serious economic losses to the plant industry (Beakes et al. 2012).

Among the animal pathogenic oomycetes, crustacean pathogen, *Aphanomyces astaci*, has caused high mortalities, virtually wiping out freshwater crayfish from UK rivers (Edgerton et al. 2004). *Haliphthoros milfordensis* and *Homarus americanus* cause disease in lobsters and penaeid shrimp, respectively (Cawthorn 2011; Hatai 1992). Oomycetes, *S. parasitica*, *A. invadens*, *S. australis* and *S. diclina*, are causing cotton wool and ulcers in fishes, such as salmonids and carps (Van West 2006; Phillips et al. 2008).

16.3 Saprolegniasis

One of the emerging oomycetes pathogens of wild and cultivated freshwater and brackish water fish, crustaceans, and plants is designated as *Saprolegnia* spp. (Sarowar et al. 2019). It causes financial losses in food fish, ornamental fish, and overall fish industries (Eissa et al. 2013). Saprolegniasis ordinarily is viewed as cottony white, dark, earthy-coloured, red or greenish masses on the skin or gills of freshwater or salty fish (Yanong 2003). *S. parasitica* causes infections by producing long 'hooked shape boat' second cysts for attachment to fish and then producing hyphae growth to germinate in fish skin/eggs to establish infections finally. It can suppress the host immunity by the production of effector-specific proteins into the host (Sarowar et al. 2019). *Saprolegnia* is responsible for causing infection in living and dead fish and their eggs (Cao et al. 2014).

Mortalities related to *Saprolegnia* are therefore limited to the late autumn, winter and early spring seasons due to the mass mortality, caused by saprolegniosis being especially devastating at lower water temperatures (Eissa et al. 2013). Salmon farming is mostly affected by *S. diclina* and *S. parasitica*, which are generally prevalent in temperate climates like Northwest Europe, Chile, Japan and Canada (Van Den Berg et al. 2013). The emergence of white or greyish cotton-like structures on eggs, gills and skin in the early stages of *Saprolegnia* infections is the first unpleasant symptom. The illness spreads swiftly and frequently results in mortality, which causes massive losses of fish and ova (Howe and Stehly 1998; Stueland et al. 2005a). Loss of equilibrium, lethargy and rubbing infected areas to the borders of tanks or ponds are a few examples of abnormal behaviour (Van West 2006). Oomycete infections spread via a host colonization process that involves destroying the epidermis with hyphae and the development of effectors that target the host (Wawra et al. 2012), respiratory failures, impaired osmoregulations (Van West 2006) and degrading enzymes (Jiang et al. 2013).

16.4 A Typical Life Cycle of *Saprolegnia* sp.

Saprolegnia, an oomycete pathogen, has a complicated and well-characterized life cycle that includes both sexual and asexual stages (Robertson et al. 2009). While sexual reproduction enables survival in unfavourable settings until they are more favourable for germination and further colonization, asexual reproduction is mostly used to acquire new hosts (Van Den Berg et al. 2013). In contrast to true fungi, Saprolegniaceae has life stages like mycelium, primary cyst, secondary cyst and germination cyst (Srivastava et al. 2018). They produce aseptate mycelium for growth and development and are filamentous and coenocyte. Zoospores are formed in sporangia and are unicellular, terminal, biflagellate and separated from hyphal filaments by basal septa (Bruno et al. 2011). The *Saprolegnia* zoospore is dimorphic and diplanetic, consisting of a pyriform primary form with flagellum insertion at the tip and a reniform secondary spore with flagellum insertion at the lateral edge

(Beakes and Ford 1983). The term ‘encysted zoospore’ or ‘cystospores’ refers to a thin-walled cyst formed when a zoospore encysts (Bruno et al. 2011).

16.4.1 Asexual Reproduction

Gemmae (or chlamydospores) are produced during asexual reproduction, and the mycelium’s hyphal cells process sporangia at their tips to release motile primary zoospores (Bruno et al. 2011). *Saprolegnia* mycelium is distinguished by having comparatively broad and thick hyphae (Diéguez-Uribeondo et al. 2007). The hyphae are coenocytic and aseptate. Rarely, septa are created in sporangia or infrequently in germlings, which are sexual structures (Liu et al. 2014). The zoosporangium then produces motile primary zoospores, which encyst to form primary cysts in less than a minute (de la Bastide et al. 2015). Prior to encysting, germinating, and releasing a secondary zoospore, primary zoospores are active for a short period of time (Robertson et al. 2009). The two flagella, tinsel and whiplash, are shed during encystment, and a cell wall is also formed (Minor et al. 2014). A secondary zoospore, or new primary cyst, can emerge from the ensuing primary cyst (Bruno et al. 2011). Primary cysts have tufts or solitary, unbranched tubular hairs between 0.5 and 1.5 μm in length, extending over them (Ali et al. 2013).

Compared to primary zoospores, secondary zoospores are motile for a longer time. The most infectious stages after encyst, secondary zoospores, cause secondary cysts to develop, which are distinguished by the appearance of long, hooked hairs (Söderhäll et al. 1991). Finding a suitable host (a fish or an egg), secondary zoospores develop into hyphal cells and mycelium in the host tissue, which starts the infection process (Van Den Berg et al. 2013). To locate a suitable host, these zoospores display chemotaxis, pH-taxis, geotaxis and electrotaxis (Masigol et al. 2020). Wide, coenocytic germ tubes loaded with cytoplasm are characteristics of direct germination. Following the period of rest, germination occurs; once germination has taken place, the life cycle may be shortened (Willoughby and Hasenjäger 1987). Production of effector host-targeting proteins, impaired osmoregulations, respiratory failures (Wawra et al. 2012; Van West et al. 2010), impaired osmoregulation, epidermis destruction by hyphae, destruction of the epidermis by hyphae (Belmonte et al. 2014), respiratory failures (Van West 2006) and degrading enzymes, such as glycosyl hydrolases, are all part of the oomycetes (Jiang et al. 2013). According to Rezinciuc et al. (2018), *S. parasitica* cysts feature long, hooked hair bundles that are involved in pathogen attachment and are approximately three times stronger than other *Saprolegnia* spp. that have shorter or no hooked hairs.

16.4.2 Sexual Reproduction

Gametangia, the male antheridium and female oogonium, are produced during sexual reproduction and merge to produce oospores (Van West 2006). Large oospores or eggs are produced by the oogonium, which varies in size, shape and number depending on the species. To conserve food reserves, saprolegniales' oospores feature a core ooplasm, a granular appearance and significant amounts of lipid (Diéguez-Uribeondo et al. 2009). Half as many chromosomes as those seen in the nuclei of hyphae are present in a male haploid (n) nucleus (Bruno et al. 2011). The only morphological identification source for species categorization and characterization is the characteristics of oospores, antheridium and oogonia. However, it can be difficult to maintain sexual reproductive stages in a lab environment, and many *S. parasitica* isolates do not engage in sexual reproduction (Fugelstad et al. 2009). After 4–6 weeks of suboptimal temperature, several isolates of *S. parasitica* frequently reproduce sexually (Bulone et al. 2019).

16.5 Morphological Identification

The basic steps for diagnosing *Saprolegnia* infections include morphological characteristics (Table 16.2) such as oogonium ornamentation, antheridium origin and oospore forms; nevertheless, confirmation research using multiple molecular methods is necessary (Tandel et al. 2021). *Saprolegnia* has been traditionally identified and distinguished using patterns of asexual and sexual characteristics (Bangyeekhun et al. 2001). While the sexual characteristics, oospore and lipid droplet position in the oospore, have been used to differentiate species, the asexual characteristics, such as mycelium and germinating cyst, have been most frequently used in identifications (Maurya et al. 2009). The length of this bundle of long, hooked hairs produced by *Saprolegnia* spp. on secondary zoospore cysts varies depending on the strain of oomycetes (Hatai 1994). On its secondary zoospore cyst, *S. hypogyna* may generate a single, long, straight hair. It also has an esterase isoenzyme similar to that of *S. parasitica* (Hatai and Hoshiai 1993). *S. parasitica* does, however, have a single short hair slightly wider than *S. diclina* (Hussein and Hatai 2002). By examining the production of hypogynous antheridia in the latter phase, isolates of *S. ferax* and *S. hypogyna* were distinguished from one another (Hatai and Hoshiai 1992). However, maintaining the sexual stages in lab settings is difficult.

16.5.1 *Saprolegnia parasitica*

Coker (1923) described *S. parasitica* from the fish hatchery. Kanouse (1932) explained the reproductive structures of *S. parasitica* Neish (1977) and reported that *S. parasitica* isolates producing reproductive structures may be assigned to *S. diclina* (Humphrey 1893). As a result, the *S. diclina-S. parasitica* complex developed, which included the five species *S. parasitica*, *S. diclina*, *S. australis*, *S. shikotsuensis* and *S. Kauffmania*. Willoughby et al. (1983) divided the complex into three subgroups based on the following: S. diclina Type I contained fungi that parasitized salmonid fishes, Type 2 was a parasite of coarse fish and Type 3 was saprophytic (Hatai 1994). The presence of long hairs on the secondary cysts, the

Table 16.2 Morphometric characteristics of *Saprolegnia* sp.

Life stages	*Saprolegnia parasitica*	*S. australis*	*S. diclina*	*S. ferax*	*S. salmonis*	*S. hypogyna*
Mycelium	Branched, with average width of 35–39 μm	Dense and diffuse	Moderately branched with average width of 35 μm	Sparingly branched with (average width of 42–44 μm		
Sporangia	Usually variable bent and irregular with average width of 325 μm	Renewed internally, cylindrical; divides into larger primary with 250 × 32 μm long, secondary up to 600 μm long	Curved cylindrical, with 420–480 μm long	Irregular, spherical or cylindrical with average 352–951 μm long		
Spore	Dimorphic with 9–11.5 μm long	Dimorphic; discharge	Dimorphic, encysted spores with diameter of 9–12 μm	Same as diclina		
Cyst	Average diameter 10–11 μm	Average diameter 11 μm	Average diameter 11 μm, spherical gemmae	Average diameter 9–11 μm		
Oogonia	Lateral or terminal with diameter between 86 and 110 μm	Lateral or terminal or intercalary with diameter between 59 and 80 μm	Required higher incubation period to culture, when grows to intercalary or terminal, lateral or with diameter of 50–70 μm	Lateral or terminal or intercalary with diameter between 60 and 80 μm in	Abundant, spherical shaped and elongated with antheridial	
Oospore	Lateral or terminal but rarely catenulate, with 86–110 μm diameter	Rarely mature to sub-centric; with 4–12 per oogonium, 22–27 μm diameter	Centric or spherical with 6–26 per oogonium and diameter between 14 and 28 μm	Centric or spherical with 14–28 μm per oogonium, 15–63 μm in diameter		
Antheridia	Antheridia diclinous	Branched or tubular	Simple	Generally tubular		Without antheridial branch
References	Vega-Ramírez et al. (2013) and Refai et al. (2016)	Refai et al. (2016)	Refai et al. (2016) and Vega-Ramírez et al. (2013)	Masigol et al. (2020)	Masigol et al. (2020)	Vega-Ramírez et al. (2013)

degree of indirect germination and isolation were used to identify the asexual *S. parasitica* species (Willoughby 1985; Beakes and Ford 1983). Long, hooked hairs arranged in bundles on the secondary cysts and indirect germination in a liquid media with little nutrition are hallmarks of *S. parasitica* (Bruno et al. 2011; Lone and Manohar 2018). According to Diéguez-Uribeondo et al. (1994a, b), *S. parasitica* was characterized based on the ornamentation of the cysts and the pattern of germination from brown trout; physiological traits such as sporulation, zoospore mobility and repeated zoospore emergence are not used to identify the species but may be used to determine pathogenicity and host specificity.

The majority of *Saprolegnia*, isolated from salmonids, exhibit *S. parasitica*-like traits. Nevertheless, even if they have these distinct physical traits, the toxicity of *Saprolegnia* strains reported from challenge trials may vary considerably (Yuasa and Hatai 1996; Fregeneda Grandes et al. 2001). Then, many authors disagree with these descriptions, and molecular markers have been used to corroborate the identification further. This can be done by employing phase-contrast microscopy to examine the intricate structure of the secondary zoospore cyst of *S. parasitica* (Inaba and Tokumasu 2002; Bangyeekhun et al. 2003). Diéguez-Uribeondo et al. (2007) showed that isolates representing varied geographical and morphological are a component of the same genetically homogenous lineage. Vega-Ramírez et al. (2013) described *S. parasitica* with characters such as abundant gemmae with irregular shape and size, often in the chain and terminating and intercalary hyphae. Irregular, bent sporangia contain 9–11.5 μm zoospore and the bundle of long, hooked hair and germination pattern. Ali et al. (2013) reported that *S. parasitica* isolates could co-develop biofilm communities where they could grow and breed. They also investigated *S. parasitica*'s ability to create biofilms for survival, reproduction and resistance against various drugs, used to control it. According to physical characteristics such as aseptic hyphae, clavate zoosporangiums, saprolegnoid zoospore discharge and the absence of sexual features, Kim et al. (2013) identified *S. parasitica* from wild brook lamprey with morphological characters showed aseptic hyphae, clavate zoosporangium, saprolegnoid zoospore discharge, whereas sexual characters were absent. A secreted serine protease from *S. parasitica* called SpSsp1 has been identified by Minor et al. (2014) as a possible vaccine target. SpSsp1 appears to be recognized by antibodies in trout serum. The function of *S. parasitica*'s bundles of long, hooked hairs as attachment structures is supported by microscopic, physiological and bioinformatics pieces of evidence. The structures are either made of N-glycosylated proteins, or they may help spread the cyst extracellular matrix on the host surface (Rezinciuc et al. 2014, 2018).

Saprolegnia species and their close oomycete relatives invade epidermal tissues of a wide range of freshwater unusually cold-water fishes and infest moribund eggs (Wilson 1976; Neish and Hughes 1980; Willoughby et al. 1983). More saprophytic species, like *S. diclina*, are typically isolated from water and sporadically from fish or eggs that have already contracted the disease. However, these isolates lack the long hairs on secondary cysts and typically cannot kill fish that have been intentionally challenged (Hatai 1994). The morphological characteristics of *S. diclina* include sub-centric oospores, and lack of centric oospores differs it from *S. parasitica*. The water moulds are mycelium-forming microfungi spread by spores, conidia or hyphal fragments. It has been found that it is challenging to specify species only based on morphology (Chukanhom and Hatai 2004). Fregeneda Grandes et al. (2001) opined that many bundles per cyst could be pathogenic isolates despite features like bundles of long and variable hair termination under transmission electron microscopes. In support of this, Stueland et al. (2005a) also suggested pathogenicity indicators, an initial growth rate of germinating cyst in pure water and long, hooked hairs on the secondary cyst of *S. parasitica* in Atlantic salmon. Particular morphological characters of *S. parasitica* are long, hooked hairs in the bundle of the secondary cyst and indirect germination in a low nutrient liquid medium. However, *S. diclina* lacks such type of characters and cannot produce any mortality in challenge trials. The complicacy in overlapping morphological characters and the development of sexual characters in lab condition for particular species are the critical issues in morphology-based species identification method (Tandel et al. 2021).

16.5.2 *Saprolegnia australis*

S. australis is closely related to *S. parasitica* and *S. diclina* and is often overlooked due to its high morphologically and phylogenetically closet to other species of *Saprolegnia* (Johnson et al. 2002). Sexual reproduction characters in culture within a short period of incubation, such as pitted oogonia with variable shapes, predominantly obpyriform with immature and mature oospores, are morphologically closet with the characters of *S. diclina* and *S. australis* (Tandel et al. 2021). *S. australis* has been isolated from infected eggs of salmonids, crucian carp in Southern China and Nile tilapia in Egypt (Liu et al. 2015; Zahran et al. 2017), and the species is reported to be pathogenic in opportunistic condition (Sandoval-Sierra et al. 2014). Vega-Ramírez et al. (2013) opined that long-stalked pitted obpyriform, elongated or spherical oogonia with partially or nearly filling sub-centric oospores and predominantly diclinous antheridial branches are the distinguished features of *S. australis* and *S. diclina*. Similar results were reported in sequence analysis of *Saprolegnia* from crucian carp eggs in Southern China and Nile tilapia (El-Ashram et al. 2007; Zahran et al. 2017).

Morphological characters of *S. australis* described briefly by Vega-Ramírez et al. (2013) include dense to diffuse mycelium; slender hyphae and cylindrical sporangia dimorphic spores; abundant gemmae; and clavate, single terminal or intercalary, pitted and smooth wall with terminal oogonia. Oogonial stalks in length: straight, curved, twisted or irregular and unbranched. Sexual characters include oospores that may or may not mature or may abort; when mature, sub-centric; spherical to sub-spherical; 4–12 per oogonium, but usually not filling it; 22–27 μm in diameter; germination not observed—antheridial branches, predominantly diclinous, monoclinous or androgynous. Antheridial cells branched or straightforward, persisting; tubular or attached in a digitated fashion; fertilization tubes present or absent, not persisting.

16.5.3 *Saprolegnia diclina*

S. diclina belongs to the order Saprolegniales (water moulds), causing saprolegniasis. *S. diclina* and *S. parasitica* are considered the extremely serious fungal diseases affecting freshwater fishes, leading to high mortality of fish and significant fin ancial losses to aqua hatcheries (Thoen et al. 2011; Van Den Berg et al. 2013; Songe et al. 2016).

The presence of abundant diclinous antheridial branches of this heteroecious species, which completely or partially envelop the oogonia, makes it easily identifiable. Both centric and sub-centric oospores are produced by *S. diclina*, and the two can coexist in the same oogonia. Milanez (cited by Johnson et al. 2002) observed sub-centric oospores in the oogonia in several of his specimens of Humphrey's species. Three variants of *Saprolegnia diclina* (parasitic forms from salmonids and perch and exclusively saprophytic ones) have been discovered by Willoughby et al. (1984) based on the length-to-diameter ratio of the oogonium. The occurrence of species has been reported from various regions such as in Canada, Czechoslovakia, Denmark, France, Finland, Germany, Iceland, India, Iraq, Japan Mexico, Belgium, the British Isles, Latvia, Middle Europe, Switzerland, the USA, the West Indies Nepal, Poland, Portugal, the Republic of China, Romania and South America (Johnson et al. 2002).

S. diclina is generally saprophytic, feeding on dead plant and animal tissues. However, it is also competent in a parasitic extant, making them facultative necrotrophs. *S. diclina* are primarily thought of as opportunistic secondary pathogens usually common in freshwater environments attacking the host in distress conditions (for instance, when they are infected by other pathogens, they suffer injuries or are exposed to environmental circumstances that are unfavourable) (Songe et al. 2016). The primary disseminative and means of infection in the life cycle of fungus are thought to be the countless sporangia that are produced by each expanding colony and released in enormous quantities as motile zoospores. The rate of spore release from infected fish might exceed 190,000 per minute (Willoughby and Hasenjäger 1987).

Effects of hyphal infection, which spreads swiftly among neighbouring eggs, lead to the destruction of aquaculture hatcheries (Smith et al. 1984). According to several studies (Cao et al. 2014; Rand and Munden 1993), *S. diclina* primarily infects fish eggs, and it has been hypothesized that this species has altered to specialize in egg invasion (Diéguez-Uribeondo et al. 2007).

S. diclina infection caused substantial alterations in the eggs of females, including an almost entirely destroyed and somewhat invisible chorion (Songe et al. 2016). According to Rand and Munden, incursion of live fish eggs by *Saprolegnia* strains may be favoured/eased by both mechanical pressure and their mycelia's enzymatic activity. They discovered enzymes on *S. diclina*-infected brook char eggs and hypothesized that these enzymes may have changed the chorionic membrane's integrity by dissolving structural polymers and allowing hyphae penetration.

16.5.4 *Saprolegnia ferax*

S. ferax, a member of Saprolegniaceae, is also considered an important pathogen causing saprolegniosis in embryonic stages of fish and amphibians (Cao et al. 2014; Fernández-Benéitez et al. 2011; Sarowar et al. 2014). These species are ubiquitous in freshwater ecosystems, more often seen as parasites than as saprophytes, and under some circumstance opportunistic pathogens as well, multiplying on fish that have physical wounds, are under stress or have infections (Pickering and Willoughby 1982). *S. ferax* species is known to cause ulcerative cutaneous necrosis (Kaminskyj and Heath 1996). Wani et al. (2017) reported the discovery of *S. ferax* for the first time in India in the waterbodies of Pachmarhi, Hoshangabad, India.

Oospores which can be central or sub-centric and spherical or elliptical and which are 10–18 in number nearly fill the oogonium, measuring 22–28 m in diameter, with gemmae having varying size and orientation, making the monoecious *S. ferax* distinguishable. Ordinarily, it can be distinguished by a combination of prevalent characteristics, such as broad, sparsely or conspicuously pitted oogonia, oospores which may be centric and sub-centric (at times within the same oogonium), discharged sporangia exhibiting oogonial sporadic development as well as the prevalence of monoclinous antheridial branches or androgynous.

The *S. ferax* mitochondrion's 47 kb compact circular genome, which codes for rRNA genes, 18 respiratory chain proteins, 37 protein, 16 ribosomal proteins, 25 tRNA genes, the import protein secY as well as large and small ribosomal subunits, has been discovered through the process of sequencing, and the division of genome into two single-copy sections is attributed to 8618 kb inverted repeat (Grayburn et al. 2004).

Asia, Australia, Belgium, British Isles, Canada, Czechoslovakia, Denmark, France, Germany, India, Iraq, Japan, Lapland, Latvia, Middle Europe, Nepal, the Netherlands, Poland and the United States all have reported *S. ferax* in their regions (Johnson et al. 2002).

16.5.5 *Saprolegnia delica*

It is one of the members of water moulds, characterized by the presence of white growth that resembles cottony wool and is common to all oomycetes. The species isolate is found to own fibrous, elongated, tapering hyphae containing zoospores within circular ends as well as a robust, non-septate mycelium growing in coenocytic hyphae at tips.

S. delica possess various life cycle stages, including cylindrical tapering zoosporangium and a mono-hyphae with multinucleated cytoplasm. Zoospores and oospores, found in the sexual and asexual structures such as the zoosporangium and oogonium, could be clearly seen when viewed under the microscope. In addition, many smooth-walled (pitted or unpitted) oogonia, each containing 5 to 22 sub-centric oospores, are believed to be present, measuring 12 to 35 μm in diameter (Magray et al. 2021). Variable antheridial cells (monoclinous or androgynous) either branched or unbranched have been found apically connected to the oogonia.

S. delica is a pervasive opportunist pathogen that may infect both rainbow trout and carp fingerlings. Several earlier investigations support the development of necrotrophic and facultative nature (deriving food from both living and dead tissues) of the *S. delica* species, thereby infecting both rainbow trout eggs and fingerlings of carps (Fregeneda-Grandes et al. 2007; Songe et al. 2016). From the investigation conducted by Rezinciuc et al. (2018), it was concluded that prolonged mortality of farmed *Salmo trutta* eggs was caused by *S. australis*, which is known to show relatedness to *S. delica*, and designated oomycetes as fundamental diseases of fish and their embryos.

Moreover, *S. delica* and other *Saprolegnia* species are considered dangerous to certain other fish species of freshwater, their embryos/young ones and even other aquatic organisms due to their intrusive infection in Atlantic salmon and salmon eggs (Phillips et al. 2008; Chukanhom and Hatai 2004). *Saprolegnia* species actively inhibits the host immunity, while the main infestation is ongoing, paving the way for it to enhance infections; therefore, it is probable that *S. delica* together with *S. ferax* and *S. parasitica* will arise as the main disease of fish and other aquatic life.

The histopathological evidence of saprolegniasis, caused by *S. delica* to fish fingerlings, whereby necrosis, skin infection, lesions, degeneration of scales and rotting of fins occurred, is corroborated by earlier studies making it a potential risk to the viability/profitability of aquaculture sector (Margay et al. 2021).

16.6 Symptoms of *Saprolegnia* Infections

Fish infected by *Saprolegnia* sp. exhibits white patches of mycelium on their skin, gills and fins. According to Pickering and Willoughby (1982), oomycete patches may contain one or more *Saprolegnia* species and turn grey due to the presence of bacteria and detritus (Bruno and Wood 1999). According to Noga and Dykstra (1986), oomycetes differ from fungal infections in fish, and it typically causes superficial infections that spread from the skin to internal organs and produce a mass of mycelium resembling a cotton ball. Oomycetes also elicits a very mild mononuclear inflammatory response. The mycelium is in charge of creating and dispersing motile zoospores, which can germinate when attached to a new host and form new mycelial mats. On the fish skin, particularly around the head, dorsal and caudal fins, gills, muscular layer and internal organs, the disease's gross symptom often appears as a relatively superficial, cotton wool-like, white proliferation of mycelia (Hussein et al. 2001). In *Anguilla anguilla*, *Saprolegnia diclina* infections led to clinical signs and histological abnormalities such as epithelium loss, ulcerations, oedema and myofibrillar degeneration, according to Pickering and Willoughby (1982). *Saprolegnia* can function as primary or secondary ectoparasite. The fish may become more susceptible to saprolegniosis as a result of stressors such as handling, other infections, mechanical injury, sexual maturity, temperature changes, inadequate hygiene or social interactions, according to Diéguez-Uribeondo et al. (2007). Low water temperature, handling, spawning times and injury were reported as predisposing factors for *Saprolegnia parasitica* in Nile tilapia. Zahran et al. (2017) also described clinical signs, including cotton wool-like white to dark grey growth due to *S. parasitica*. Osmoregulatory dysfunction and electrolyte homeostasis disruption are the main causes of death (Thoen et al. 2011). The loss of protective mucus from the epidermis caused by a sudden drop in water temperature makes it easier for zoospores to connect to the skin and cause infection (Fregeneda-Grandes et al. 2007).

Histology provides in-depth insight into the health of a fish's whole environment and aids in the pathogen identification process (Aranguren and Figueras 2016). Several publications have documented the histological changes, caused by *Saprolegnia* species infections in fish eggs and other organs (Hussein et al. 2001; Songe et al. 2016; Shin et al. 2017). *S. parasitica* causes osmoregulatory issues by destroying the fish's epidermis and dermis layers (Pickering and Willoughby 1982). However, hyphae destroy the chorionic membrane, which controls the osmosis of embryo, in fish eggs (Liu et al. 2014). According to microscopic histopathology study, *Saprolegnia* hyphae enter epidermal tissues, causing cellular necrosis and penetrating the muscle and blood vessels of the infected fish (Shin et al. 2017). *S. parasitica* infections result in epidermal and dermal alterations, such as spongiosis in the epidermis, haemorrhagic foci or mononuclear inflammation between the thick layer of connective tissues (Gieseker et al. 2006). However, *S. parasitica* harms the eggs by piercing the intact chorion with hyphae, but *S. diclina* is finished with the chorion (Songe et al. 2016). Bly et al. (1992) described histological alterations brought on by saprolegniasis and looked at the destruction of mucus-secreting cells, the absence of leucocytes and the presence of fungal hyphae at the lesion's degraded dermal surface. In *S. parasitica*-infected *Ctenopharyngodon idella*, gill histology revealed severe necrosis, disappearance of branchial epithelium and loss of epithelial interlayer with secondary lamellae (de Freitas Souza et al. 2019).

16.7 Molecular Description of *Saprolegnia* spp.

DNA fingerprinting, genetic diversity by random amplification of polymorphic DNA (RAPD-PCR), internal transcribed spacer (ITS) regions of ribosomal DNA genes and nuclear ribosomal DNA (nrDNA) are used in the molecular identification and characterization of *Saprolegnia* spp. (Sandoval-Sierra and Diéguez-Uribeondo 2015). *Saprolegnia* spp. are responsible for the disease in the wild as well as cultured aquatic animals. Therefore, there is an increasing interest in the identification and characterization of pathogenic *Saprolegnia* isolates. It has not been possible to distinguish the species based on sexual reproductive characters due to ambiguity, which often fails to produce sexual and asexual characters of the genus *Saprolegnia* (Johnson et al. 2002). To resolve the taxonomic identification ambiguities in *Saprolegnia*, different molecular tools have facilitated species identification through sequencing of internal transcribed spacer (ITS) regions of ribosomal DNA genes, the nrDNAs (White et al. 1990; Diéguez-Uribeondo et al. 2007).

Additionally, *Saprolegnia* typing techniques like random amplified microsatellite polymorphism (RAMP) and random amplification of polymorphic DNA (RAPD-PCR) allow differentiation between genotypes of *Saprolegnia* isolates (Bangyeekhun et al. 2003; Naumann 2014). The fish pathogenic *Saprolegnia* genome has been analysed, using restriction fragment length polymorphisms (RFLPs) and Random amplification of polymorphic DNA (RAPD). DNA polymerase chain reaction (RAPD-PCR) methods offer a sensitive and quick assay for determining the genetic distance between various *Saprolegnia* isolates. Random amplified polymorphic DNA (RAPD)-PCR has been used within the oomycetes to distinguish different strains and species.

To distinguish between numerous *Saprolegnia* strains and species more effectively, it would be highly desired to develop fingerprinting techniques like multilocus sequence typing (MLST), microsatellites or one of several polymorphism techniques (Molina et al. 1995). Molecular characterization of fish pathogenic *Saprolegnia* is helpful for advancing epidemiological investigations into the point of infection, how the disease spreads and how to control it. Saraiva et al. (2014) characterized the tyrosine gene encoding the mono-oxygenase enzyme that catalyses the O-diphenols to quinines from *S. parasitica* for melanin formation and suggested that the application of gene silencing can be used to characterize gene functionally.

16.8 Control of *Saprolegnia* sp. in Aquaculture

Due to mutagenicity, teratogenicity and carcinogenicity, the use of malachite green, n-methylated diaminodiphenylmethane as fungicides or ecto-parasiticide has been prohibited since 2002 (Srivastava et al. 2004). Moreover, permitted chemical formulations and treatments, such as formalin and hydrogen peroxide, pose a significant risk to people and wildlife. Therefore, they will probably be outlawed soon. Therefore, attempts have been made to find out alternative antimycotic medicines that are suitable for fish of all the life stages and are safe and efficacious (Shah et al., 2021). Formalin, copper sulphate, hydrogen peroxide, boric acid, ozone, iodophor, sodium chloride and peracetic acid are among the alternatives to malachite green. Biocontrol agents like bacteria and some of the bioactive ingredients like curcumin, cinnamaldehyde and eugenol are still under investigation for fish.

To prevent fungus infections in aquaculture, formalin (an aqueous solution of 37% formaldehyde) is frequently used (Gieseker et al. 2006). A practical and safe dose of 150–300 mg/L formalin gives protection against *Saprolegnia* in rainbow and brown trout (Seymour 1970). However, Bailey and Jeffrey recorded effective control of fungal outbreaks in rainbow trout, following a 60-min exposure at 250 ppm. Bly et al. (1996) reported 12.5 mg/L formalin for zoospore inhibition and being suppressive at 7.5 mg/L for channel catfish. Gieseker et al. (2006) said 100 mg/L was very useful and reduced 29% mortality in rainbow trout. Willoughby (1985) reported that acriflavine at a dose of 750 mg/L improves tilapia eggs' hatchability. US Food and Drug Administration, USFDA, in 2018, has approved formalin for egg treatment in aquaculture. Still, formalin has been banned or discouraged in several countries because of its harmful effects (Romansic et al. 2006).

Furthermore, the use of formalin in fish is uneconomical and undesirable as fish are destined to human consumption. Boric acid or boracic or borax is a weak acid with antifungal properties which have been demonstrated against *Candida glabrata* (Ray et al. 2007), *C. vaginitis* (De Seta et al. 2009) and against *Saprolegnia* sp. (Ali et al. 2014). The mechanism of action as an antifungal is the disruption of fungal cell wall (Lilley and Roberts 1997), mitochondrial degeneration or disruption and inhibition of oxidative metabolism or enzymes that are toxic to *Saprolegnia* sporulation and germinations (Ali et al. 2014, 2019). Boric acid is a hydrate of boric oxide: the weak conjugate acid of a dihydrogen borate, which is reported as antiseptic, anti-oomycetes, antifungal and anti-viral. It is used to control *Saprolegnia* infection in eggs and yolk-sac fry. Ali et al. (2014) studied the in vitro efficacy of boric acid, which decreased *Saprolegnia* spore activity, and mycelial growth at a concentration of above 0.2 g/L.˙ The complete inhibition of germination growth was observed at a concentration of 0.8 g/L. Peracetic acid is a mixture of acetic acid and hydrogen peroxide, which disintegrates to hydrogen peroxide and acetic acid when dissolved in water (Straus et al. 2012). Peracetic acid degradation products are non-toxic and can easily dissolve in water.

Copper sulphate acts as an anti-oomycete by disturbing energy biogenesis, protein synthesis and developing internal oxidative stress (Hu et al. 2016). Copper sulphate is approved as algicide, herbicide and molluscicide by US Environmental Protection Agency, and also it is listed in Allowed Synthetic Substances by USDA National Organic Program (NOP) for use in organic livestock production. It is demonstrated as an anti-parasiticide, i.e. *ichthyophthiriasis* (Noga 2010), and acts against saprolegniasis in channel catfish (Straus et al. 2012). The recommended dose is 10 mg/L for channel catfish, for *Ictalurus punctatus* eggs and also for North African catfish, *Clarias gariepinus* fry and yolk-sac stages (Ataguba et al. 2013), 0.5 mg/L for the inhibition of *S. parasitica* mycelium and 1 mg/L for reduction of primary zoospore in grass carp, *Ctenopharyngodon idella* (Sun et al. 2014).

The efficacy of sodium chloride (NaCl) as an antifungal and environment-friendly agent has been reported by many authors in freshwater finfish aquaculture (Khodabandeh and Abtahi 2006). NaCl acts by changing osmotic gradient, thereby increasing osmoregulation (Stockwell et al. 2012). Rasowo et al. (2007) reported 1000 ppm NaCl concentration with 30-min exposure to effectively control saprolegniasis during egg incubation in *C. gariepinus*. However, Pérez et al. (2003) suggested 2500–5000 ppm for crayfish, and Ali et al. (2011) advised 8000 ppm and 12,000 ppm for *Saprolegnia diclina* and *Aphanomyces,* respectively. Iodine has been applied in the hatchery production of rainbow trout for routine disinfection of eggs once they reach the eyed stage. The recommended dose is 50 mg/L for 5 min (Stueland et al. 2005b) and 60 mg/L as bath up to 30 min (Eissa et al. 2013).

16.8.1 Environment-Friendly Control Measures of Oomycetes Infections in Fishes

As alternatives to teratogenic agents, Frenken et al. (2019) proposed seven biological concepts for protecting aquatic organisms, amphibians and plankton against zoosporic diseases, which may be useful, less harmful and more sustainable than the available chemical methods. Which includes prevent or reduce transmission (control of distribution pathways) and vectors, increase the diversity of host species, vaccination and immunization, stimulate defence and production of antifungal peptides by the host, use probiotics hyperparasitism, and use parasite eaters.

There has been a significant achievement in controlling saprolegniasis in aquaculture, which includes the use of immunostimulants in feed such as pyridoxine (Saha et al. 2016), fluconazole (Saha et al. 2017) and miconazole nitrate (Singh et al. 2018), for *Labeo rohita*. The aloe vera (*Aloe barbadensis*) (Mehrabi et al. 2019), dietary nettle (*Urtica dioica*) (Mehrabi et al. 2020), muli bamboo (*Melocanna baccifera*) (Khan et al. 2018) leaves ethanolic extract, and 1,3; 1–6- β-D- glucans has also been tried to control saprolegniasis (Hamad and Mustafa 2018). The inhibitory activity of antibacterial metals such as silver zeolite (Nemati et al. 2019) and copper nanoparticles was used to control saprolegniasis in white fish, *Rutilus frisii kutum* eggs (Kalatehjari et al. 2015). Recently, commercial formulations like Vikron-S (Rahman and Choi 2018); addition of bacterium (*Aeromonas* media strain A199), *Burkholderia* sp. HD05 (Zhang et al. 2019), quellenin from *Aspergillus* sp. (Takahashi et al. 2018) and cladomarine from *Penicillium coralligerum* YK-247 (Takahashi et al. 2017); as well as the use of antimicrobial peptides (antifungal peptide from *Pseudomonas* protegens XL03) (Wang et al. 2011) have been used for the control of saprolegniasis in aquaculture.

16.9 Conclusion

Oomycetes, which resemble fungi, are many of the pathogens that cause devastating diseases in cold-water aquaculture. Around the world, saprolegniasis significantly reduces the production and profitability of trout farms and hatcheries. Despite these hurdles, the use of hazardous chemicals and the lack of suitable therapies make existing fungal management strategies in cold-water aquaculture ineffective and unsustainable. In order to address the issue, new techniques to control/treat infectious diseases may be examined, including the use of plant extract, novel drug delivery vehicles and natural-origin substrates/compounds or essential oils.

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17 Antimicrobial Peptides: An Alternative to Antibiotics for Environment-Friendly Hill Aquaculture

Vinita Pant, Khangembam Victoria Chanu, and Dimpal Thakuria

Abstract

Antimicrobial peptides (AMPs) are emerging as promising alternative to antibiotics, especially due to their activity against drug-resistant pathogenic strains. A vast number of AMPs have been characterized and purified from various natural sources, ranging from bacteria, fungus, plants, to higher vertebrates including mammals. Many of them have also been produced using either chemical synthesis or the recombinant technology. Both synthesized and expressed AMPs showed significant inhibitory activity against a number of economically significant pathogens. Majority of AMPs kill pathogens by disruption of cell membranes. Hence, chances of developing resistance by the microbes are less. Fish are reservoirs of these peptides, and they express majority of AMPs. However, application of AMPs in field condition is not at advanced stage, which may be due to issues like cost of production, stability, and toxicity to host cells. This can be addressed through artificial designing of short peptides to reduce the manufacturing cost and to enhance stability. AMPs not only kill microbes directly but also help in immunomodulation and may be highly useful for fish, which mainly depends on its innate immune system to fight against pathogens.

Keywords

Antimicrobial peptides · Classification · Mechanism of action · Fish · Artificial AMP · Production of AMP

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17.1 Introduction

Natural defense systems are vital for survival of organisms in varying conditions and environments. In vertebrates, this system is composed of two subdivisions, the innate immune system and the adaptive immune system. The innate immune system acts quickly and non-specifically providing the first line of defense against invading pathogens. It is not specific to a particular antigen and has no immunologic memory. On the other hand, adaptive immunity is antigen specific and has memory, enabling the host to produce effective immune response on later exposure to the antigen (Marshall et al. 2018). In fish, innate immunity is the central mechanism of defense as their adaptive immune system has some constraints such as limited repertoire of antibodies, affinity maturation and memory, and slow proliferation of lymphocytes (Magnadóttir 2006).

Innate immunity acts through defense mechanisms, physical barriers such as the skin which prevents the entry of pathogens, cellular components (e.g., macrophages), and humoral responses (e.g., antimicrobial peptides), which may produce direct bactericidal effects (Magnadóttir 2006). Antimicrobial peptides (AMPs) are gene-encoded, ribosomally synthesized, host defense peptides carrying a net positive (cationic) and has molecular weight less than 10 kDa (de Zoysa et al. 2015; Raju et al. 2020). AMPs are mainly encountered at the portal of pathogen entry that encompass circulating myeloid cells and skin and mucosal and epithelial surfaces where they are usually stored in secretory granules, destined for extracellular secretion (Adem Bahar and Ren 2013). The main tissues or organs of fish that are at the high-risk targets of pathogens are epithelial cells of the skin, gills, gastrointestinal tract, gut, and respiratory organs. Hence, AMPs are typically localized in these tissues (Scocchi et al. 2016). AMPs are synthesized as pre-proproteins that include a signal sequence which undergoes hydrolytic degradation to form the active molecules (Raju et al. 2020). They are conserved effector molecules that play a key role in the first line of defense against invading pathogens prior to the activation of adaptive immunity. Although these peptides are enormously diverse in terms of their biosynthesis, sequences, and structures, they all share certain structural characteristic features like small size (<100 amino acids), cationic nature at physiological pH, amphipathicity, broad-spectrum antimicrobial activity, and similar mode of action (Sathyan et al. 2012; Chaithanya et al. 2013). The cationic nature of AMPs helps them in initial binding with the anionic bacterial surface, and their amphipathic nature enables them to ravage the bacterial membrane structure, ultimately killing the bacteria (Brogden 2005). In most organisms, AMPs are multifunctional molecules that are involved not only in attacking the pathogen but also in other important biological functions like immune modulation, wound healing, and cancer cell growth inhibition and/or as signaling molecules, for example, hepcidins, besides acting as antimicrobial, are also involved in iron regulations (Shi and Camus 2006; Tincu and Taylor 2004). The common functional characteristic of most AMPs is their induction, following the exposure of host to pathogen-associated molecular patterns (PAMPs) (Rončević et al. 2020). Their expression is either constitutive (within secretory cells) or upregulated during an infection, highlighting their role as antimicrobial. The induction pathways for AMP synthesis have been conserved evolutionarily in almost all organisms (Hancock and Diamond 2000; Acosta et al. 2019).

Increase in antibiotic-resistant bacteria and re-emergence of various infectious diseases have stimulated the exploration of these evolutionarily ancient components of the defense system as new therapeutic candidates to replace the conventional antibiotics and as cancer therapeutics. AMPs show exceptional specificity against prokaryotes, with low toxicity toward eukaryotic cells. Further, their rapid mode of killing mechanism gives very narrow escape for microbes to develop resistance (Chen and Lu 2020; Deslouches et al. 2015). They are highly effective even at micromolar concentrations and often exhibit synergistic effects with conventional antibiotics (Hancock and Diamond 2000; Yan and Hancock 2001). When many antibiotic treatments result in sepsis due to release of endotoxins from dead bacterial cells, AMPs bind to those endotoxins, reducing the septic shock (Bao et al. 2006). They have broad-range activity against Gram-positive and Gram-negative bacteria, fungi, some parasites, and enveloped viruses and on cancer cells. AMPs are one of the most promising alternatives to antibiotics because they are effective even against multidrug-resistant pathogens (Rima et al. 2021). Many researchers are also with the opinion that AMPs could offer the best promising solution to fight against microbial infection in aquaculture with no harmful effect on the environment (Chaturvedi et al. 2020; Valero et al. 2020). Interestingly, many AMPs, including those originated from fish, are being discovered and studied. Fish are considered as potential sources of AMPs, owing to their innate immunity being the major defense system. Here, we discuss the naturally occurring AMPs derived from fish, artificial designing of AMPs, and mechanism of action and highlight the possibility of their large-scale production for therapeutic applications.

17.2 History of Antimicrobial Peptides

AMP was discovered in 1939, when an antimicrobial agent named gramicidin, isolated from a soil bacterium, *Bacillus brevis*, protected mice from pneumococcal infection (Dubos 1939). Hirsch (1956) reported the first AMP of animal origin, defensin, isolated from leukocytes of rabbit. AMPs have also been isolated from plants, for example, purothionin, obtained from *Triticum aestivum*, is effective against fungi and some phytopathogenic bacteria (Balls et al. 1942; De Caleya et al. 1972). The field of AMP research expanded further with the contribution of Hans Boman, Michael Zasloff, and Robert Lehrer, who autonomously identified and purified insect cecropins, amphibian magainins, and mammalian defensins, respectively (Steiner et al. 1981; Zasloff 1987; Ganz and Lehrer 1994). Over the last few years, a number of unconventional AMPs have also been discovered that are proteolytically processed from larger and functionally different proteins usually following a microbial infection (Bulet et al. 2004; Reverter et al. 2018). Although a lot of vertebrate antimicrobial peptides were discovered by the mid-1980s, it took yet another decade to discover the antimicrobial activity of fish peptides. In 1980, a toxic peptide named pardaxin from Moses sole flatfish was characterized, but its antimicrobial activity was not observed until 1996 (Primor and Tu 1980; Oren and Shai 1996). Since then, a number of AMPs have been identified in fishes. AMP family characterized in fish includes piscidins which are homologous to cecropins, while other AMPs such as defensin, hepcidin, and cathelicidin have equivalent counterpart in vertebrates (Masso-Silva and Diamond 2014).

17.3 Fish Antimicrobial Peptide

As aquatic animals are rich source of AMPs, a myriad of them have been identified from these organisms. Many of these peptide families express in more than single species and cell type with different gene copy number in different fish species. AMPs have been isolated from mucus, skin surfaces, and mast cells of different aquatic organisms. The AMPs identified from fishes are reported to possess antibacterial, antiviral, antifungal, antiparasitic, and in some cases antitumor properties as well (Campagna et al. 2007; Falco et al. 2008; Chang et al. 2011). Most of the AMPs in fish are detected in early developmental stages with the highest expression level at post-fertilization for some and post-hatching for others, indicating the critical role of AMPs in protection against infections during embryonic development. Majority of the AMP mRNA transcripts expression are upregulated after bacterial infection, confirming their role in fish defense (Magnadóttir 2006; Milne et al. 2019). There are five major families of AMPs in fish and some peptides with no clear homology with any known bioactive peptides (Su 2011).

17.3.1 Piscidins

They are linear, amphipathic, α-helical antimicrobial peptides, widely distributed in various species of teleost fishes (Milne et al. 2019). Piscidin was first purified from the mast cells of hybrid striped bass (*Morone chrysops* (white bass) × *Morone saxatilis* (striped bass)) (Silphaduang et al. 2006). Their amino acid sequence length ranges from 18 to 46 residues, comprising a high proportion of basic amino acids (mainly histidine), phenylalanine, and isoleucine (Qiao et al. 2021). A broad-spectrum antibiotic activity of piscidins includes antibacterial, antifungal, antiviral, and antiparasitic properties (Colorni et al. 2008; Zahran and Noga 2010; Hu et al. 2019; Zheng et al. 2021). Members/paralogues, comprising piscidin family, are enlisted in Table 17.1.

In addition, there are also multiple structurally similar but functionally different piscidin isoforms identified in different fish species as well as within the same species. Among other piscidin isomers (i.e., Piscidin 1–7), Piscidin-1 shows the highest antibacterial activity, even against MRSA and has potential to permeabilize cancer cell membranes as well (Noga and Silphaduang 2003; Lin et al. 2012; Raju et al. 2020). LcP5L4, a piscidin-5 isoform isolated from *Larimichthys crocea*,

Table 17.1 Antimicrobial peptides in the piscidin family

AMPs	Length (amino acids)	Source	Expression site	Antimicrobial activity	References
Pleurocidin	25	*Pleuronectes americanus* (Winter flounder)	Skin, mucus cell, intestines	Gram positive (MRSA) Gram negative Anti-biofilm Yeast and Molds	Cole et al. (1997), Villalobos-Delgado et al. (2019) and Ko et al. (2019)
Misgurin	21	*Misgurnus anguillicaudatus* (Mudfish)	Whole body	Gram positive Gram negative Fungus	Park et al. (1997)
Chrysophsin-1 Chrysophsin-2 Chrysophsin-3	25 25 20	*Chrysophrys major* (Red sea bream)	Gills	Gram positive Gram negative	Mason et al. (2007) and Saitoh et al. (2019)
Moronecidin	22	*Morone chrysops* (White Bass)	Gill, skin, intestine, spleen, anterior kidney, and blood cells	Fungi, yeast Gram positive Gram negative Antibiotic-resistant bacteria like MRSA, *P. aeruginosa*, and vancomycin-resistant *E. faecalis*	Lauth et al. (2002)
Dicentracin	22	*Dicentrarchus labrax* (European sea bass)	Macrophages, granulocytes, and monocytes from head, kidney, peripheral blood, and peritoneal cavity	Antibacterial, antiviral, and antiparasitic activities	Salerno et al. (2007)
Epinecidin-1	25	*Epinephelus coioides* (Orange spotted grouper)	Head, kidneys, gills, liver, intestines, and skin	Antibacterial (both Gram positive and Gram negative), antifungal, antiviral, antiprotozoal,	Yin et al. (2006)

(continued)

Table 17.1 (continued)

AMPs	Length (amino acids)	Source	Expression site	Antimicrobial activity	References
				anticancer, immunomodulatory, and wound healing properties	
Myxinidin	12	*Myxine glutinosa* L. (Hagfish)	Epidermal mucus cavity	Gram positive and Gram negative with highest sensitivity shown by *A. salmonicida*, *L.* anguillarum, and *Y. ruckeri*	Subramanian et al. (2009)
Gaduscidins (GAD-1 and 2)	22 and 19	*Gadus morhua* (Atlantic cod)	Spleen, head kidney, peripheral blood, gill		Browne et al. (2011)
Chionodracine		*Chionodraco hamatus* (icefish)	Gills	Gram-positive and Gram-negative bacteria	Olivieri et al. (2015)
Trematocine		*Trematomus bernacchii* (red blooded Antarctic fish)	Head kidney, gills, lungs		Della Pelle et al. (2020)

showed antiparasitic activity against the parasite *Cryptocaryon irritans* (Zheng et al. 2021). Five piscidin isoforms have been identified from Nile tilapia *Oreochromis niloticus* (named TP1–5) (Peng et al. 2012) and six different piscidins from *Dicentrarchus labrax* that possess broad-spectrum antimicrobial activity (Barroso et al. 2020). A lot of studies have reported that piscidins exhibit strong activity against both fish and human bacterial pathogens, including some MDR-bacteria such as MRSA, vancomycin resistant *Enterococci* (VRE), etc. It interacts and disrupts the target cell membrane using toroidal pore mechanism (Falco et al. 2008).

17.3.2 Hepcidins

Hepcidin was first isolated from bacterially challenged hybrid striped bass, and since then, it has been screened in more than 40 teleost fish species (Shike et al. 2004). Mammalian, fish, and other predicted hepcidins share four to eight cysteine residues at conserved positions in N-terminal, which is crucial for both its optimal conformation and its antimicrobial activity (Hocquellet et al. 2012). The peptide has been detected in several tissues, and a high amount of hepcidin transcripts was rather found in acidophilic granulocytes of the spleen, heart, and stomach instead of the liver (Cuesta et al. 2008; Wang et al. 2009). Accumulating evidences have indicated that all fish hepcidin antimicrobial peptide (HAMP) isoforms can be categorized into two classes: HAMP1 and HAMP2. HAMP1 is more involved in iron regulation while HAMP2 in antimicrobial activity (Hilton and Lambert 2008; Mu et al. 2018; Neves et al. 2017). Hepcidin isolated from *Salmo caspius* (Caspian trout), having antimicrobial activity against *Streptococcus iniae* and *Aeromonas hydrophila*, belongs to HAMP2 class (Shirdel et al. 2019). Hepcidin from *Epinephelus coioides* shows rapid and potent inhibitory activity against *S. aureus* and *P. stutzeri* (Mohapatra et al. 2019). The teleost hepcidin is also found to be effective against protozoan parasitic infections caused by *Trypanosoma carassii* (Xie et al. 2019). Some hepcidins like PsHepcidin, from starry flounder *Platichthys stellatus*, show synergistic interaction with antibiotics and hence are used in combination with antibiotic therapy for the treatment of bacterial infections (Liu et al. 2018).

17.3.3 Defensins

Defensins are another cysteine-rich CAMP that are extensively distributed in nearly all life forms. Based upon the bonding pattern of conserved 6 cysteine residues to form intramolecular disulfide bonds, defensin family can be sub-categorized into α, β, and θ. Whilst α- and θ-defensins have only been found in mammals to date, the β-subfamily has a widespread distribution in all major vertebrate lineages from fish, amphibians, birds, reptiles, to mammals (Zou et al. 2007). In contrary to mammals, fish β-defensins are found to be encoded by three exons, producing a pro-peptide and a mature peptide with a signature motif of 6 conserved cysteine residues (Casadei et al. 2009). The peptide acts through interaction with bacterial membrane followed by insertion and permeabilization by generating multiple pores in the membrane (Chaturvedi et al. 2015). The peptide is reported to be an effective antimicrobial with activity against G+ and G- bacteria, fungi, protozoa, and enveloped viruses (Chang et al. 2011; Contreras et al. 2020; Cuesta et al. 2011). ScBD, a beta-defensin type 2, isolated from mandarin fish *Siniperca chuatsi*, effectively inhibited *E. coli*, *S. aureus*, and *A. hydrophila* (Wang et al. 2012).

17.3.4 Cathelicidins

Cathelicidins are another class of antimicrobials, produced as pre-propeptides, which include a signal sequence and a highly conserved cathelin-like domain and a variable C-terminus antimicrobial domain (Tomasinsig and Zanetti 2005). Cathelicidin was first isolated from Atlantic hagfish *Myxine glutinosa*, and first jawed-fish cathelicidin, rtCATH_1, was identified from rainbow trout (Sun et al. 2007; Chang et al. 2005). It has been reported that CATH possess antibacterial activity against fish pathogen *V. anguillarum* with no hemolytic activity and also has a role in immunomodulation of fishes (Bridle et al. 2011). Cathelicidin also acts against a number of Gram-positive and Gram-negative bacteria by permeabilizing their lipid membranes (Uzzell et al. 2003). Fish cathelicidins are enriched with Arg, Gly, and Ser, forming β-sheet and/or random coil and exhibit no cytotoxic activities (Jiang et al. 2018; Maier et al. 2008). Based on the secondary structure, fish cathelicidins are roughly divided into two groups: peptides forming a disulfide bond and peptides forming an extended structure (Chen et al. 2019). Like other AMPs, gene copy number of cathelicidins also varies species to species (Maier et al. 2008; Zhang et al. 2015a, b).

17.4 Mechanism of Action

The mode of action of AMPs is one of the reasons for being popularly considered as a replacement over antibiotics. The secondary structure of AMPs, which is influenced by their microenvironment, is crucial for their antimicrobial activity. It has been reported that the α-helical structure is responsible for the salt-insensitivity of the peptide, as in the case of piscidins and some α-helical cathelicidins (Broekman et al. 2011). AMPs typically target the microbial cell membrane rather than a specific receptor. The cytoplasmic membrane of both Gram-positive and Gram-negative bacteria is rich in phospholipids with negatively charged head groups like phosphatidylglycerol, cardiolipin and phosphatidylserine. An additional electronegative charge is conferred on the outer leaflet due to the presence of teichoic acid in Gram-positive and LPS in Gram-negative bacterium (Gong et al. 2020). In contrast to bacteria, the outer leaflet phospholipid composition in higher vertebrates is predominantly of zwitterion molecules like phosphatidylcholine, phosphatidylethanolamine, and sphingomyelin, while the negatively charged head groups, if present, are found mostly in the inner leaflet of the membrane facing the cytoplasm

(Mahlapuu et al. 2016; Kumar et al. 2018). Thus, the positively charged AMP interacts with bacterial membrane selectively. After the initial interactions, the AMPs accumulate and then self-assemble on the bacterial membrane after reaching a certain concentration (Epand et al. 2016). AMPs thus embed themselves into the hydrophobic regions of the lipid membrane, thereby causing disintegration and permeabilization of the bacterial membrane, leading to leakage of cell contents and dissipation of transmembrane potential and/or pose multiple stress on the membrane proteins, ultimately leading to cell death (Bessin et al. 2004). There are three models explaining the action of AMPs on the target membranes: (1) carpet model, (2) barrel-stave model, and (3) toroidal-pore model.

The carpet model is a non-pore-forming type also known as the self-promoted uptake model. According to this technique, AMPs act by adsorbing parallel to the lipid bilayer of the target's membrane till it reaches a threshold concentration to cover the entire membrane surface, thus, forming a "carpet." Consequently, this unfavorable interaction leads to loss of membrane integrity eventually resulting in thinning of membrane bilayer, followed by disintegration of the membrane in the form of micelles, producing a detergent-like effect. The barrel-stave model is a trans-membrane pore type where the antimicrobials initially align parallel to the membrane and then insert in the bilayer in perpendicular manner, which facilitates lateral peptide-peptide interaction. The amphipathic structure of peptide is crucial for pore formation, where the hydrophobic region interacts with the membrane lipids and hydrophilic residues form the channel lumen. The toroidal-pore model is another trans-membrane pore formation type. In this, AMP insertion is similar to barrel-stave model; however, the specific peptide-bilayer interaction is absent. The aggregation of AMPs bends the membrane bilayer, and a pore is formed partly by the peptide and partly by phospholipid head groups. Some peptides are able to translocate to the cytoplasmic leaflet of the membrane and enter cytoplasm, thereby, targeting intracellular components (Epand et al. 2016; Dawood and Koshio 2016; Kumar et al. 2018).

17.5 Artificial Designing of AMPs

Many studies have reported the antimicrobial activity of natural AMPs. However, they are associated with several disadvantages such as cytotoxicity, low stability, and high cost of production (Hancock and Scott 2000). It is also reported that antimicrobial activity decreases with chain length and longer peptides are more cytotoxic (Dong et al. 2018). To overcome the problems associated with natural AMPs, many studies have been carried out to develop compositionally simple and short peptides through artificial designing (Hu et al. 2011; Kim et al. 2014; Qi et al. 2010). We have designed a short peptide of 12 residues using only 3 types of amino acids (RRWYRRWYRRWY). It was synthesized by solid-phase peptide synthesis using Fmoc chemistry. The peptide showed antimicrobial activity different fish bacteria such as *Edwardsiella tarda*, *Aeromonas sobria*, and *Vibrio parahaemolyticus* and is also potent against important oomycete, *Saprolegnia* *parasitica*. The peptide was effective even against gentamicin and methicillin-resistant *Staphylococcus aureus*. The peptide showed stability at higher temperature and even in the presence of serum (Hussain Bhat et al. 2020). The main advantage of artificial designing and chemical synthesis of AMPs is the possibility to modify to make the peptide more stable, potent, less toxic to host cells, and less costly in terms of production due to shorter length (Bagheri et al. 2016; Carotenuto et al. 2008; Grieco et al. 2013). In the similar line, another peptide of 16 residues was designed and synthesized (Bhat et al. 2022). The peptide also produced antimicrobial effect against various pathogens and could inhibit the growth of *S. parasitica* in embryonated fish eggs. The peptide has less cytotoxic and hemolytic activity and retained its activity even in the presence of serum and salt. Findings in our studies indicate that artificially designed and chemically synthesized AMPs may serve as an alternative to antibiotic for combating bacterial and fungal pathogen encountered in aquaculture.

17.6 Production of AMPs

Isolation of AMPs from natural sources is not feasible enough to meet the rising demands of basic research and clinical trials. Therefore, exploring alternative strategies for large-scale production of AMPs is important for downstream application. For production of AMPs, two approaches, viz., chemical synthesis and recombinant technology, have been reported. Though chemical synthesis might prove to be economical, it can be done for peptide having a length up to 40 residues. Hence, heterologous expression is preferred for synthesis of longer peptides (Meng et al. 2021). The recombinant technology for AMP production offers less complicated, environment-friendly, and cost-effective method. Among various reported microbial systems, *E. coli* is one of the most widely used host systems. However, it poses some limitations such as contamination of final product with bacterial LPS. Other popular expression hosts are yeast *Pichia pastoris*, and now insect cells have also come up as an attractive option for AMP expression (Karbalaei et al. 2020; Käßer et al. 2022). Insect cells are used for insect AMP expression since they might pose toxicity to bacterial or fungal host. *P. pastoris* has been used for the low-cost production of Tilapia piscidin-4, Ch-penaeidins, and Mytichitin-CB (Meng et al. 2021; Li et al. 2005; Neshani and Eidgahi 2018). *E. coli* was used for large-scale production of myticusin-beta, Vpdef, and was studied for their potential as antibiotics and immunomodulatory molecule (Oh et al. 2020; Zhang et al. 2015a, b). Sathyan et al. (2012) reported that some of the peptides, obtained through recombinant approach, showed reduced potency compared to their chemically synthesized counterparts.

Many of the naturally occurring AMPs have been chemically synthesized for use in research to elucidate their biological activity. These synthetic AMPs were found to be as effective as naturally occurring ones, and in some cases, they gave better performance. Synthetic Fi-His1–21 showed significant inhibition of *V. vulnificus*, *P. aeruginosa*, *V. parahaemolyticus*, *V. cholerae*, and *S. aureus*. It also showed DNA-binding activity and anti-cancerous activity (Sruthy et al. 2019). Synthetic BsHep elevated the expressions of immune-relevant genes in liver of *Bostrychus* *sinensis* and also improved its survival against *V. parahaemolyticus* infection (Shen et al. 2021).

17.7 Conclusion

A number of researches on AMPs are going on, leading to discovery of different peptides with antimicrobial property. With increase in comprehensive studies of AMPs at structural, functional, and genetic level, it is expected that soon AMPs will be commercialized as therapeutic replacement of antibiotics. In order to facilitate their commercial development, more attempts should be made on developing strategies to reduce the cost of production, to enhance stability, and to reduce toxicity to host cells. As isolation of AMPs from the natural source for application will be an expensive venture, heterologous expression may be considered. For development of short and effective AMPs, artificial designing and chemical synthesis may be advantageous.

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Advances in Detection Techniques for Fungus-like Organisms of Aquaculture Importance

18

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Abstract

Oomycetes are a class of eukaryotic organisms that are similar to fungus in morphology and lifestyle. The cell wall of oomycetes is composed of cellulose, unlike fungus, where chitin is the main component. These organisms are generally considered saprophytes with the ability to cause secondary infection. However, some species are highly pathogenic and cause severe diseases in fish. Important fish pathogens of this class belong to the genus *Saprolegnia*, *Achlya*, and *Aphanomyces* under the order Saprolegniales. These organisms have caused huge economic loss in aquaculture and are even considered responsible for the decline in populations of wild fish and amphibians. Previously, these organisms were effectively controlled by use of malachite green, which was later banned. This has led to the emergence of these organisms with increased incidence, virulence, and host range. The diagnosis of the disease can be made by observing the gross lesion of white cotton wool-like growth at the site of infection, but identifying a causative agent is not possible. Identification of the genus and up to the species level is made through various ways such as microscopic observation of the reproductive structures, antibody-based methods, and molecular identification techniques. With advancement in technology, rapid, specific methods have been developed that can identify as well as quantify the causative agent in a given sample. Fast and accurate identification of pathogen will enable us to act promptly against the infection to prevent further spread.

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Oomycete · *Saprolegnia* · *Aphanomyces* · *Achlya* · Morphology · Antibody-based detection · Molecular identification

18.1 Introduction

Fungi constitute a group of heterotrophic, eukaryotic organisms that are now considered separate kingdom different from plants and animals. Fungi are usually filamentous and multicellular, though non-filamentous and unicellular ones also exist. The filaments, also known as hyphae, are cylindrical thread-like structures, which can grow up to several centimeters. Hyphae grow at the tip and at the branches, leading to the development of a network of fungal threads known as mycelium (Fricker et al. 2007). Fungi lack chloroplast and, hence, cannot photosynthesize. They instead obtain their food from the surroundings by absorbing dissolved molecules. They can utilize almost any carbon source as food (Leaño 2001). Fungi contain chitin in addition to glucans in their cell wall. This feature differentiates the fungi from other morphologically similar fungus-like organisms such as oomycetes (water molds).

Oomycetes are a phylogenetically distinct class of organism with similar morphology and lifestyle to fungus. Previously, they were considered a fungus, but, later, they were classified as Stramenopiles and phylogenetically grouped with diatoms and brown algae (Baldauf et al. 2000; Beakes et al. 2012; Diéguez-Uribeondo et al. 2009; van West 2006). Unlike fungus, oomycetes have a cell wall, composed of cellulose (Van der Auwera et al. 1995). They rarely have septa in their hyphae or are present at the base of sporangia (Kortekamp 2005). They cause some of the most devastating diseases in plants and aquatic animals, resulting in huge economic loss and damage to natural ecosystems (Kamoun and Smart 2005; Phillips et al. 2008). Aquatic oomycetes have received lesser attention than their counterparts that infect plants (Diéguez-Uribeondo et al. 2009; van West 2006). Majority of the oomycete species that cause diseases in fish belong to the genus *Saprolegnia*, *Achlya*, and *Aphanomyces* under the order *Saprolegniales*, while a few numbers are from the genus *Pythium* (Gozlan et al. 2014). Generally, these organisms are considered secondary pathogens growing on injured or stressed fish, but some are highly virulent and can cause primary infections (Willoughby 1978; Pickering and Christie 1980). For example, *Aphanomyces invadans*, the etiological agent of the epizootic ulcerative syndrome (EUS), can cause up to 100% mortality in farmed fish (Iberahim et al. 2018). Similarly, highly virulent *Saprolegnia parasitica* has been isolated from striped catfish farms in Uttar Pradesh, India, which can cause 100% mortality in experimental infection (Ravindra et al. 2022). The genus *Achlya* also has virulent species that can cause infections in fish (Khulbe et al. 1995; Sati 1991). Some *Pythium* species were found to infect fish in natural and experimental conditions (Czeczuga et al. 2004; Khulbe 2009).

Previously, diseases caused by oomycetes were controlled effectively by using malachite green. However, this compound has been banned due to its carcinogenic and mutagenic effects (Srivastava et al. 2004). Since then, there has been a recrudescence of the disease, and new host species of the pathogens are being identified (Sarowar et al. 2013; Choi et al. 2019; Sosa et al. 2007). Infections by *Saprolegnia*, *Achlya*, and *Aphanomyces* species are often observed as a white or gray cotton wool-like appearance at the site of infection (Greeff-Laubscher et al. 2019; Mondal and De 2002; Liu et al. 2017). Thus, it is not possible to identify the causative agent by observing only the gross lesion. Therefore, to initiate effective and appropriate control measures to prevent further spread of the disease, it is crucial to correctly identify the pathogen. This will also enable the selection of appropriate chemicals and optimum doses for treatment leading to judicious use of the therapeutic compound. Requirement of drug dose may vary depending on the species, and we have also observed that different species under the same genus, *Saprolegnia*, showed variable sensitivity to antifungal compounds (unpublished data). So, species identification is essential to develop suitable programs for controlling and treating infectious agents. Identification of oomycetes is conventionally done through morphological observation, but at present, molecular techniques using DNA markers are more commonly followed.

18.2 Morphological Identification

Isolation and culture of the causative agent from the lesion or water bodies have been integral for its identification. It is a time-consuming as well as a laborious process. In our laboratory, the isolation process involved direct inoculation of the sample on potato dextrose agar (PDA) incorporated with an antibiotic (Choi et al. 2019; Parra-Laca et al. 2015; Fregeneda-Grandes et al. 2007a, b). On PDA, *Saprolegnia* and *Achlya* species produced white hyphae, some growing inside the agar and the rest extending above the surface. Each colony showing different growth morphology is further sub-cultured until a pure culture is obtained (Shin et al. 2017). Morphological identification often requires observation of different reproductive stages. In the life cycle of oomycetes, several developmental stages can be observed microscopically for identification. Their reproduction occurs sexually and asexually. In asexual mode, motile zoospores are produced and released from sporangium or zoosporangium. The zoospores swim through a pair of flagella and exhibit a chemotactic response to infect new hosts (Walker and van West 2007). In *Saprolegnia*, the primary zoospore encysts, after a short time, release the secondary zoospore, which is the most important infective stage. In *Aphanomyces*, the primary zoospore immediately encysts at the tip of hyphae; hence, the secondary zoospore is the only motile stage (Cerenius et al. 1987). In *Achlya*, it is monoplanetic, that is, the released zoospores are the only dispersal form (Daugherty et al. 1998; Johnson et al. 2002). Sexual reproduction occurs through the production of oogonia and antheridia. Structurally, antheridia are usually small and filamentous carrying nuclei containing the genome. In contrast, oogonia are large, swollen filled with oospheres, each carrying a haploid nucleus. During fertilization, the antheridium fuses with the oogonium and releases the antheridial nuclei, which fuse with the oospheres inside the oogonium leading to the development of oospores. The oospores are spherical and double-walled and can survive in adverse environmental conditions (Gozlan et al. 2014).

Routine identification of oomycetes is made by microscopic examination of sexual reproductive structures Vandersea et al. 2006). For structural observation, oomycetes are cultured on PDA, containing sterile sesame seeds. The colonized seeds are then transferred to a new dish, containing sterile tap water and incubated for a few days. Later, the oomycetes on seeds are observed under a microscope for structures like zoosporangium, zoospores, hyphae, and sexual structures (Sandoval-Sierra and Diéguez-Uribeondo 2015). Usually, *Saprolegnia* strains, isolated from fish, do not exhibit any sexual structures in laboratory culture, and many a time, identification can be done up to genus level only (Stueland et al. 2005; Diéguez-Uribeondo et al. 2007). In addition, many species may produce similar or overlapping structures which are not stable (Diéguez-Uribeondo et al. 1996). Identification of species depending completely on morphological characteristics is not authentic and sometimes even impossible (Ke et al. 2009; Diéguez-Uribeondo et al. 2007). Instead, decorations on the secondary encysted zoospores such as long hooked hairs in bundles are considered as criteria for the identification of virulent *Saprolegnia parasitica* (Willoughby 1985; Beakes et al. 1994; Yuasa et al. 1997; Shin et al. 2017). Other saprophytic species, such as *S. diclina* and *S. ferax*, do not exhibit such characteristics (Stueland et al. 2005). In *Achlya*, the morphology of gemmae is one of the structures used for species identification. For example, spherical gemmae are a characteristic distinguishing feature of *Achlya bisexualis* (Barksdale 1962). Similarly, characteristic structures of zoospores encysted as a cluster at the orifice of zoosporangium, oogonium, and antheridium are observed to identify *Aphanomyces* species (Takuma et al. 2010). As morphological identification of oomycetes is often challenging, different detection methods based on an antibody, DNA, or RNA are being developed.

18.3 Antibody-Based Detection

The ability of antibodies to bind selectively to an antigen with high affinity has been extensively applied in many research and clinical applications. Antibodies are components of the immune system that helps the body to fight against foreign substance such as bacteria, fungi, and viruses. Antibodies may be used in diagnosis either in polyclonal or monoclonal form. Polyclonal antibodies are a mixture of antibodies that can react with a specific antigen, each identifying a different epitope (Sabeta and Ngoepe 2015). In contrast, monoclonal antibodies are derived from a single parent cell and have an affinity for the same epitope (Lipman et al. 2005). Lilley et al. (1997a, b) developed polyclonal antibodies for the detection of *A. invadans* but were found to cross react with other oomycete species. They concluded that monoclonal antibodies (MAbs) against *A. invadans* hyphal material would provide a more specific probe for immunohistochemical detection of EUS.

Miles et al. (2003) used a monoclonal antibody against a hyphal protein of *A. invadans* for detection of the pathogen by immunofluorescent staining on tissue sections of infected fish. The antibody did cross-react with *A. astaci* but not with other oomycetes of fish. Moreover, the technique was more sensitive than the conventional methods for detection of *A. invadans*. Ganapathi et al. (2008) used monoclonal antibody (MAb)-based immunodot to screen for the presence of *A. invadans* in tissues of grossly healthy and ulcerated fishes. They found that this technique can detect the pathogen before the appearance of a lesion. They have also stated that the technique can be used for early detection of *A. invadans* and to predict EUS outbreaks at least 2 months ahead. Adil et al. (2013) have developed a monoclonal antibody-based flow-through immunoassay (FTA) to detect *A. invadans*. The assay has a detection limit of 7 μg/mL for *A. invadans*. The test is rapid, can be completed within 10 min, and is simple, cost-effective, and suitable for on-site screening to detect *A. invadans* in fish from disease outbreaks. Detection of *Saprolegnia* using monoclonal antibodies has also been reported (Bullis et al. 1996; Fregeneda-Grandes et al. 2007a, b). One group found that MAbs produced against *S. parasitica* ATCC 52719 recognized all *S. parasitica* isolates in an indirect immunofluorescence assay. Another group found variable affinity among the MAbs. They found a MAb that can recognize an epitope expressed mainly in the asexual isolates in the long-haired *S. parasitica*. They also discovered that isolates with bundles of long hairs share a number of antigens with other species of *Saprolegnia*.

18.4 Molecular Identification

In recent years, molecular detection and identification of microbes or infectious agents have become a routine work in many diagnostic laboratories. Molecular identification methods detect unique nucleic acid sequences specific to the pathogen. These techniques are more sensitive and specific than the conventional detection method. Molecular methods, owing to their high sensitivity, can detect infections at an early stage. Moreover, these methods have been successfully used for the identification of new and non-culturable agents (Morshed et al. 2007). These methods can complement the conventional method of morphological examination and serological methods for the identification of causative agents. Some highly specific methods can detect even a single nucleotide change in the nucleic acid sequence (Zaidi et al. 2003). The most powerful molecular detection method is the amplification of the target gene by polymerase chain reaction (PCR), followed by sequencing for species identification. There are other advanced forms of PCR, and many have been applied in the detection and identification of oomycete species. In addition, molecular methods do not require amplification of the target gene or nucleic acid but use a complementary probe, for example, fluorescent in situ hybridization (FISH). The types of molecular techniques developed and used for detecting and identifying fish oomycete pathogens are discussed below.

18.4.1 PCR and Sequencing

Amplification of the internal transcribed spacer (ITS) region, followed by sequencing, is commonly done to identify oomycete species. The ITS region is routinely amplified because its copy number is high, enabling detection even in a small quantity of DNA, it is small in size, it has high variation even between closely related species, and it is flanked by highly conserved sequences (Baldwin et al. 1995). The ITS region is situated between 18S and 26S gene and includes ITS1 and ITS2 separated by 5.8S gene in the nrDNA. Amplification of ITS region is done by using universal primers, developed by White et al. (1990). In our study, ITS1 (forward, 5′-TCCGTAGGTGAACCTGCGG-3′) and ITS4 (reverse, 5′--TCCTCCGCTTATTGATATGC-3′) primers have been used. In *Saprolegnia* and *Achlya*, these primers yielded a PCR product of 750 bp approximately. The PCR products were cleaned and subjected to Sanger sequencing for species identification. The sequence is then compared with the available nucleotide sequences in the database through Basic Local Alignment Search Tool (BLAST), and species was identified. Based on the sequences of the ITS region, 29 DNA-based molecular operational taxonomic units (MOTUs) were identified, which supported the validity of 18 species of *Saprolegnia* and 11 potentially new species (Sandoval-Sierra et al. 2014). Another commonly targeted gene for the identification of oomycetes species is cytochrome *c* oxidase subunit I (COI), which is a relatively new approach. Amplification of the ITS region uses genomic DNA, whereas mitochondrial DNA is used for COI. It has been reported that COI, in some case, is more delimiting than ITS at the species level (Robideau et al. 2011).

18.4.2 Identification Without Sequencing

Nucleotide sequencing is the process of determining the order of four nucleotides in nucleic acid. Identification of species by Sanger sequencing is time-consuming, and a higher cost is involved as often the service needs to be outsourced. Therefore, different types of PCR for species identification without sequencing have been developed or applied. Random amplification of polymorphic DNA (RAPD) PCR was used to analyze the genetic diversity in *Aphanomyces astaci*, the etiologic agent of crayfish plague, and to trace the origin of outbreaks (Huang et al. 1994; Lilley et al. 1997a, b). Bangyeekhun et al. (2001) applied RAPD-PCR to characterize *Saprolegnia*, isolated from catfish, and confirmed the presence of three genetically distinct groups. In RAPD PCR, arbitrary primers are used to amplify random segments of the target gene. When separated in a gel, the PCR products give a distinct DNA fingerprint.

Another technique that has been used for species identification in oomycetes is restriction fragment length polymorphism (RFLP). It is a technique in which one or more restriction endonucleases digest the DNA sample, and the digested fragments are separated in gel electrophoresis. The DNA fragments are then transferred to the membrane through Southern blotting. Then the RFLP probe is allowed to hybridize with the DNA fragments, giving a unique blotting pattern characteristic of a particular species. Since the isolation of enough DNA for RFLP is time-consuming and laborious, PCR amplification is performed before digestion with restriction enzymes. Molina et al. (1995) used restriction fragment length polymorphisms (RFLPs) to characterize and identify *Saprolegnia*. They subjected amplified products of the ITS region to a number of restriction endonucleases to generate several fingerprints. They found that endonuclease BstUI generates identical fingerprints for all strains of *S. parasitica*, regardless of its origin. Like RFLP, amplified fragment length polymorphism (AFLP) also uses restriction enzymes. It is a highly sensitive and reproducible technique. In this technique, genomic DNA is first digested, and adaptors are ligated to the sticky ends of the fragments. Then selective amplification of the fragments using primers complementary to the adaptor and restriction site is carried out. The amplicons are separated on denaturing gel, and the band pattern is visualized (Vos et al. 1995). Rezinciuc et al. (2014) stated that AFLP is an alternative method to RAPD-PCR for genotyping *A. astaci*. Elameen et al. (2021) used AFLP technique to study the genetic diversity and relationships of *Saprolegnia* spp. collected from different geographical locations. They found that AFLP analysis has a significant correlation with ITS sequence data.

Significant development of PCR technology is real-time PCR, also referred to as quantitative PCR. As the name indicates, this method detects and measures the generated products in real time. Here, the detection of the product can be achieved in two ways: (1) use of a non-specific fluorescent dye that intercalates with double-stranded DNA and emits fluorescence and (2) use of a sequence-specific probe labelled with fluorescent reporter, which emits fluorescence when cleaved by *Taq*DNA polymerase during extension of primer toward the probe. The intensity of the fluorescence is measured with a detector corresponding to the increase in the amplified product (Heid et al. 1996). Rocchi et al. (2017) developed a real-time quantitative PCR (qPCR) to quantify *S. parasitica* in a river as well as drinking water. Di Domenico et al. (2021) developed real-time PCR TaqMan assays to distinguish the five genotype groups of *A. astaci.* They stated that the technique is suitable for fast genotyping of *A. astaci* during crayfish plague outbreaks and in latent infections. Ghosh et al. (2021) have developed loop-mediated isothermal amplification (LAMP) to detect *Saprolegnia* species. The detection method targeted the ITS region and COI gene and was specific only to *Saprolegnia* genus. The method is highly sensitive, with a detection limit of 10 fg of DNA.

DNA probes labelled with a fluorescent dye are also used in the molecular cytogenetic technique known as fluorescence in situ hybridization (FISH) for species identification (Frickmann et al. 2017). This method can detect specific nucleic acid targets in cells and tissue samples. In this assay, the probe is allowed to hybridize to its complementary sequence in the denatured DNA present in the specimen. The hybridization between the probe and the target DNA can be visualized using a fluorescent microscope. Vandersea et al. (2006) have developed fluorescent peptide nucleic acid in situ hybridization (FISH) assays to detect *A. invadans* in ulcerated lesions. They found that the results of the assay exactly matched with PCR targeting the region containing the 18S gene and ITS1.

18.4.3 Visual Detection

Parra-Laca et al. (2015) designed a PCR-free *Saprolegnia* detection kit using hemolymph from the adult female insect *Dactylopius coccus*. They conceptualized the idea based on the reports that the immune components of the insect react with the fungal cell wall component such as N-acetylglucosamine and 1–3 glucan and form melanin, which can be observed visually. Their study found that *Saprolegnia* sp.-induced reaction was utilizing the pigment carminic acid of the insect hemolymph. Consequently, there was a formation of melanin which could be observed visually, and the presence of *Saprolegnia* was identified. The assay is capable of identifying the presence of *Saprolegnia* between 5 and 282 zoospores.

18.5 Conclusion

Fish disease, caused by oomycetes, is fast emerging, as there is no effective treatment against these pathogens. The disease is no longer confined to only freshwater fish. It has also been reported from marine species. This class of organism is generally considered secondary pathogens that infect only when there are injury or primary infections. However, some species are highly virulent and can cause huge mortality in farmed fish. Moreover, the new hosts of the pathogens are being discovered. Therefore, it is important to delineate the pathogenic species from the non-pathogenic ones. There have been many developments in the detection and identification methods of oomycetes, but point-of-care diagnostic system is lacking. Future research may aim to develop a rapid, easy, or user-friendly identification system having field application. This will help in early diagnosis at the farm level, and immediate necessary measures can be taken to prevent further spread of the disease.

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Nutritional Quality and Human Health Benefits of Important Cold-Water Fishes of the Indian Himalayas

19

Prakash Sharma, Rini Joshi, Alexander Ciji, Md. Shahbaz Akhtar, and Debajit Sarma

Abstract

The world is still fighting to eradicate the problem of malnutrition on the one hand, and on the other, lifestyle diseases are growing alarmingly due to overnourishment with unhealthy food and a sedentary lifestyle. The world at present needs both nutritious and functional food to deal with this dual burden of nutrition. There is a need to expand the quality of food availability in every corner of the world. Over time, more health foods are being supplied to local and global food markets. Fish, among others on the list of nutritional and functional food, is a promising nutritional package that has a potential to reach the plate of every individual because of its diversity, variety, and wide range of affordability. Aquatic habitats of the Indian Himalaya harbor fishes of immense nutritional and functional value. Among these, *Tor* spp., *Neolissochilus* spp., *Schizothorax* spp., *Barilius* spp., *Crossocheilus* spp., and *Garra* spp., along with *Cyprinus carpio* and *Oncorhynchus mykiss*, are some of the important food fishes of the Indian subcontinental Himalaya. These fishes are a good source of protein, balanced amino acids, polyunsaturated fatty acids (eicosapentaenoic, docosahexaenoic, and arachidonic), and minerals (calcium, phosphorus, iron, copper, zinc, and manganese). Their overall nutrient richness contributes significantly to the daily requirements of humans of all ages, sex, and different physiological conditions.

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Keywords

Indian Himalayan fishes · Mahseer · Snow trout · Rainbow trout · Nutrient composition

19.1 Introduction

Consumption of nutritionally deficient food due to unavailability or unaffordability, or the complete deprivation of food, and inadequacy of required nutrients for growth and development lead to malnutrition or malnourishment. Protein, energy, vitamin A, iron, and iodine deficiencies have been the leading cause of malnutrition-related health anomalies (WHO 2003). Prolonged malnourishment cases eventually lead to nutritional deficiency diseases (NDDs). NDDs are more prevalent in developing and underdeveloped nations of Asia, Africa, and South America. Globally, cases of undernourishment declined from 810.7 (12.4%) in 2005 to 615 million (8.1%) in 2017; however, instead of declining further, the cases started to increase after 2018 and reached 768 million (9.9%) in 2020 due to the global emergency, caused by the COVID-19 pandemic (FAO et al. 2021). Among these 768 million cases, the majority are from Asia (418 million), Africa (282 million), and Latin America, including the Caribbean (60 million), in descending order (FAO et al. 2021). The commonly reported signs of NDDs include growth retardation, developmental impairment (both physical and mental), compromised immunity, morbidity, and even mortality (Gragnolati et al. 2005).

On the one hand, some concerned global organizations are still struggling to bring down the cases of NDDs. And on the other, cases of lifestyle diseases (LDs), due to overnourishment and sedentary lifestyle, are rising globally. The main reasons behind the emerging and ever-increasing LDs include industrialization, globalization, global expansion of the food market, and consequently the polarization of packaged energy-dense food, sedentary working style, etc. (WHO 2003). The commonly reported LDs are obesity, diabetes, hypertension, cardiovascular diseases (CVDs), cancer, stroke, arthritis, osteoporosis, arteriosclerosis, sleep disorders, dementia, etc. (WHO 2003). Among these, CVDs, cancer of different types, chronic respiratory diseases, and diabetes are responsible for 82% of LD-related deaths (WHO 2014). Globally, cases of LDs are increasing year after year in an erratic fashion, affecting the global workforce, and had caused 38 million mortality in 2012, and the same is projected to reach 52 million by 2030 (WHO 2014).

Inappropriate food consumption, either due to unavailability of food or excessive intake from the prescribed limit, leads, respectively, to NDDs or LDs. Unhealthy eating habits involve eating unhealthy food, processed or energy-dense food, and nutritionally poor food. LD-related death can be avoided by including fruits, vegetables, whole grains, and lean meats, especially fish, in our diet in the correct proportion (Hasler 1998). With the rise of LDs, the concept of healthy food is becoming popular worldwide. The origin of the idea of healthy food is linked to the famous quote of Hippocrates, “Let thy food be thy medicine and thy medicine be thy food," given long back, i.e., around 400 BC (Witkamp and van Norren 2018). However, the world's first commercial functional food appeared very recently, i.e., during the mid of the 1980s, in the Japanese market (Hasler 1998). After that, the concept of evaluating the potential food materials for their nutritional and functional quality became popular. Worldwide, all possible food materials, from vegetables, spices, and herbs to animals, especially fishes, are being evaluated for their nutritional and functional quality (Rayner et al. 2004). Based on these evaluations and the presence of any bioactive compounds, foods are being included in the functional category.

Information on the nutrient composition of native fishes from every possible corner of the world are being recorded. As a consequence, more and more food fishes are merging into the global food market. Similarly, the nutritional compositions of the Indian subcontinental fishes are also being evaluated, and a good body of nutritional information is developed (Bogard et al. 2015; Joshi et al. 2017, 2018; Joshi 2017; Mohanty et al. 2014, 2016a, b; Sarma et al. 2013, 2014, 2019, 2022). The nutrient profiling of Indian fishes was started long back, initiated by Saha and Ghosh (1938–1939, 1939–1940, 1941). Again, after three to four decades, some more nutrient information on Indian fishes came to light, authored by Sen et al. (1977), Nair and Gopakumar (1977, 1978), Lilabati and Viswanath (1996), Ghosh and Dua (1997), and others. Realizing the importance of nutritional and functional information of food fishes, the Indian Council of Agricultural research (ICAR) started a nationwide fish nutrient profiling program to generate compositional information of possibly all Indian fishes. In this process, some more nutrient profile data of Indian fishes came into the picture (Joshi 2017; Joshi et al. 2017, 2018; Sarma et al. 2013, 2014, 2019, 2022; Mohanty et al. 2014, 2016a, b).

Indian Himalayan cyprinids (IHCs) contribute to a large extent to Himalayan fisheries (Joshi et al. 2017). Out of the several such IHCs, partial nutritional information is available for *Tor putitora*, *Neolissochilus hexagonolepis*, *Labeo dero*, *L. dyocheilus*, *L. pangusia* (Sarma et al. 2013, 2014; Mohanty et al. 2014, 2016a, b); *Schizothorax curvifrons*, *S. esocinus*, *S. labiatus*, *S. niger*, *S. progastus*, *S. plagiostomus*, and *S. richardsonii* (Joshi 2017; Joshi et al. 2017, 2018); and *Barilius bendelisis*, *Garra lamta*, and *Crossocheilus latius* (Sharma et al. 2020; Sharma and Singh 2020). These fishes are distributed in the Indian cold-water habitats from Jammu and Kashmir to Arunachal Pradesh, contributing a considerable share to the local fishery of Himalayan belts (Singh and Akhtar 2015). These sources of information on the nutrient composition of Indian subcontinental Himalayan fishes are scattered in different forms, such as research articles, dissertation documents, books, bulletins, etc.; if it is made available on a single platform, they form a valuable database. In this chapter, the authors have attempted to compile the scattered nutritional and functional information of these fishes as a single document for better understanding.

19.2 Fish as a Functional Food

Among the long list of functional foods, fish has a long history of protecting humans from many diseases and death (Lund 2013). Fish as functional food was known from the evidence of reduced cardiovascular illness-related mortality among Eskimos on fish consumption (Lancet 1983). Fish is consumed by people, irrespective of whether they are rich or poor, young or old, healthy or unhealthy. Some prefer to eat for its delicacy, while others may eat for its availability, affordability, functionality, or richness in nutrient contents (Lund 2013; Kawarazuka 2010). Depending on species, their habitat, and food and feeding habits, different fishes have different nutrient and nutraceutical compositions (Kawarazuka 2010).

Fish is a functional food for its superior oil and fatty acids composition. However, it not only contains long-chain n-3 polyunsaturated fatty (n-3 LC-PUFAs; eicosapentaenoic acid, EPA; and docosahexaenoic acid, DHA) acids, but it also is a source of other healthful nutraceuticals like vitamin A, D, B12, selenium, iodine, iron, zinc, choline, and taurine (see Fig. 19.1; Lund 2009). Therefore, the habit of fish eating is a healthy practice. This healthy eating habit can protect us against cardiovascular diseases (CVDs) (Leaf and Webber 1988), atherosclerosis, arrhythmia (Givens et al. 2006), thrombosis (Harris 2004), inflammation (Simopoulos 2002), rheumatoid arthritis (Berbert et al. 2005), and depression (Horrobin and

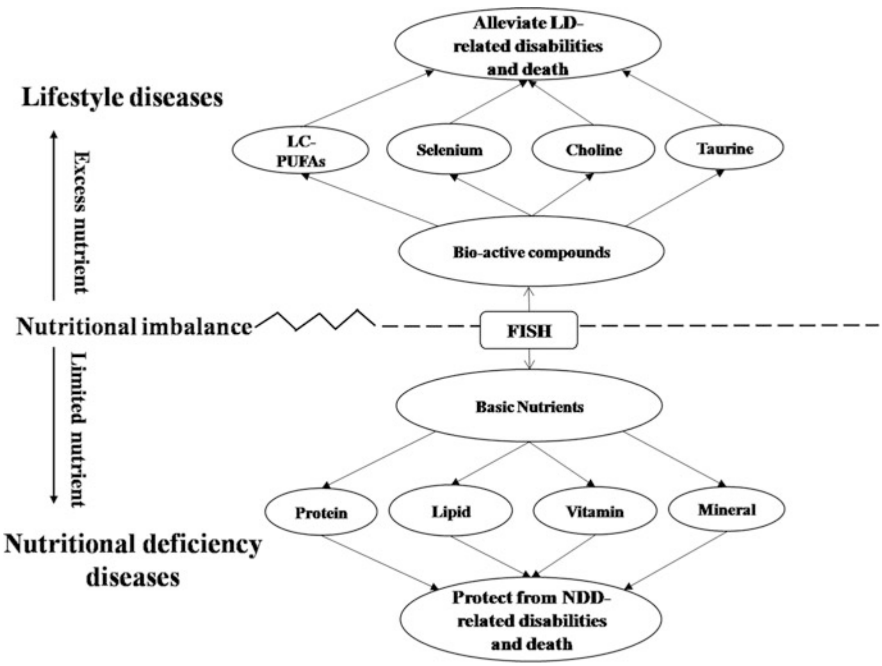

Fig. 19.1 Illustration of the nutritional and functional potential of fish for reducing the double burden of nutritional imbalance

Bennett 1999). Due to their superior nutrient composition, especially, the easily digestible protein, balanced amino acids (particularly the essential ones, EAAs), oil, fatty acids, and other bioactive components like taurine, choline, vitamins, and minerals, they are considered as functional food with dual potential to fight the evils of neurodegenerative diseases (NDDs) and lifestyle diseases (LDs).

The preference for fish over other animal proteins is growing among health-conscious elites in urban communities. Consequently, the proportion of the fish-eating population and per capita consumption are increasing year after year (FAO 2022). The global per capita fish consumption has increased from 15.7 in 2006 to 17.2 kg/person/year in 2010 (World Bank 2013) and 20.5 kg/person/year in 2019 (FAO 2022). Because of the variety of nutrients and nutraceutical content, fish cannot be replaced with other animal meat (Gogus and Smith 2010). Even vegetable oil, like linseed, sunflower, and soybean oil, cannot substitute fish oil, although they contain higher levels of n-3 and n-6 PUFAs, because no other oil is as superior as fish oil, in terms of EPA and DHA content (Burdge and Calder 2005). Rather than consuming individual concentrated nutraceuticals, which may prove harmful, eating fish as a whole is always beneficial because essential nutrients and nutraceuticals are retained in a diluted form, which are slowly released in the gastrointestinal tract during digestion (Gormley 2006). Depending on the flavor and functionality of fish, the price and demand are adjusted with maximum possible margins, favorable for the producers and retailers. For this delicate balance of preference, demand, and supply, fish has become affordable for all classes of the population.

Depending on the species (genetic lineage), habitat (marine or freshwater), and habitat-linked food and feeding habit, they show differences in nutrient compositions and functionality (Grigorakis 2007). Some fishes are lean, while others are fatty; some are good in taste and flavor, and some have medicinal values. For example, marine fatty fish have more lipid and higher levels of n-3 LC-PUFAs than freshwater fish (Ackman 2002). Because of this diversity, availability, and species-specific uniqueness in nutrient content and flavor of fishes, consumers can make healthful choices depending on their preference and price with a higher degree of freedom. The nutritional and functional attributes of fishes vary from species to species; therefore, evaluating the nutraceuticals and nutrient composition of all edible fish is essential to rank them on their nutritional and functionality values.

19.3 An Overview of the Nutritional Composition of Fish

The primary nutrient compositional information is based on an estimated four major components of fish, namely, moisture, protein, oil, and ash (minerals) (Joshi 2017). Since fish is the source of protein and oil, and carbohydrate and fiber contents are negligible, therefore, their estimation is not essential (Shearer 1994). Biochemical composition not only varies at family and genera but also at species level (Shearer 1994). Therefore, the nutrient composition of fishes is species-specific and depends on their food and feeding habits. Each fish is unique in morphology, morphology-driven locomotion, food-acquiring mechanism, food and feeding habit, niche, and habitat preferences. Due to this complexity in the interaction of these morphological, physiological, and ecophysiological variations, they exhibit a similarly higher degree of heterogeneity in nutrient composition. The nutrient and nutraceutical contents of a species cannot be taken for generalizing the same of other species of the family. Therefore, evaluating the same in all edible fish species is essential to assess their nutrient content and contribution potential.

In nature, the food and feeding of fish change with their own physiological rhythm and the ecological dynamics of their living environment (Joshi 2017). The cyclic physiological rhythm brought by the reproductive cycle, pre-spawning gonadal development, spawning, post-spawning recovery, etc. brings corresponding changes in biochemical composition (Sharma et al. 2021). Similarly, ecological dynamics brought by the seasonality of natural food abundance also contribute to the seasonal nutrient dynamics (Joshi 2017). In natural habitats, seasonal feeding restriction due to unavailability results in depletion of protein and lipid, in general (Wang et al. 2006). Otherwise, the reports on micronutrient dynamics in such a situation are rarely reported in fish. During the post-spawning and consequent intense feeding, nutrients are recovered first to compensate for the loss. Eventually, the nutrients are accumulated over time to form a reserve for the subsequent gonadal development or the next migration event (Hatch 2012). The lipid dynamics and corresponding fatty acid changes are studied deliberately in fishes, than the protein and amino acids. Although the level of protein as well changes in some situations, this change is being overlooked.

Within the species, increase in fish size with aging also brings compositional dynamics; lipid content of fish increases with an increase in weight, due to their accumulation in the muscle, subcutaneous tissue, and peritoneal cavity, and this leads to decreases in protein and minerals (Brown and Murphy 1991; Martinez et al. 1992). Similarly, protein content increases with a growth-related increase in fish size (Grigorakis et al. 2002; Kim and Kaushik 1992; Weatherley and Gill 1983). Information on weight-dependent lipid accumulation in fishes is consistent (Fig. 19.2). However, the information on size-dependent protein content is not. Some investigators have reported the protein increase to a certain size during early growth (Grigorakis et al. 2002) or until fingerling (Weatherley and Gill 1983), or throughout life (Kim and Kaushik 1992). Contrarily, others have reported the decrease in protein with the growth or aging of fish (Martinez et al. 1992).

Even the biochemical composition, especially the lipid content, of muscle from different parts of a fish is also not the same; the ventral muscle is more rich in oil than the dorsal (Aursand et al. 1994; Kinsella et al. 1977; Zhou et al. 1996). Similarly, head and anterior muscle have more oil than the posterior and peduncular muscle (Austreng and Krogdahl 1987; Kinsella et al. 1977; Stansby 1973). Oil content differs with the muscle type in a steak of the same part; the red muscle contains more oil and less protein (Austreng and Krogdahl 1987; Kiessling et al. 1989; Ingemansson et al. 1991).

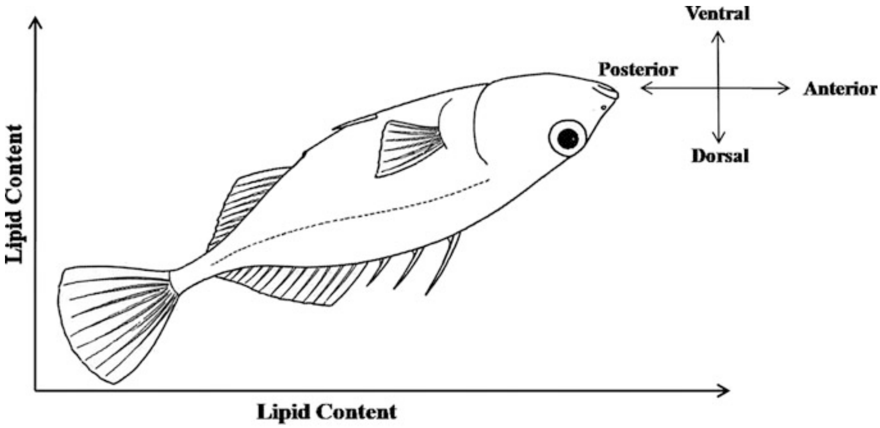

Fig. 19.2 Lipid distribution in fish body

19.4 Fish as a Source of Protein

Fish protein is considered the best among animal proteins for consumption due to its high digestibility and amino acid composition. Out of the total muscle proteins, structural (actin, myosin, tropomyosin, and actomyosin), sarcoplasmic (albumin, myoalbumin, globulin, etc.), and connective tissue proteins (collagen, elastin, etc.) contribute to 70–80%, 25–30%, and 3–5%, respectively, in fishes (Joshi 2017; Ryu et al. 2021). Otherwise, the respective protein compositions in mammals are 40%, 35–40%, and 15–20% (Joshi 2017). The comparatively higher muscle protein (structural) and lesser connective tissue protein in fish, than in mammals, make the fish meat easily digestible compared to that of mammals (Jacquot 1961).

The nutritional quality of meat is evaluated based on the absolute value of protein content and its digestibility, its amino acid composition (especially the essential amino acids; EAA), and the bioavailability of amino acids upon digestion. Fish protein contains all the EAAs and, like milk, eggs and most of the edible mammalian meat protein. Based on evaluation criteria like chemical or amino acid score, biological value, and protein efficiency ratio, fish protein is superior to milk, beef, pork, and chicken (Sheeshka and Murkin 2002). The chemical score of fish muscle (70) is better compared to beef (69) and milk (60) (Sheeshka and Murkin 2002). Similarly, the biological value (76%) is higher than that of beef (74.3%), pork (74.0%), and chicken (74.3%) (Sheeshka and Murkin 2002).

Among the Indian cold-water fishes, information on protein content is available for *C. carpio* (collected from the Himalayan region), *O. mykiss*, *N. hexagonolepis*, *T. putitora*, *S. curvifrons*, *S. esocinus*, *S. labiatus*, *S. niger*, *S. plagiostomus*, *S. progastus*, *S. richardsonii*, *B. bendelisis*, *C. latius*, and *G. lamta* (Joshi 2017; Joshi et al. 2017; Mohanty et al. 2014; Sarma et al. 2013, 2022; Sharma et al. 2020; Sharma and Singh 2020). The protein content and their contribution potential (daily

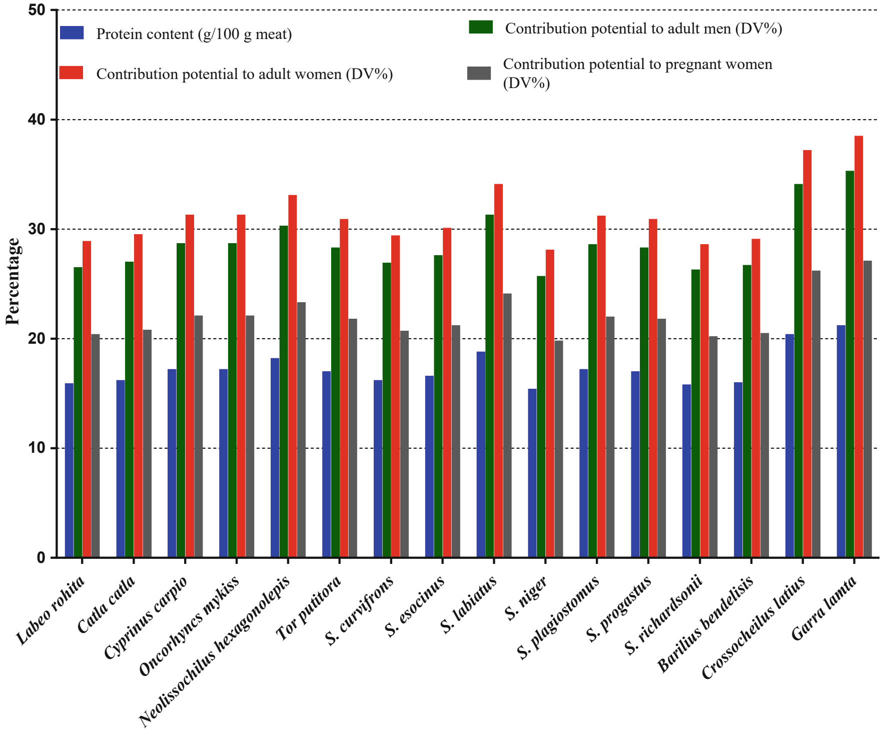

Fig. 19.3 Protein content (mg/100 g) of some common tropical edible carps and cold-water fishes from Indian Himalaya and their daily value (DV%) percentage to meet the daily protein requirement of adult men, women, and pregnant women (DV% calculated based on RDA recommended by ICMR 2010). The data are compiled from published reports (Joshi 2017; Joshi et al. 2017; Mohanty et al. 2014; Sarma et al. 2013, 2022; Sharma et al. 2020; Sharma and Singh 2020)

value percentage; DV%) to recommended dietary allowance (RDA) to a human at different physiological stages of cold-water fishes are summarized and presented in Fig. 19.3, along with those from common edible IMCs (*L. rohita* and *C. catla*). The protein contents of some of the cold-water fishes are significantly higher (>18%) than those of tropical IMCs (16%); these include *G. lamta*, *C. latius*, *S. labiatus*, and *N. hexagonolepis* (Joshi 2017; Mohanty et al. 2014; Sarma et al. 2022). Other fishes with moderately higher protein (17%) content include *O. mykiss*, *C. Carpio*, *T. putitora*, *S. plagiostomus*, and *S. progastus* (Joshi 2017; Joshi et al. 2017; Mohanty et al. 2014; Sarma et al. 2022). According to these reports, these fishes were collected for evaluation, from different locations in the western and central Himalayan region, but the reported protein content is independent of the collection site (Joshi 2017; Sarma et al. 2022). The local biotic and abiotic factors and region-specific feeding did not alter the protein composition.

19.5 Dietary Protein Contribution Potential

Protein is adequately required in the human diet to maintain healthy growth and functioning. The requirement varies with developmental stages and physiological conditions. Protein requirement is critically higher in pregnant and lactating women, as additional protein is required for the growth and development of the fetus and newborn. Otherwise, in the adult stage, it is needed only for compensating the wear and tear of body protein, not for growth. Human dietary protein requirements are fixed, based on methods such as nitrogen balance (widely used and most recommended), nitrogen losses, and protein utilization efficiency (ICMR 2010).

ICMR (2010) has recommended the daily protein requirements for adult men and adult, pregnant, and lactating women, specifically for the Indian population, as 60, 55, 78, and 74 g/day, respectively. Based on these RDA data and protein contents of evaluated Indian Himalayan fishes, the calculated DV% [(protein available per gram of meat/RDA) × 100] is significantly higher in *G. lamta* and *C. latius* and moderately high (higher than IMCs) in *S. labiatus*, *N. hexagonolepis*, *O. mykiss*, *C. Carpio*, *T. putitora*, *S. plagiostomus*, and *S. progastus*. In India, nearly 46% of preschool children and around 30% of adults suffer from malnutrition with different levels of severity, i.e., moderate to severe (ICMR 2010). The problem of malnutrition exists in pockets of the country where people cannot afford to buy sufficient food or nutritional food and food items rich in protein are expensive compared to those rich in carbohydrates. These protein-rich Himalayan fishes may help fight against the existing remains of malnutrition in the Indian subcontinental Himalaya.

19.6 Amino Acid Composition of Fish

Amino acids are the basic units of macromolecular protein of all different types and functions. Additionally, some of the amino acids serve as either substrate or intermediates in various metabolic pathways for the synthesis of physiologically important biomolecules such as nucleotides, hormones, neurotransmitters, polyamines, glutathione, creatine, carnitine, carnosine, thyroid hormones, serotonin, melanin, melatonin, heme, etc. (Blachier et al. 2011; Kong et al. 2012; Wu 2009). Therefore, they are essential in the diet, and most of them are served in the form of dietary protein. The requirements of dietary amino acids vary depending on developmental stage, physiological status, gut microflora, environmental factors, and the pathological condition of the individual (Dai et al. 2011, 2012a, b; Wu et al. 2013).

Along with protein, fish is a good source of a balanced composition of EAAs and NEAAs (Bruke et al. 1997; Buttery and D'Mello 1994; Dahhar and Elshazly 1993). Each fish has unique amino acid compositions depending on its species-specific food and feeding habits (Grigorakis 2007). The compositional uniqueness of amino acids not only depends on genetic lineage, but it also varies within the species depending on their distribution, size, sex and sexual maturity, environment, and food availability (Ozyurt and Polat 2006). The annual gonadal cycle is a significant intrinsic feature that brings seasonality to the amino acid composition (Duyar 2000).

Table 19.1 Essential amino acid composition (g/100 g protein) of some common Indian tropical carps and Indian Himalayan cold-water fishes (captured from wild)

Amino acids (g/100 g protein)	Met	Arg	Trp	Thr	Val	Ile	Lys	Leu	Phe	His
Labeo rohita	2	1	1	6	6	6	3	9	6	4
Catla catla	2	2	1	6	7	6	4	8	5	5
Cyprinus carpio	1	2	1	1	1	1	1	2	1	<1
Oncorhynchus mykiss	3	7	6	6	5	7	4	6	3	1
Neolissochilus hexagonolepis	1	2	<1	1	2	1	2	2	1	1
Tor putitora	4	4	7	4	4	4	9	8	6	1
Schizothorax curvifrons	1	4	–	3	5	5	2	10	7	1
S. esocinus	2	5	–	4	5	6	2	13	12	2
S. labiatus	3	5	–	6	7	10	4	21	17	2
S. niger	2	6	–	5	6	7	2	15	13	2
S. plagiostomus	2	5	–	4	5	6	3	12	10	2
S. progastus	3	6	–	6	7	7	2	16	13	7
S. richardsonii	4	6	–	5	7	8	4	18	11	2

The mean values only are presented here from different sources (Joshi 2017; Joshi et al. 2017; Mohanty et al. 2014; Sarma et al. 2013, 2022)

Among the Indian cold-water fishes, information on amino acids content is available for *C. carpio* (collected from the Himalayan region), *O. mykiss*, *N. hexagonolepis*, *T. putitora*, *S. curvifrons*, *S. esocinus*, *S. labiatus*, *S. niger*, *S. plagiostomus*, *S. progastus*, *and S. richardsonii* (Joshi 2017; Joshi et al. 2017; Mohanty et al. 2014; Sarma et al. 2013, 2022). The EAA compositions of cold-water fishes are summarized from these published sources of literature and are present in Table 19.1, along with the composition from common edible IMCs (*L. rohita* and *C. catla*). The most abundant amino acids are glutamic and aspartic acid (Joshi 2017; Sarma et al. 2022). After analyzing the EAA abundance pattern from Table 19.1, the following compositional conclusion is drawn. *T. putitora*, *S. richardsonii*, *O. mykiss*, *S. labiatus* and *S. progastus* are rich in methionine (3–4 g/100 g protein). *O. mykiss*, *S. niger*, *S. progastus*, *S. richardsonii*, *S. esocinus*, *S. labiatus* and *S. plagiostomus* are rich in arginine (more than 5 g/100 g protein). *O. mykiss* and *T. putitora* are rich in tryptophan (6 g/100 g protein).

Threonine, valine, isoleucine, and lysine are poor (around 1 g/100 g protein) in *C. carpio* and *N. hexagonolepis*; otherwise, most of the evaluated species are comparatively rich in these EAAs as *L. rohita* and *C. catla* do. Isoleucine has a vital role in growth, muscle formation (Charlton 2006), and renal function (Vuzelov et al. 1999). Similarly, leucine and phenylalanine are rich in most of the evaluated *Schizothorax* spp. (more than 10 g/100 g protein). Leucine has several physiological importance, such as the induction of muscle protein synthesis (Etzel 2004) and reduction of stress conditions such as trauma, burn, sepsis, etc. (De Bandt and Cynober 2006). Similarly, phenylalanine has an important role in immunity (Wu and Meininger 2002), neurotransmission (through epinephrine, norepinephrine, and dopamine; Malinski

2000), regulation of blood pressure (Malinski 2000), regulation of metabolism (through thyroid hormone synthesis; Kim et al. 2007), etc. The only cold-water species rich in histidine (compared to *L. rohita* and *C. catla)* is *S. progastus*. Otherwise, most of the other cold-water species are poor in histidine content.

19.7 Amino Acid Score

Apart from amino acid composition, the protein quality is graded by amino acid score (AAS). Among many forms of protein quality testing tools and parameters, such as protein efficiency ratio, net protein utilization, and biological value (where in all these cases animals for bioassay are needed), the AAS method is easy, efficient, and best for qualifying and ranking EAAs (FAO-WHO 1990). Generally, AAS is done for preschool children, because they need more EAAs in their diet, i.e., 30% of dietary protein, but in adults, it is just 15% of dietary protein. Scoring evaluation done with preschool children gives extra margin for adults. The calculated AAS values of all evaluated cold-water species are presented in Fig. 19.4, along with the values of *L. rohita* and *C. catla*. Among all evaluated cold-water fishes, *C. carpio* and *N. hexagonolepis* have low AAS values for most essential amino acids. Otherwise, most of the *Schizothorax* spp. have a comparatively better AAS value. Further, among all evaluated Indian Himalayan *Schizothorax* spp., *S. labiatus* has the best combination of AAS values (Joshi 2017; Sarma et al. 2022).

19.8 Fish Oil

Generally, oil or fat refers to triglyceride, while lipid refers to triglyceride and phospholipids (polar fraction) (Ackman 1967). Lipid is the fraction of fish extracted by organic solvents (Brianna and Brian 2006). In the current context, the authors are using the term oil instead of lipid, as oil is standard in human nutrition, and it matches with the scope of this chapter. The fish oil contains phospholipids and triglycerides; the phospholipid forms an integral part of the cell membrane, called structural lipid, while the triglyceride is the storage form of lipid, and it is called depot fat (Ackman 1967). Abundantly oil-containing fish tissues have a higher TAG proportion than tissues deficient in oil; otherwise, in low oil-containing tissues, PLs are abundant (Linder et al. 2010). Phospholipids are the functional constituents of biological membranes, and they contain more PUFAs (up to 58%), with proportionately more DHA than other fatty acids (Henderson and Tocher 1987). In IMCs, compared to muscle, the liver contains more oil (Ackman 2002).

Oil is distributed in various locations of the fish body, such as the liver, muscle, and peritoneal cavity along with viscera, head (abundantly in brain and eyes), and to some extent in gills, skin, bone, and gonad (Henderson and Tocher 1987). Depending on the oil content, Ackman (1967) classified fishes into different categories like lean (<2% fat), low fat (2–4% fat), medium fat (4–8% fat), and high fat (>8% fat). Generally, in lean fishes, the liver contains more oil, while in

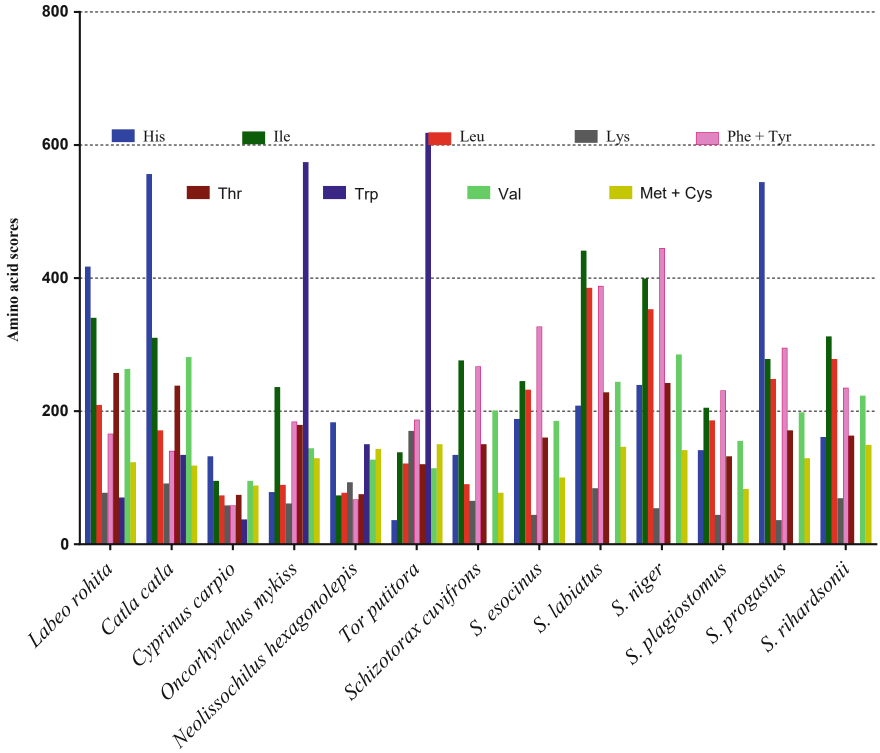

Fig. 19.4 Amino acid scores of cold-water fishes from Indian subcontinental Himalayas and of *Labeo rohita* and *Catla catla*. The AAS calculation is based on the EAA requirement for the preschool children (2–5 years). The mean values only are presented here from different sources (Joshi 2017; Joshi et al. 2017; Mohanty et al. 2014; Sarma et al. 2013, 2022)

fatty fishes, the muscle and peritoneal cavity contain more (Ackman 1967; Cowey 1993).

Based on this classification, *L. rohita* and *C. catla* are low-fat-containing fishes (Mohanty et al. 2016a). Among cold-water species, *S. progastus* and *S. richardsonii* are lean fishes. *C. carpio*, *O. mykiss*, *N. hexagonolepis*, *S. plagiostomus*, *C. latius*, and *G. lamta* are low-fat-containing fishes, while *T. putitora*, *S. curvifrons*, *S. esocinus*, *S. labiatus*, *S. niger*, and *B. bendelisis* are medium-fat-containing fishes. None of the Indian cold-water fishes, evaluated for nutritional composition, is found to fall in the category of fatty fishes. As none of these fishes contain oil above 8 g/100 g muscle tissue, similarly, their contribution potentials to meet the RDA for moderately working adult men and women are also negligible (Fig. 19.5).

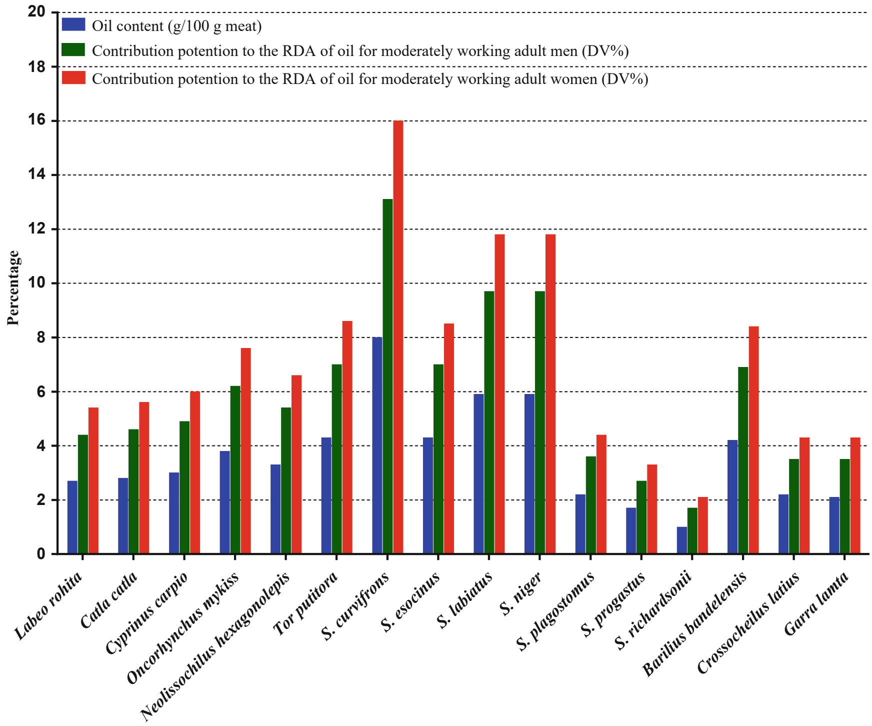

Fig. 19.5 Oil content (mg/100 g) of some common tropical edible carps and cold-water fishes from Indian Himalaya and their daily value percentage to meet the daily oil requirement of moderately working adult men and women (DV% calculated based on RDA calculated in the box below. The data are compiled from published reports) (Joshi 2017; Joshi et al. 2017; Mohanty et al. 2016a; Sarma et al. 2013, 2022)

Calculation for recommended dietary allowance (RDA) of fat

RDA value of dietary fat, for adult male and female, according to ICMR (2010) is 20% of the total energy intake per day.
The total energy requirement of moderately a working man is 2730 kcal/day (ICMR, 2010)
The total energy requirement of moderately a working woman is 2230 kcal/day (ICMR, 2010)
The energy requirement from dietary fat for a man = (20 × 2730)/100 kcal/day=546 kcal/day
The energy requirement from dietary fat for a woman = (20 × 2730)/100 kcal/day=446 kcal/day
A gram of dietary fat on oxidation yield 9 Kcal energy.
In other way round, for getting 9 Kcal energy, 1 g of dietary fat is required.
For getting 1 Kcal energy, 1/9 g of dietary fat is required.
For getting 546 Kcal energy, (1/9) × 546 (i.e., 60.67) g of dietary fat is required.
For getting 546 Kcal energy, (1/9) × 446 (i.e., 49.55) g of dietary fat is required.

After rounding off the figures, it can be stated that:
The dietary fat requirement per day for a moderately working man is = 61 g/day
The dietary fat requirement per day for a moderately working woman is = 50 g/day

19.9 Fatty Acid Composition of Fishes

Fatty acids are crucial nutrients for all animals, including humans, and oil is the only source of these nutrients as the constituents, along with glycerol. They are sources of energy like carbohydrates but yield ATP through a different pathway called β-oxidation. Fatty acids serve as precursors of several bioactive compounds; some have structural and functional roles in cell membranes. Fatty acids have 4–24 (C4 to C24) aliphatic carbon chains, with a carboxylic acid group at the end. They can be either saturated or unsaturated, depending, respectively, on the absence or presence of double bonds.

Further, depending on the number of double bonds, they are classified as monounsaturated (MUFAs; monoene; one double bond in a chain), PUFAs (diene or triene; 2–3 double bonds in a chain), and LC-PUFAs (carbon chain 20–24 with 4–6 double bonds). Among PUFAs and LC-PUFAs, depending on the position of double bonds from the methyl terminal, they are classified either as n-3 or n-6 FAs. Some common n-3 PUFAs include α-linolenic acid (ALA; C18:3n-3), stearidonic acid (SDA, C18:4n-3), and n-3 LC-PUFAs which include EPA and DHA, while n-6 PUFAs include linoleic acid (C18:2n-6; LA), and n-6 LC-PUFAs include arachidonic acid (C20:4n-6, ARA). Animals, including fish to humans, cannot convert saturated and monounsaturated fatty acids to LA and ALA; therefore, their inclusion in the diet is indispensable. Therefore, LA and ALA are essential fatty acids (EFA; Tocher 2003). However, they (including fish) can bioconvert these EFAs to C20 and C22 LC-PUFAs like ARA, EPA, DPA, and DHA (Tocher 2003).

19.10 Habitat and Food-Dependent Fatty Acid Dynamics in Fishes

The ability of fish to elongate and desaturate LA and ALA to respective LC-PUFAs depends on the abundance and activities of elongases and desaturases (especially Δ6 and Δ5) and the availability of precursor and product fatty acids in their diet or natural food (Tocher 2003). The ability of marine fish to convert LA and ALA to LC-PUFAs is limited; however, freshwater counterparts are comparatively more efficient because LC-PUFAs in freshwater habitats are less prevalent than in marine (Tocher 2003, 2010). This ability in freshwater fishes through evolution is enhanced by nutritional discrepancy (Castro et al. 2012; Tocher 2010). Therefore, compared to marine, freshwater fishes are rich in C16 and C18 fatty acids, LA, γ-linolenic acid (GLA; C18:3-n-6), ALA, and AA but poor in EPA, DPA, and DHA (Ackman 1967; Lovern 1942, 1964; Ackman and Eaton 1966; Ackman 1967; Ozogul and Ozogul 2007; Ozogul et al. 2008). The fatty acid composition of fish muscle depends on food and feeding habit. For example, algae and phytoplankton-eating fishes (herbivores) are rich in both LA and ALA (Henderson and Tocher 1987; Brown et al. 1989). In contrast, zooplankton and prey fish-eating fishes are rich in n-3 LC PUFAs but poor in LA and AA (Brown et al. 1989).

The fatty acid composition also varies within the same species, depending on whether the fish is wild-caught or farm-reared. Fish caught from wild have different fatty acid profiles compared to farmed fish (Grigorakis 2007; Alasalvar et al. 2002; Grigorakis et al. 2002; Saglik et al. 2003; Mnari et al. 2007). Generally, cold-water fishes are known to have more n-3 LC PUFAs compared to warm-water counterparts and vice versa, because low temperature triggers the desaturation of membrane lipids to maintain flexibility and permeability of cells (Henderson and Tocher 1987; Lovell 1991).

19.11 Seasonal Variation of Fatty Acids

Fatty acid composition in fish flesh also changes with the change in season, and this is mainly due to gonadal cycling; seasonal change in environmental conditions like temperature, salinity, etc.; seasonal dynamics of natural fish food abundance; and their respective changes in fatty acid (Bandarra et al. 2001; Gökçe et al. 2004). There are many reports on seasonal changes in fatty acid profile of fishes of both marine (*Trachurus trachurus*, *Engraulis encrasicolus*, *Sardina pilchardus*, *Sprattus sprattus*, *Solea solea*, *Spicara smaris*) and freshwater (*Sander lucioperca*, *Carassius auratus*, *Colossoma macropomum*, *Leporinus friderici*, *Prochilodus nigricans*, *Brachyplatystoma filamentosum*, *Brachyplatystoma flavicans*, *Thymallus arcticus*) groups (Pirini et al. 2010; Gökçe et al. 2004; Zlatanos and Laskaridis 2007; Guler et al. 2007; Dal Bosco et al. 2012; Petenuci et al. 2016; Sushchik et al. 2007).

In most of these reports, information on sex-specific seasonal fatty acid dynamics is missing, because in their analysis, male and female fishes were not separated and their gonadal status was also not taken into account. Otherwise, fatty acids, like other macronutrients such as protein and lipid, get partitioned from the muscle toward the gonad, especially at depending phases of the gonadal cycle for the development and maturation of testis and ovary (Johnson et al. 2017).

The seasonal muscle fatty acid dynamics due to changing gonadal status is stronger in females than males because of the vitellogenesis and yolk formation. In this process, a significant proportion of lipid and FAs get partitioned from different parts of the body toward the gonad for gonadal development (Sharma et al. 2021; Cejas et al. 2004). In a seasonal fatty acid partitioning study conducted in *T. putitora*, from wild lacustrine habitat, gonadal seasonality-dependent muscle fatty acid dynamics were observed, especially more strongly in females than males (Sharma et al. 2021; Sharma et al. 2022). The detailed illustration of sex-specific seasonal fatty acid dynamics, observed in *T. putitora*, is presented in Fig. 19.6.

19.12 Fatty Acid Profile of Indian Himalayan Fishes

Among the Indian cold-water fishes, information on fatty acids profile is available for *C. carpio* (collected from the Himalayan region), *O. mykiss*, *N. hexagonolepis*, *T. putitora*, *S. curvifrons*, *S. esocinus*, *S. labiatus*, *S. niger*, *S. plagiostomus*,

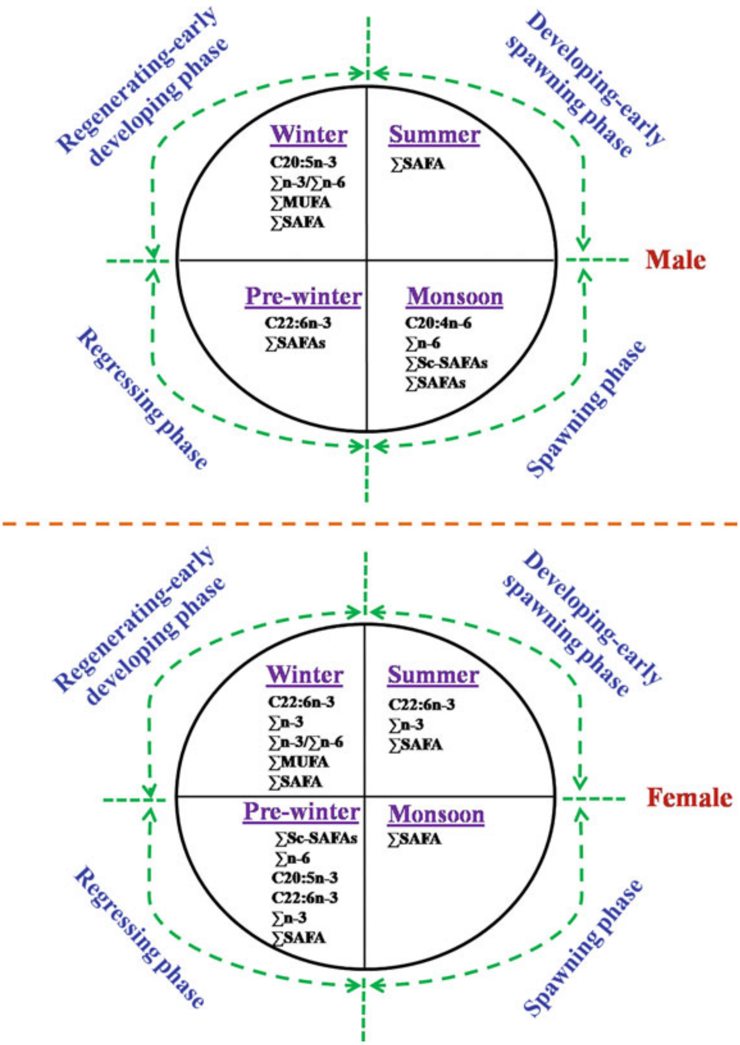

Fig. 19.6 Sex-specific seasonal dynamics of fatty acid profile in *T. putitora*

S. progastus, and *S. richardsonii* (Joshi 2017; Joshi et al. 2017; Mohanty et al. 2016a; Sarma et al. 2013, 2022). The fatty acid compositions of cold-water fishes are summarized from these published bodies of literature and are presented in Table 19.2. Like any other fish species, C16:0 (palmitic acid) is abundant among all saturated fatty acids in all cold-water fishes. Irrespective of their habitat and physiological condition, whether they are wild-captured or farmed, male or female, etc., in almost all evaluated fishes, palmitic acid is abundant in their muscle tissue (Alasalvar et al. 2002; Andrade et al. 1995; Grigorakis et al. 2002; Jabeen and Chaudhry 2011; Sarma et al. 2013; Sharma et al. 2010; Swapna et al. 2010).

Table 19.2 Fatty acid composition (mg/100 g protein) of some Indian Himalayan cold-water fishes (captured from wild)

Fish species	C14:0	C16:0	C18:0	∑SAFAs	C16:1	C18:1	∑MUFAs	LA	AA	∑n-6	EPA	DHA	∑n-3	∑n-6/∑n-3
Cyprinus carpio	60	1050	210	1380	300	510	930	300	120	420	–	152	300	1.40
Oncorhynchus mykiss	152	836	304	1330	312	923	1330	532	76	684	82	225	532	1.29
Neolissochilus hexagonolepis	83	983	195	1462	366	360	789	251	89	340	302	210	690	0.49
Tor putitora	215	1359	413	2279	413	520	1208	318	77	417	202	116	370	1.13
Schizothorax curvifrons	886	2815	145	3885	937	675	1716	124	255	603	7	163	170	3.55
S. esocinus	479	2001	203	2708	614	879	1559	1	179	365	4	166	171	2.14
S. labiatus	303	1145	1297	3009	1010	814	1824	4	194	198	145	124	588	0.34
S. niger	749	2777	3.92	3565	930	71	1096	141	283	653	6	159	165	3.97
S. plagiostomus	283	1249	185	1745	300	558	910	115	34	255	5	56	61	4.17
S. progastus	285	1276	169	1745	373	216	606	<1	26	243	5	76	81	2.99
S. richardsonii	187	644	185	1019	526	361	918	51	19	80	236	93	398	0.20

The mean values are presented here from the different sources (Joshi 2017; Joshi et al. 2017; Sarma et al. 2013; Mohanty et al. 2016a, b) Abbreviations: *SAFAs* saturated fatty acids, *MUFAs* monounsaturated fatty acids, *LA* linoleic acid (C18:2n-6), *AA* arachidonic acid (C20:4n-6), *EPA* eicosapentaenoic acid (C20:5n-3), *DHA* docosahexaenoic acid (C22:6n-3)

Further, in these fishes, the sum of all saturated fatty acids is more than monounsaturated fatty acids; and this is common in most wild-caught freshwater fishes (Jabeen and Chaudhry 2011; Sharma et al. 2010). The proportion of PUFAs in muscle tissue, compared to the sum of all saturated or monounsaturated fatty acids, is low in most freshwater fishes (Vlieg and Body 1988; Sharma et al. 2010; Jabeen and Chaudhry 2011; Sarma et al. 2013). Similarly, in cold-water fishes as well, the sum of PUFAs is lower than saturated or monounsaturated fatty acids. Among monounsaturated fatty acids, C16:1 and C18:1 are the most abundant in their muscle lipid. The sum of all n-6 fatty acids, compared to n-3, is abundantly available in muscle lipid of *C. carpio*, *O. mykiss*, *T. putitora*, *S. curvifrons*, *S. esocinus*, and *S. niger*. Otherwise, all other species like *N. hexagonolepis*, *S. labiatus*, *S. plagiostomus*, *S. progastus*, and *S. richardsonii* are rich in n-3 PUFAs. The predominance of n-6 fatty acids over n-3 in freshwater fishes is a common phenomenon, and this is due to their natural food, in which n-6 PUFAs, especially LA, predominate over ALA (Ackman 1967). *O. mykiss*, *N. hexagonolepis*, *S. plagiostomus*, *S. labiatus*, and *S. richardsonii* are rich in n-3 LC-PUFAs such as EPA and DHA; otherwise, all the rest are rich in AA.

19.13 Importance of Dietary N-3 LC-PUFAs and Contribution Potential of Cold-Water Fishes

Fatty acids, mostly short-chain and saturated or monounsaturated, are nutrients for energy sources, through mitochondrial β-oxidation (Tocher 2015). However, the long-chain and highly unsaturated fatty acids serve as functional constituents of phospholipids, which in turn have important structural and functional roles in the cell membrane by altering the fluidity of the membrane. Membrane functionality thus influences membrane transport (exchange of nutrients, metabolites, etc.), signal transduction, enzyme function, etc. (Tocher 1995). LC-PUFAs, also serve as a precursor for synthesizing prostaglandins, leukotrienes, lipoxins, resolvins, protectins, etc. (Tocher 2010, 2015).

More importantly, DHA is involved in the development of the fetal brain, eye retina, and cognition (Birch et al. 2000). Thereby, LC-PUFAs regulate the delicate balance of lipid metabolism and favor negative fat balance by regulating the PPAR-alpha receptor-mediated pathway (FAO-WHO 2010). Dietary inclusion of n-3 LC-PUFAs lowers blood cholesterol and TAG, maintains optimum platelet function, and lowers the risk of hypertension, CVD, rheumatoid arthritis, inflammatory bowel disease, respiratory burst, atherosclerosis, arrhythmia, thrombosis, ADHD, depression, dementia, Alzheimer's disease, and colorectal, breast, and prostate cancers (Calder and Yaqoob 2012; Tocher 2015; Gil et al. 2012; Miles and Calder 2012; Cabré et al. 2012; Calder 2013; Givens et al. 2006; Harris 2004; Dangour et al. 2012; Gerber 2012).

The FAO/WHO and Indian Council of medical Research (ICMR) recommended the dietary requirements of FAs based on national survey studies, equilibrium maintenance of nutrients (balance between the tissue deposition and excretion, out

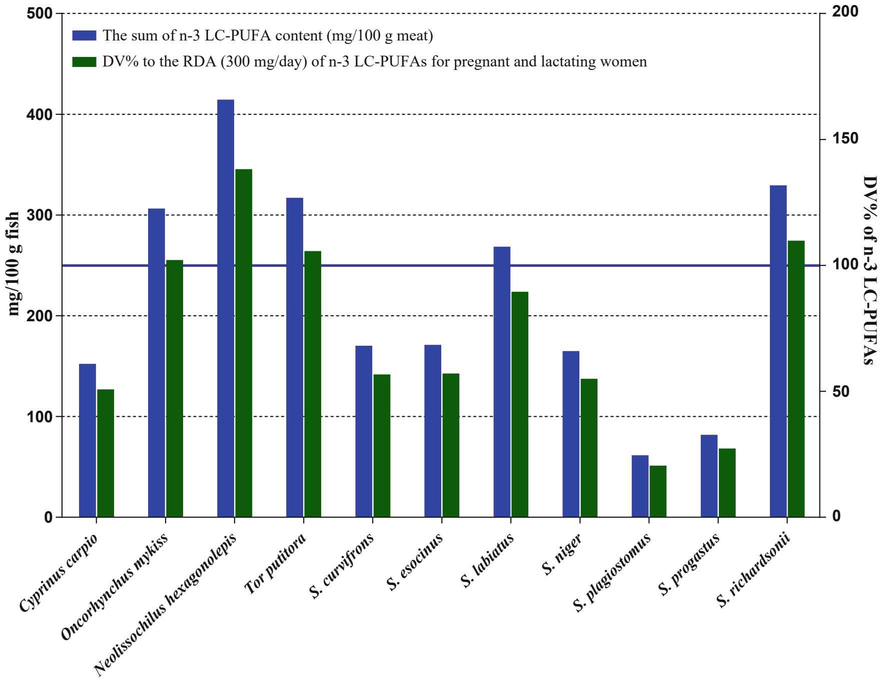

Fig. 19.7 The sum of n-3 long-chain polyunsaturated fatty acids (n-3 LC-PUFA) content (mg/100 g) of cold-water fishes from the Indian Himalaya, and their contribution potential (daily value percent; DV%) to meet the recommended dietary allowance (RDA) for pregnant and lactating women. The data are compiled from published reports (Joshi 2017; Joshi et al. 2017; Mohanty et al. 2016a; Sarma et al. 2013, 2022)

of ingested amount), and data based on animal studies (FAO-WHO 2010; ICMR 2010). Daily intake of 100 g of *O. mykiss* or *N. hexagonolepis* or *T. putitora* or *S. richardsonii* sufficiently (more than 100%) serves the daily requirement of n-3 LC-PUFAs (Fig. 19.7). 100 g of *S. labiatus* marginally serves the daily requirement. However, to meet the daily requirement of LC-PUFAs, around 200 g of *C. carpio* or *S. curvifrons* or *S. esocinus* or *S. niger* is needed. *S. plagiostomus* and *S. progastus* have limited content of LC-PUFAs in their muscle, and they poorly serve to meet the daily requirement.

19.14 Minerals

Minerals are inorganic elements that are vital constituents of animal bodies, including fish and humans. They exist either as ions (sodium, potassium, chlorine, etc.) or as complex molecules (as a constituent of metalloprotein like iron in hemoglobin and myoglobin, calcium-phosphate complexes of the bone, etc.). The inclusion of minerals in the diet is essential to maintain their required levels in the body for normal body function, growth, and development and to replace wear and tear due to aging (NRC 1989). Some are required in higher concentrations in the diet and are called macrominerals, while others are required in lower concentrations and are called microminerals. Dietary macrominerals are sodium, potassium, calcium, magnesium, and phosphorus, while microminerals are iron, copper, zinc, manganese, and selenium (Mohanty et al. 2016b). Microminerals, on the other hand, act as components of hormones, enzymes, vitamins, or other vital biochemical compounds and help in maintaining the normal physiological functioning of a human body by regulating various biochemical processes (NRC 1989).

19.15 Fish as a Source of Dietary Minerals

Fish, in general, contains a fair combination of dietary minerals such as calcium, phosphorus, and microminerals. Compared to the mineral content of the wild-caught marine, freshwater, and cold-water fish, the composition is more or less similar. However, there are some inter-species variations in the composition of some particular minerals (Bogard et al. 2015; Mohanty et al. 2016b). For example, the calcium content in SIFs such as *Gudusia chapra* and *Xenentodon cancila* is very high (3000–5000 mg/100 g), but the same is comparatively low (120 mg/100 g) in *Tenualosa ilisha* (Mohanty et al. 2016b). The composition of some minerals (not all) in fish muscle, like other nutrients, varies with season. However, the reports on seasonal variability of mineral contents of fishes are very few to date. The minerals which show their seasonality in fish muscle include iron, manganese (summer > spring > autumn > winter), and zinc (autumn > summer > spring > winter) (Mendil et al. 2010). The exact reason behind this phenomenon is yet to be found. The seasonal change in the composition of macrominerals is not reported in fish.

19.15.1 Mineral Composition of Cold-Water Fishes of Indian Himalaya

Among the Indian cold-water fishes, information on fatty acids profile is available for *C. carpio* (collected from the Himalayan region), *O. mykiss*, *N. hexagonolepis*, *T. putitora*, *S. curvifrons*, *S. esocinus*, *S. labiatus*, *S. niger*, *S. plagiostomus*, *S. progastus*, and *S. richardsonii* (Joshi 2017; Joshi et al. 2017; Mohanty et al. 2016b; Sarma et al. 2013; Sarma et al. 2022). Mineral compositions of cold-water fishes are summarized from these published sources of literature (Table 19.3). Among macrominerals, sodium content is high in *C. carpio* (268 mg/100 g) and *S. richardsonii* (260 mg/100 g) and low in *S. labiatus* (80 mg/100 g) and *S. progastus* (70 mg/100 g); potassium content is very high (400–1200 mg/100 g) compared to *L. rohita* and *C. catla* (except *T. putitora*). Similarly, calcium and phosphorus are also high in all cold-water fishes. Among microminerals, iron and zinc contents are comparatively high (than *L. rohita* and *C. catla*) in all *Schizothorax* spp., except in

Table 19.3 Mineral composition (mg/100 g) of some common tropical edible carps and cold-water fishes from Indian Himalaya

	Macrominerals (mg/100 g)						Microminerals (mg/100 g)			
Minerals	Na	K	Ca	Mg	P		Fe	Cu	Zn	Mn
Labeo rohita	202	268	206	–	125		2.20	–	1.90	0.40
Catla catla	198	284	161	–	147		1.60	–	1.30	0.30
Cyprinus carpio	268	1126	409	–	–		0.50	–	3.20	0.30
Oncorhynchus mykiss	215	1217	419	–	–		1.30	–	1.30	0.20
Neolissochilus hexagonolepis	214	575	1175	–	–		20	–	1.90	0.20
Tor putitora	173	1016	116	–	–		0.90	–	1.30	0.20
Schizothorax curvifrons	150	460	430	90	640		11.82	0.72	6.45	0.43
S. esocinus	140	480	410	70	680		11.54	1.24	4.62	1.43
S. labiatus	80	1090	440	110	890		7.02	1.17	6.62	0.74
S. niger	140	580	430	100	670		11.45	1.73	6.03	1.62
S. plagiostomus	180	700	360	150	830		11.83	1.14	2.64	1.02
S. progastus	70	450	350	80	580		12.59	1.81	5.4	1.26
S. richardsonii	260	610	300	90	630		12.02	1.52	5.62	1.32

The mean values of the mineral (sodium Na, potassium K, calcium Ca, magnesium Mg, phosphorus P, iron Fe, copper Cu, zinc Zn, and manganese Mn) contents are presented here from different sources (Joshi 2017; Joshi et al. 2017; Sarma et al. 2013; Mohanty et al. 2016b)

the case of zinc content in *S. plagiostomus*. Similarly, manganese content is also high in all *Schizothorax* spp. (>1 mg/100 g fish except in *S. labiatus*).

19.15.2 Dietary Mineral Requirements and Dietary Contribution Potential

Assessment of mineral requirements in the human diet is based on several approaches such as mineral balance studies (for calcium, phosphorus, magnesium, zinc, and other microminerals), accretion and mineralization dynamics (for calcium and phosphorus), clinical trials using dose-response studies (for calcium and phosphorus), turnover studies (for magnesium and zinc), and basal loss (for iron) (ICMR 2010).

Mineral requirements vary for different age groups, sexes, and physiological and pathological conditions of the subject. The RDA values given by the ICMR (2010) for the Indian context are valuable for deducing the species-specific mineral contribution potentials of the different food item, including fish. The dietary mineral contribution potentials of cold-water fishes of Indian Himalaya are presented in Fig. 19.8. Dietary sodium, potassium, and magnesium contribution potential of all cold-water fishes are negligible as those of *L. rohita* and *C. catla*. However, the dietary calcium and phosphorus contribution potential of cold-water fishes are high,

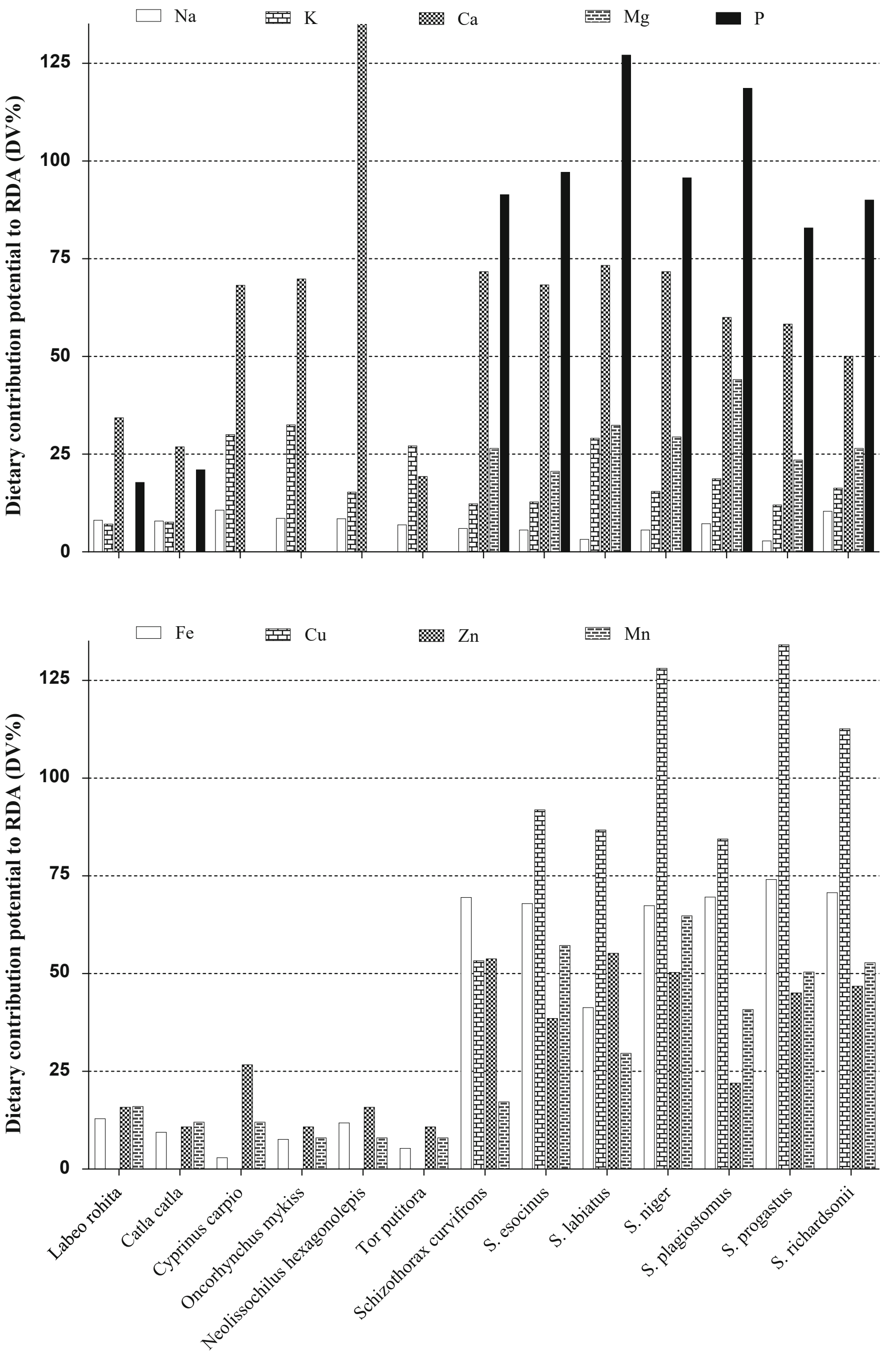

Fig. 19.8 The dietary contribution potential (daily value percent; DV%) of macrominerals and microminerals to meet the recommended dietary allowance (RDA) of cold-water fishes, along with DV% of *L. rohita* and *C. catla*. The data are compiled from published reports (Joshi 2017; Joshi et al. 2017; Mohanty et al. 2016b; Sarma et al. 2013, 2022). The RDA of sodium (Na), potassium

compared to *L. rohita* and *C. catla*. More specifically, calcium contribution potential of *N. hexagonolepis* and phosphorous contribution potential of *S. labiatus* and *S. plagiostomus* are more than 100%.

The dietary micromineral contribution potential of seven species of *Schizothorax* are significantly higher than those of *L. rohita*, *C. catla*, *C. carpio*, *O. mykiss*, *N. hexagonolepis*, and *T. putitora* (Fig. 19.8). Dietary copper contribution potentials of *S. niger*, *S. progastus*, and *S. richardsonii* are well above 100% per 100 g of fish. Those for the rest of other *Schizothorax* spp. are between 50 and 100%.

19.16 Conclusion

Consumption of fish may provide both nutrients and nutraceuticals to fight against NDDs and LDs. Fish has an important place in human nutrition for its unique n-3 LC-PUFAs content, abundant bioavailable micronutrients, and highly digestible protein. Compilation of information on the nutrient composition of cold-water fishes revealed that they are rich in nutrients with ample potential to contribute to the daily nutrient requirement of humans of all ages, sex, and physiological condition. Especially, the micronutrient contents of almost all cold-water fishes are superior to that of *L. rohita* and *C. catla*. Species like *N. hexagonolepis*, *S. labiatus*, *C. latius*, and *G. Lamta* are very rich in protein. *S. labiatus*, *S. richardsonii*, *S. esocinus*, and *S. progastus* are rich in most of the essential amino acids. *S. curvifrons*, *S. labiatus*, *S. niger*, *O. mykiss*, *T. putitora*, *S. esocinus*, and *B. bendelisis* are specifically rich in oil.

The n-3 LC-PUFAs, on the other hand, are abundantly available in *O. mykiss*, *N. hexagonolepis*, *S. richardsonii*, *T. putitora*, *S. curvifrons*, and *S. labiatus*. Fishes rich in minerals are *O. mykiss*, *T. putitora*, and all species of *Schizothorax* spp. (Fig. 19.9). The cold-water fishes of the Indian Himalaya are rich in one or the other nutrients and the corresponding dietary contribution potential. This compiled nutritional information of all cold-water fishes of the Indian Himalayan region may prove valuable to nutritional scientists for further research on fish processing, product development, and value addition.

Fig. 19.8 (continued) (K), calcium (Ca), magnesium (Mg), and phosphorus (P) are, respectively, 2500, 3750, 600, 340, and 700 mg/day. The RDA of iron (Fe), copper (Cu), zinc (Zn), and manganese (Mn) are, respectively, 17, 1.35, 12, and 2.5 mg/day

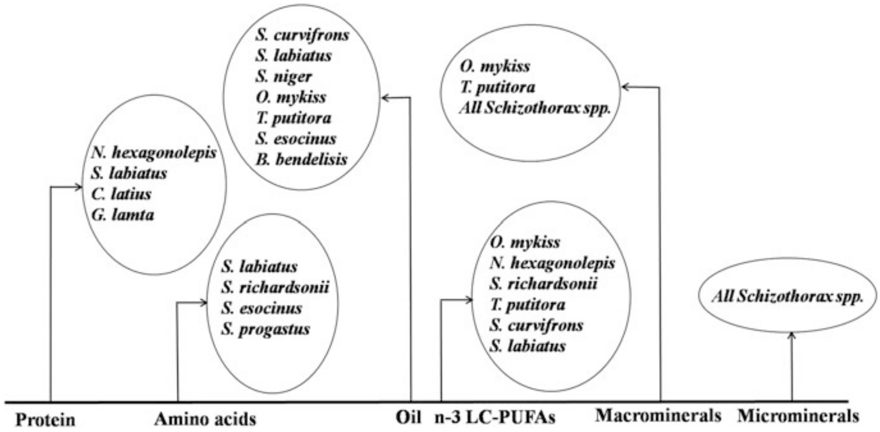

Fig. 19.9 Species-specific nutrient abundance in cold-water fishes of the Indian Himalaya

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20 En Route to Aquaponics in Cold Water: Identifying the Gaps in Principles and System Design

Maibam Birla Singh and Yumnam Rameshori

Abstract

Aquaponics is now poised to become a climate-resilient sustainable food production system. It has come a long way from having its origin from the integrated fish and rice farming in Asia and Chinampas (floating gardens in Aztec) of Mexico to its modern-day form. However, the exact potential of aquaponics is yet to be realized and is mostly confined to small-scale and warm climates. This chapter reviews aquaponics—its principle, physicochemical parameter, system components, and designs, with more emphasis on aquaponics in cold water, its current status, some adaptations, and challenges. Some possible solutions and research areas to push cold water aquaponics toward commercialization have also been suggested.

Keywords

Aquaponics · Climate-resilient technology · Cold water · Commercialization

20.1 Introduction

Increasing environmental concerns, rapidly growing population, and decreasing cultivable lands, coupled with limited water resources have necessitated the development of environment-friendly sustainable food production technology. An important aspect of the global food-energy-water nexus is the issue of fresh water for

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agriculture (Reinhard et al. 2017). Aquaponics is a modern scientific adaptation of the ancient techniques of food production used in natural lakes or other water bodies to produce food. At present, aquaponics is recognized as one of the most promising sustainable productive food systems that use fish wastewater for plant production. It may be noted that the use of fish waste as fertilizer for crops is practiced since ancient times (Turcios and Papenbrock 2014). In China, rice-cum-fish culture was practiced for about 2000 years ago (Campanhola and Pandey 2019). It was practiced in the vicinity of Hanzhong and Mian Countries in Shanxi Province and in Emei country in Sichuan Province. The fish stocked in the rice fields were common carp (*Cyprinus carpio*), crusian carp (*Carassius auratus*), and grass carp (*Hypophthalmicthys molitrix*) (Turcios and Papenbrock 2014). The most well-known examples of integrated farming are the "stationary islands" in shallow lakes in Aztecs, Mexico, in 1150–1350 BC (Crossley 2004). An agriculture method called *Chinampa* was practiced, where plants were raised on floating gardens and waste materials dredged from water channels or canals and surrounding areas were used to irrigate and grow the plants. *Chinampas* are long, narrow, elevated (by 50–150 cm) rectangular strip fields, forming islands in the wetlands or lakes built with the sediments from the bottom of water bodies. The water channels are usually 1.5 m in depth and separate the floating islands by creating a web of water channels. *Chinampas* are constructed by staking out the shallow lake bed, creating a rectangular perimeter, and then fencing with wattle. The fence-off area was then layered with soil by filling the *Chinampa* with two layers of soil, one with organic matter and one made out of sludge till the level is above the level of the lake. Often trees are planted at the corners to secure the *Chinampa*. The sludge, formed due to sediment and decaying vegetation in *Chinampa*, is rich in nutrients. The waste from the fish settled at the bottom of the canals was used to fertilize plants. These stationary or floating gardens had very high crop yields with four (up to seven) harvests a year (Van Tuerenhout 2005). The cultures around Inle Lake in Myanmar, the Waru Waru agriculture of the Uru people along the shores of Lake Titicaca in Peru (Moldovan and Bala 2015), and Phumdi in Loktak Lake in Manipur, India, are also examples of integrated framing in water bodies (Singh and Khundrakpam 2011) (Fig. 20.1).

Aquaponics started with a combination of soilless plant production, also known as hydroponic cultivation of plants with fish culture. The first studies of soilless cultures were in hydroponics, in Francis Bacon's work *Sylva Sylvarum* (1627). Later in 1666, Boyle carried out studies on plant growth in pure water with added nutrients from soil. Further, Justus von Liebing (1803–1873) developed the theory of mineral nutrition of the plants that led to call the method "nutriculture" by two German botanists, Julius von Sachs and Wilhelm Knop (1859–1865) (Moldovan and Bala 2015). Later developments are attributed to Dr. William Gericke at the University of California in 1929 (Gericke 1937). The method was named by Gericke as "hydroponics" or the science of cultivating terrestrial species in nutrient substances (Gericke 1937).

The modern aquaponics started with Sneed et al. (1975), where they used the effluent from catfish holding tanks for growing plants without any biofiltration. Further, Naegel (1977) combined Recirculatory Aquaculture System (RAS) with

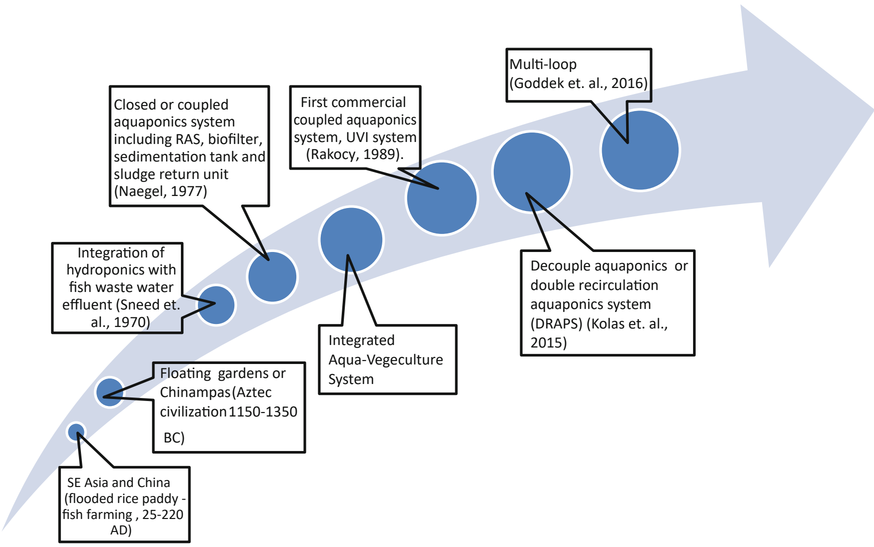

Fig. 20.1 The chronology of developments in sustainable integrative farming leading to present-day aquaponics

hydroponic raft cultivation and included biofiltration, sedimentation tank, and with a sludge return with denitrification in a bypass. Subsequently, Lewis et al. (1978), Watten and Busch (1984), Rakocy (1989a, b) and, McMurtry et al. (1990, 1997) contributed in the development in system design, biofiltration, and the identification of the optimal fish-to-plant ratios that led to the creation of first known closed systems that allow for the recycling of water and nutrient buildup for plant growth, thus pointing to the suitability of integrated aquaculture and hydroponic systems for raising fish and growing vegetables. Rakocy is attributed to the development of the first commercial scale aquaponics, set up in the University of Virgin Island. Further, Savidov et al. (2007) and Lennard and Leonard (2006) provided key calculations and production plans on commercial aquaponics system design. A recent survey, conducted by Love et al. (2015), showed that aquaponics had been receiving growing interest since then, promoting an alternative integrative farming approach toward food security and sustainability.

The objective of this chapter is to review the principle of aquaponics, physico-chemical parameters, system components, and designs and to understand the limitations of various systems. This is done to facilitate the development of standardized design, working principles, and standard operating protocols and help integrate aquaponics to various integrated agriculture food production system. Further, we specially focus on aquaponics in cold water, review some existing designs, and stress on the improvement that can be made to make this technology more economically viable than existing cold-water RAS technology. The chapter concludes with some important challenges in implementation of cold-water aquaponics and possible integration with some sustainable technology and research areas to close the gap between the principles of aquaponics and practical system design.

20.2 Integrating the Aquaculture with Hydroponics

Aquaculture is the farming and production of fish and other aquatic animals and plants species (Somerville et al. 2014). In conventional fish farming, such as open water systems, pond cultures, and flow-through systems, feed are provided to fishes in water. The fish waste and uneaten feed pollute the water. The waste nutrient-rich water is then released in water bodies, causing eutrophication and hypoxia. A simple concept to mitigate this problem is by integrating with plants. Hydroponics is a method of cultivation where mineral fertilizers are added to the water and fed to the plants in a soilless medium (Gericke 1937). However, it utilizes costly, unsustainably sourced mineral chemical fertilizers to produce crops, consumes energy, and produces wastewater, which is also discarded, resulting in environmental issues. Further, concentration of the solutions needs to be constantly monitored. On the other hand, aquaponics is a technology which treats and reuses the waste aquaculture water from the RAS and use the nutrient-rich water to grow plants hydroponically. It overcomes the issue of providing chemical fertilizer in hydroponic system via fish sludge, which needs to be treated separately in RAS.

20.3 Principle of Aquaponics

Aquaponics is based on the concept of integrating farming methods with a view to reuse the wastewater for plant growth, thereby, reducing the environmental impacts. Working principle of aquaponics is based on the concept of re-circulating aquaculture system (RAS) and the use of nutrient-rich aquacultural wastewater as source of nitrogenous compounds for growing plants in a hydroponic culture unit, which in the process depurates the water that is returned to the aquaculture tanks (Goddek et al. 2019). It simply combines the advantages of RAS and hydroponic system while overcoming the individual stand-alone drawbacks. The system results in a symbiosis between fish, microorganisms, and plants and encourages sustainable use of water and nutrients, including their recycling. Within this synergistic interaction, the respective ecological weakness of aquaculture and hydroponics are converted into strengths. This substantially minimizes the need for input of mineral fertilizers and output of waste, unlike when run as separate systems.

Figure 20.2 shows how the fishes, bacteria, and plants are interrelated symbiotically in an aquaponics system to form an ecosystem. In general, three major processes occur in one complete cycle of an aquaponics system. Firstly, the introduction of fish feed into the system results in uneaten fish feed and feces, which are rich in organic nitrogen, which decompose and accumulate ammonia in the water by the process called ammonification. Secondly, the ammonia is converted into nitrites and then to nitrates by the process called nitrification, performed by nitrifying

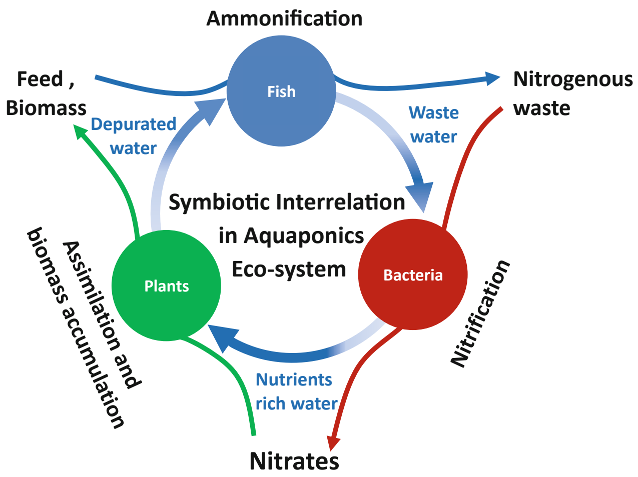

Fig. 20.2 Schematic diagram showing material flow, the symbiotic interrelation in plants, fish, and bacteria in an aquaponics ecosystem after (Goddek et al. 2015)

bacteria. Thirdly, the nitrates are absorbed by the plants, resulting in assimilation of biomass formation, and in the process act as natural filter for the water, thereby detoxifying the water, allowing for recirculation back to the fish. In the whole process, the aquacultural fish waste is converted to plant biomass like vegetable or fruits, which has economic value. Thus, this technology is also called "waste-to-wealth technology."

20.4 System Components and Design Principles

The essential components of aquaponics are fish-rearing tanks, solid removal components (mechanical filtration, e.g., clarifiers, microscreen), biofilters (nitrification unit), a hydroponic subsystem, and a sump (Rakocy 2012; Somerville et al. 2014) (Fig. 20.3).

One of the most distinguished features of aquaponics is the circular flow of water or number of loops or cycle. The understanding of concept of loops is an important aspect as it is the mechanism by which the system operates. The nature of flow and the ways or the number of loop by which the water in the aquaponics system circulate has many implications in the effective functioning and control of the aquaponics system. It also depends on the coupling of water or nutrients in the various subsystems. Aquaponics systems may be broadly divided into two water or nutrient-related coupling types: (1) permanently coupled, permanent coupling with tightly coupled units ("coupled" system) and (2) on-demand coupled, on-demand coupling with loosely coupled units ("decoupled" system) (Baganz et al. 2022; Goddek et al. 2018). In the next sections, we discuss various coupled and decoupled

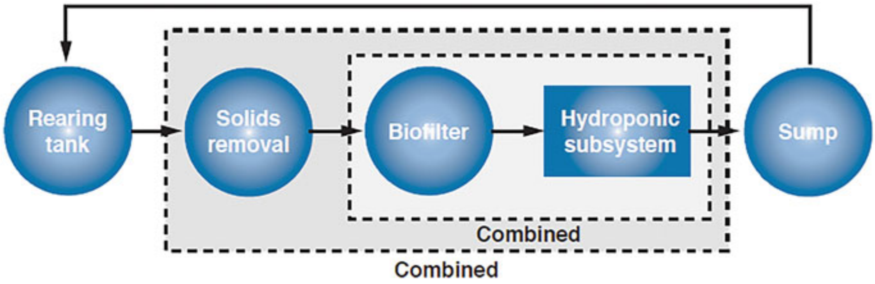

Fig. 20.3 Conceptual diagram of a coupled single-loop aquaponics system components (Rakocy 2012). The direction of arrow shows the flow of materials. The dotted boxes indicate the components that may be combined in other system design

systems, nature of flow system, and their associated features based on the number of loops.

20.5 Coupled Aquaponics System

20.5.1 Closed One-Loop/Single Recirculating Aquaponics System

In one-loop aquaponics system, the water flows in one direction or outlet continuously. Such designs are often used in home-based or small-scale system. In this type of system design, the water flows in both the fish tank and the grow beds in a coupled manner. Such systems are called coupled aquaponics system. A classic example of a one-loop coupled aquaponics commercial system is the University of Virgin Islands (UVI) aquaponics system (Rakocy 2012). It combines the solid removal unit, biofilter, and the hydroponic subsystem in one unit, which effectively acts a solid waste removal unit. The basic idea of one-loop design is to make a constant flow or supply of nutrients. The simple nature of the design and fully closed recirculation enriched the water with nutrients. However, the simple single closed coupled-loop design fails to address the different requirements of fish and plants independently. Also the system is problematic in cases of pest or disease outbreaks in the system.

20.5.2 Decoupled Aquaponics System

Another system design is to consider the independent control of each system, because plants and fish have different environmental requirements. Systems where the individual subsystems—aquaculture unit (RAS), hydroponic unit, and fish sludge remineralization unit—can be independently controlled are called decoupled aquaponics system. It is an open-loop system. A decoupled aquaponics system consists of an RAS unit connected to hydroponic unit via one-way valve. In this system, the water is separately circulated within each subunit and supplied on demand from RAS to hydroponic unit, but not returned again to the system (Kloas et al. 2015; Goddek et al. 2016; Monsees et al. 2017b).

20.5.3 Double- or Two-Loop Aquaponics System

In a double- or two-loop aquaponics system, the RAS and hydroponic subsystem are separated, and there are two water flow loops: one in an RAS water flow loop and another in a hydroponics water flow loop. It is also known as double re-circulating aquaponics system (DRAPS) (Kloas et al. 2015; Suhl et al. 2018). The basic idea of DRAPS is to separate the 2 units, i.e., RAS unit and the hydroponic unit, to address the different requirements of fish and plants individually. In this system, the two subsystems—RAS and a re-circulating hydroponic system—are unidirectionally connected to deliver fish water containing nutrients into the hydroponic reservoir as fertilizer. The basic components of DRAPS are RAS unit, including the fish-rearing tanks, mechanical filter (sedimentation), pump system, trickling biofilter, and pump sump. The hydroponic unit includes a re-circulating system where the nutrient solution from a storage tank is delivered to the plant grow unit. Both systems are connected via one-way delivery system. A major problem in DRAPS is the loss of nitrogen due to the secondary clarifier. This leads to inadequate nutrients in the hydroponic unit (Suhl et al. 2018) and creates a need to add additional fertilizer (Fig. 20.4).

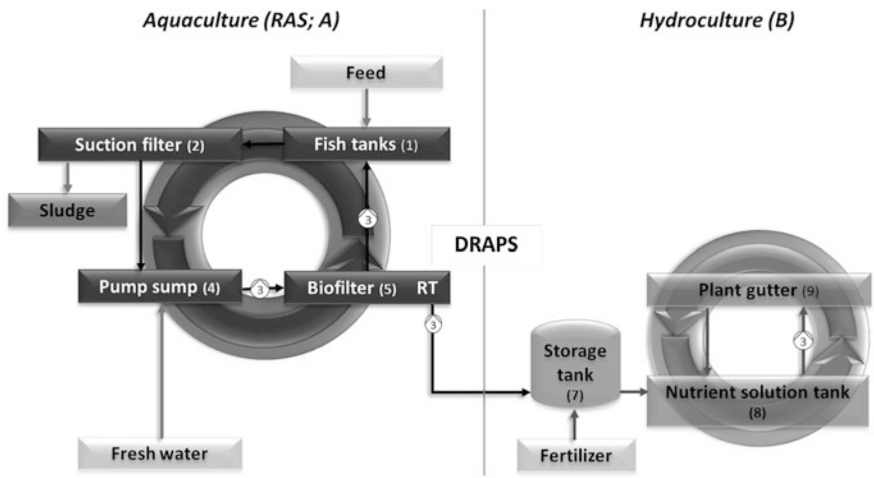

Fig. 20.4 Schematic flow diagram in modified double re-circulating aquaponics system (DRAPS). The re-circulating aquaculture system (RAS: **a**) loop consisting of fish-rearing tanks, sedimentation mechanical filter, biofilter, and pump sump. The re-circulating hydroponic loop (**b**) consists of a nutrient solution tank and hydroponic grow beds. The two loops are connected via one-way delivery system (Suhl et al. 2018)

20.5.4 Three-Loop Aquaponics System

In coupled and decoupled system, the nutrient is enhanced in RAS unit, and not in the hydroponic unit (Goddek 2018). In order to increase the nutrient availability through efficient nutrient recovery in the hydroponic unit, a three-loop system was proposed (Goddek et al. 2016; Yogev et al. 2016) via introducing a re-mineralization loop**.** In a three-loop system, there are three independent loops—(1) RAS loop, (2) hydroponic loop, and (3) the sludge re-mineralization unit loop. The hydroponic and the sludge re-mineralization units are connected by a one-way valve with a view to increase the nutrient availability in the hydroponic unit. The sludge re-mineralization unit may consist of sludge digester (aerobic or anaerobic), mineralization tank, settling tank, solid removal tank, and degassing tank. Remineralization is crucial with regard to treatment and nutrient recovery in the aquaponics system. Goddek et al. (2016) have showed that decoupled three-loop aquaponics systems are evapotranspiration-dependent and that a mineralization loop can improve performance. Although a wide variety of aerobic and anaerobic unit processes (Monsees et al. 2017a; Goddek et al. 2018) are being developed, implementation on a commercial scale is still not achieved. In aerobic mineralization processes, significant amount of oxygen must be provided through aeration. Although aeration is not required for anaerobic processes, mechanical mixing may be needed. However, it is important to note that even though most of the water and nutrients are recovered, there is still a sizable amount of solid waste that is disposed. Goddek et al. (2018) used an upflow anaerobic sludge blanket reactor (UASB) followed by an expanded granular sludge bed (EGSB) and compared them to simple static anaerobic and aerobic reactors. It was found that the nutrient recovery via UASB is pH dependent. However, at present, the process in sludge digester is not well understood. It will be crucial to understand the role of bacteria in the re-mineralization process (Fig. 20.5).

20.6 Multi-Loop Aquaponics System

20.6.1 Four-Loop Aquaponics System

The idea of integrating or introducing a desalination loop as a fourth loop in a three-loop system was proposed by Goddek et al. (2016) and Kloas et al. (2015). These workers conceived that the integration of desalination technologies can improve the design and practical applications and also anticipated a multi-loop aquaponics systems. Goddek et al. (2018) showed how implementation of desalination processes increases the nutrient concentration within the hydroponic loop. The introduction of a small-scale desalination unit is to concentrate the hydroponic nutrient solution and to direct demineralized water to the RAS subsystem. There are three different reasons for the implementation of desalination technology in multi-loop aquaponics systems: (1) to improve water quality in the RAS, (2) to increase nutrient concentration from RAS to plants in the hydroponic loop, or (3) a combination of both. Also,

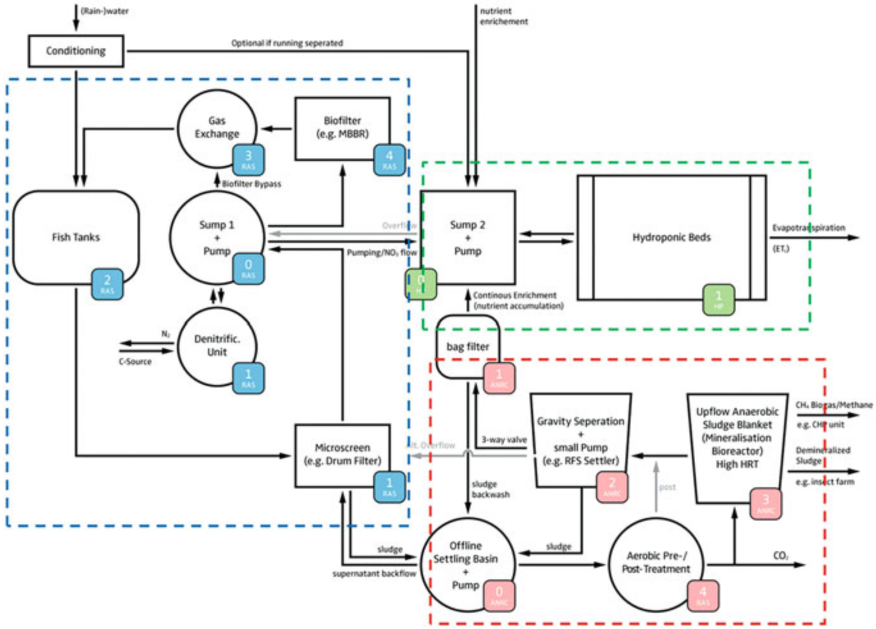

Fig. 20.5 Process flow of a basic decoupled three-loop aquaponics system. Here, the three loops are the RAS loop (enclosed in blue dotted lines), hydroponic loop (enclosed in green dotted lines), and the mineralization loop (enclosed in red dotted lines). The RAS unit which is confined inside the blue dotted lines (the components are shown in blue tags), the hydroponic unit (components are shown in green tags), and the sludge treatment unit (with anaerobic nutrient remineralization components (ANRC) in the red tags). The levels of each component associated are tagged with numbers. The high numbers refer to high positioning and low numbers to low positioning in ground level. For example, in the case of the RAS unit, 0 indicates the lowest level, and 4 indicates the highest level. The system is gravity flow, where water flows from high levels to low levels, and pressurized flow via pump is required when the flow goes from low to high numbers (Goddek et al. 2016)

apart from the suggested reasons of implementing desalination technologies, a denitrification side loop has the potential to lower the RAS nitrate levels (Goddek et al. 2018). Another way is to integrate the anaerobic sludge mineralization loop into the RAS sub-system, to promote denitrification. However, these two options would reduce the total nitrogen availability in the system, leading to higher fertilizer requirements. Thus, a mineralization loop, independent from RAS and hydroponic loop, may be utilized for providing the plants with $NH4^+$ (preferred form of nitrogen) (Jones and Jacobsen 2005) as well as ensuring optimal conditions for anaerobic bacteria (de Lemos Chernicharo 2007). The introduction of desalination loop can contribute to the nitrate balances in multi-loop aquaponics systems to attain optimal growth conditions for both fish and plants, by concentrating the hydroponic nutrient solution while diluting the RAS process water. However, the economics has to be taken into account as desalination is an energy-consuming process (Fig. 20.6).

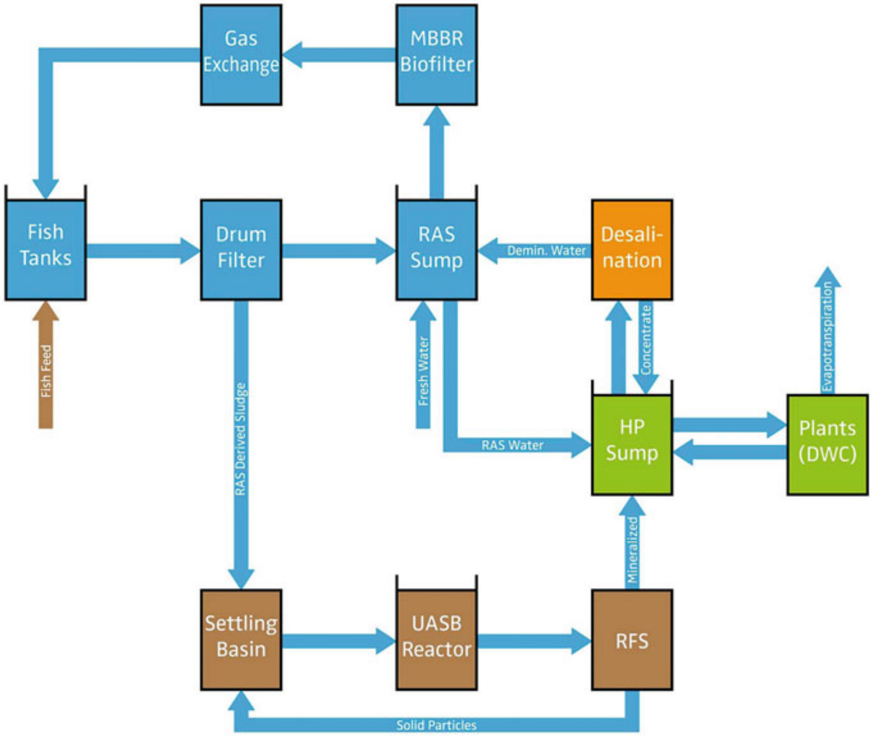

Fig. 20.6 Scheme of multi-loop (four-loop) aquaponics system showing the flow of water (arrows indicate the direction of flow) after (Goddek and Keesman 2018). The main modification in the system is the inclusion of desalination unit. The purpose of the unit is to concentrate the nutrients in the hydroponics sump via two separated flows: (1) demineralized water to the RAS and (2) concentrated nutrient solution flowing back to the hydroponic loop. The system also includes the *RFS* radial flow settler, *UASB* upflow anaerobic sludge blanket reactor, *DWC* deep water culture, *HP* hydroponic, *MBBR* moving bed bioreactor. The RAS components are shown in blue, the hydroponic unit in green, re-mineralization unit in brown, and desalination unit in orange. The figure shows a flowchart of a multi-loop system incorporating a decoupled four-loop aquaponics system consisting of (1) an RAS loop (blue units), (2) a hydroponic loop (green unit), (3) a mineralization loop (brown unit), and (4) a desalination, i.e., nutrient concentration, loop (orange unit)

20.7 Flow-Through Aquaponics System

This system of aquaponics is based on the concept of integrating flow-through fish culture (ponds, raceways) with hydroponics and mainly used in cold-water systems. The flow-through fish culture systems differ from RAS in that water is not reused or recycled and nutrients do not accumulate over time (see Fig. 20.7). Integrating it with hydroponic unit makes the system environment-friendly and provides additional economic value (Adler et al. 2000). It improves the quality of effluent water,

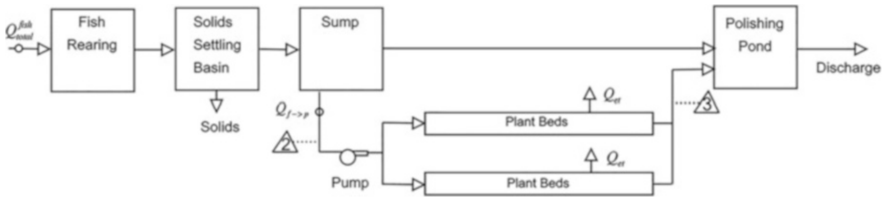

Fig. 20.7 Process flow for a flow-through aquaponics system (Colt et al. 2022)

thereby mitigating the environmental impacts in a cold-water ecosystem. Since the fish species vary in their adaptability to an aquaponics environment, and plants displaying variable growth rates as well as nutrient removal capacity, it is important to choose the right fish-plant species combination in such system (Maucieri et al. 2018). In order to maximize the benefits of symbiotic relationship of fish, plants, and bacteria, local adaptation to climatic conditions, optimal for a particular biological component, is absolutely necessary in flow-through fish culture aquaponics system. Generally, flow-through fish culture systems are used to rear cold-water fishes like trout and other salmonids and require a temperature range of 7.2 °C and 15.6 °C for optimum growth (Piper et al. 1982). A wide variety of source waters used in cold-water aquaculture including springs, well water, lake water, and stream water could potentially be used in aquaponics culture, but comprehensive studies are lacking. Pumping may be required for some system design, but gravity-fed flow system can be designed adapting to perennial water source, making the system more economical. Due to constant flow-through, there is less contact time between the water and the fish, and hence, nutrient concentrations are commonly lower than those found in either hydroponic culture or effluent from recirculating fish culture (Buzby and Lin 2014). For example, the nutrient concentrations in these systems may only be 1/200 to 1/500 as those in RAS systems. The effect of different flow rates has been studied by Buzby et al. (2010). An important aspect for flow-through system is the high-volume water included in removal of dissolved nutrients, requiring large plant growing area for efficient removal of nutrients. Further, the water temperature in the root zone is largely controlled by the influent water temperature rather than local climatic conditions. It is important to integrate flow-through system to greenhouses and water source like spring. In such design system, the combination of a constant temperature spring water supply and passive temperature control (in a greenhouse or high tunnel structure) allows all-year-round lettuce production in temperate regions (Johnson et al. 2016).

20.8 Factors Affecting Aquaponics System Design: General Considerations

There is a growing body of literature that stresses the importance on the factors that affects the design and hence the mass balance equations for aquaponics system design (Goddek et al. 2016; Love et al. 2015; Colt et al. 2022; Palm et al. 2018). Research has been carried out to include the factors in developing model aquaponics systems. Various factors that require general consideration in designing an aquaponics system include feed quality, feeding rate, water quality (DO (dissolved oxygen), ammonia, nitrite, and nitrate level), waste management and sludge removal, control of pH, fish-plant combinations, and temperature.

Feed quality and input feed: The first source of nutrients in aquaponics system is the fish feed. The types of nitrogenous waste and the consequent process of converting the waste to nutrients very much depend on the input and quality of feed. While the amount of input is related to the waste generated, the feed quality is important for the efficient growth of fish (food conversion ratio, FCR). An efficient feeding strategy and optimization for a particular fish is required. It may also depend on the type of fish culture adopted—sequential or staggering. It may be noted that amount of the input feed and system design limits the number of plants that can be grown in the hydroponic unit. A proper account of input feed-to-area of plant ratio (FAR) must be considered.

Waste management and sludge removal: Fish feed is the source of waste in aquaponics. Only 1/3 of feed nutrients are digested, absorbed, and utilized in the metabolic processes and retained in biomass, while the rest are excreted as non-fecal or fecal losses into the environment (Gichana et al. 2018). This solid waste must be removed from the fish tank via effluent water flow, filtering, or settling before it enters the hydroponic component. If solids are not removed, they will adhere to plant roots, decrease DO levels as they decay, and affect the uptake of water and nutrients. This will also have an adverse effect on nitrifying bacteria (Table 20.1). On decomposition of solids, fish waste, oxygen is consumed, and ammonia is produced, which is also lethal for fish. This may further necessitate extra aeration, increasing the energy cost. If not removed, the solid organic matter generated in aquaponics systems can clog aggregate media (pea gravel, perlite, etc.) and reduce water flow. The clogged areas become anaerobic (as the organic matter decomposes) due to lack of oxygen, will lead to rotting of plant roots, and become a dead zone in the system. Adequate biofiltrations must be ensured so that the ammonia excreted by the fish may not accumulate in large amount and reach toxic level. The oxidation of ammonia to nitrate by nitrifying bacteria can reduce the toxic ammonia to plant usable nitrates. It is necessary to maintain optimum feeding rate to plant ratio. However, a biofilter is needed in aquaponics systems to host the bacteria and maintain the process of nitrification (Gichana et al. 2018). In case where all the sludge is not converted into nitrates, the removal of the solid sludge may be necessary.

Table 20.1 Effect of DO, pH, and temperature on nitrification rate of nitrifying bacteria (Gerardi 2006)

Dissolved oxygen (mg/L)	*Effect on nitrification*
<0.5	Nitrification initiated but insignificant
0.5–0.9	Rate of nitrification begins to accelerate
1.0–2.0	Rate of nitrification significant
2.1–2.9	Sustained nitrification
3.0	Maximum rate of nitrification
> 3.0	Nitrification may improve
pH	*Effect on nitrification*
4.0–4.9	Nitrifying bacteria inactive but present
5.0–6.7	Nitrifying bacteria stunted activity
6.8–7.2	Optimal pH range for activated sludge nitrification
7.3–8.0	Assumedly constant range of nitrification
8.1–8.5	Theoretical optimum pH range for nitrification
Temperature (C°)	*Effect of nitrification*
30	Optimum temperature for nitrification
15	Approximately 50% of optimum nitrification
10	Approximately 20% of optimum nitrification
5	Nitrification ceases

20.8.1 Water Parameters (DO, Ammonia, Nitrite, and Nitrate Level)

The quality of water is the most critical factor in effective operation of an aquaponics system. Water aeration is essential in an aquaponics unit to ensure a high level of DO for intensive fish production. Fishes, plants, and bacteria in aquaponics systems require adequate levels of dissolved oxygen (DO) for maximum health and growth. DO levels of 5 mg/L or higher should be maintained in the fish-rearing tank and in the water surrounding plant roots. It is also essential to maintain healthy populations of nitrifying bacteria, which convert toxic levels of ammonia and nitrite to relatively nontoxic nitrate ions. Ammonia is secreted by fish mainly through their gills. One genus of bacteria (*Nitrosomonas*) converts ammonia to nitrite, while another genus of bacteria (*Nitrobacter*) converts nitrite to nitrate. Oxygen is required for these chemical transformations, a process known as nitrification. The growth and development of root system in deep water culture (DWC) are also affected by the level of DO. In DWC, plant root may be very well developed if oxygen concentration of 5 mg/L is maintained. An anaerobic zone may be created in the system if aeration is poor, resulting in inefficient oxygen. This may further preclude the growth of nitrifying bacteria.

Table 20.2 shows the various water parameters that must be maintained in an aquaponics (warm and cold water). Table 20.2A shows the water parameters for individual organism—fish, hydroponic plants, and nitrifying bacteria. Also, in Table 20.2B, the compromised water parameter for a coupled aquaponics system is shown. It may be observed from the table that the value of temperature and DO in

Table 20.2 (A) Ideal water parameters for fish (warm or cold water), hydroponics plants, and nitrifying bacteria; (B) compromised water parameters in an aquaponics system (Somerville et al. 2014)

A. Water parameters for individual organism						
Organism type	Temp (°C)	pH	Ammonia (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	DO (mg/L)
Warm-water fish	22–32	6–8.5	<3	<1	<400	4–6
Cold-water fish	10–18	6–8.5	<1	<0.1	<400	6–8
Plants	16–30	5.5–7.5	<30	<1	–	>3
Bacteria	14–34	6–8.5	<3	<1	–	4–8
B. Compromised water parameters for coupled aquaponics system						
System	Temp (°C)	pH	Ammonia (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	DO (mg/L)
Aquaponics	18–30	6–7	<1	<1	5–150	>5

Table 20.2B is less favorable for cold-water fish. It may be noted that cold water has more stringent condition in terms of DO, ammonia, and nitrite concentrations. Also, it is inferred from the table that plant and fish have different requirements in terms of pH and temperature. This factor has to be considered while designing aquaponics. In a commercial-scale system, high dissolved oxygen (DO) levels near 80% saturation (6 to 7 mg/L) are maintained by aerating the hydroponic tanks with numerous small air diffusers. Table 20.3 shows the water qualities under operating conditions in commercial- or pilot-scale RAS.

A comparison of the water parameter listed in Tables 20.2 and 20.3 shows the difference in water quality maintained in aquaponics and RAS. While in the RAS system, specific optimum conditions for a specific fish may be maintained. However, how to effectively operate a hydroponic unit, coupled or decoupled, maintaining the water parameter, is a challenge. Cold-water fish have more restriction in temperature and hence less effective nitrification process (Table 20.1).

Controlled pH: pH of water affects the nitrification efficiency by the bacteria (Table 20.1). Nitrification is more efficient at pH 7.5 or higher and practically ceases at pH values less than 6.0. pH must be measured daily, and base (calcium hydroxide and potassium hydroxide) may be added to neutralize the acid. The pH of a solution affects nutrient solubility especially trace elements. Essential nutrients such as iron, manganese, copper, zinc, and boron are less available to plants at pH above 7.0, while the solubility of phosphorus, calcium, magnesium, and molybdenum sharply decreases at pH below 6.0 (Raviv and Lieth 2008; Schwarz 1995). If pH is too high, nutrients precipitate out of solution; plants display nutrient deficiencies, and growth and production decrease (Schwarz 1995). If pH is too low, ammonia accumulates to levels that are toxic to fish, and a different set of nutrients precipitate out of solution with similar detrimental effects to plant growth and production. Therefore,

Table 20.3 Water quality parameters observed under general conditions in operating commercial- or pilot-scale RAS (Dalsgaard et al. 2013)

Parameter	Temperature (°C)	O_2[b] (mg/L)	CO_2 (mg/L)	pH	Salinity (ppt)	TAN (mg/L)	NO_2-N	NO_3-N	Density (kg/m^3)
Arctic char	5–12	9–11	≤22	6.5–8.5	<24–26	≤1.0	<0.50	<10	85–130
Atlantic salmon smolt	12–14	10	≤12	6.8–7.3	0	<0.2	<0.20	≤90	45–50
European eel	23–28	6–8	10–20	5.0–7.5	0.5	0.0–5.0	0.1–5.0	50–120	8–9
European lobster	18–20	>6	n.a	7.8–8.2	28–35	<0.3	n.a.	n.a	n.a.
Pike perch	22–25	6–8	10–20	6.5–7.5	0	0–10.0	0.1–5.0	≤56	15–60
Rainbow trout	2–21	6–8	≤15	6.5–8.0	0–30	<7.5	<1.00	<200	50–80
Sturgeon	18–25	8	n.a.	7.0–8.0	0	<3.0	<0.50	<25	80–100
Tilapia	20–30	4–6	≤30–50	6.5–8.5	≤10–15	<3.0	0.05–1.00	100–200	85–120

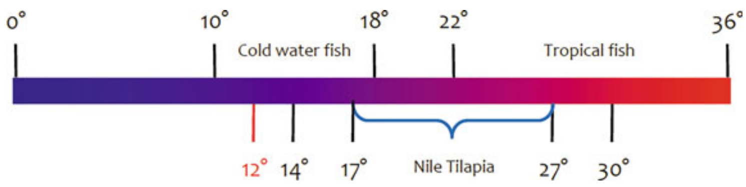

Fig. 20.8 Optimum temperature range of cold, warm, and tropical fishes (Thorarinsdottir 2015)

monitoring and control of pH are essential. A compromise must be reached between nitrification and nutrient solubility. Usually, plants and fish have different pH requirements; therefore, it is recommended that pH 7.0 should be maintained in an aquaponics system. However, the optimum nutrient availability pH range of 5 to 6 is by far the most suited for plants. In a coupled aquaponics system, the pH is compromised between various organisms in the system (Table 20.2), whereas in the decoupled system, the individual pH requirements can be maintained.

pH of warm-water fish ranges from 6 to 9 (Piper et al. 1982). An important factor that affects the pH of water is the CO_2 partial pressure and its amount dissolved in the water. It affects alkalinity. Both high and low alkalinities are not favorable for aquaponics. High alkalinity is dangerous for fish, and low alkalinity affects the nitrification process and, hence, the pH. Nitrification releases hydrogen and hence reduces the pH; therefore, in aquaponics, the nitrification process controls the pH in the long run.

Water temperature: Water temperature is one of the important critical parameters in an aquaponics system. Water temperature affects the health of the fish and growth of plants and bacteria in an aquaponics system. For example, in cold water, the growth rate of tilapia is low compared with warm water (Fig. 20.8).

Further, proper temperature range is essential for the breakdown of sludge, uptake of nutrients by plants, and mineralization of wastes generated in aquaponics. Maintaining a temperature range of 14–34 °C is essential for proper growth of bacteria (Gerardi 2006). Also, high temperature can restrict the absorption of nutrients, such as calcium in plants. Moreover, the temperature of water has an effect on DO as well as on the toxicity (ionization) of ammonia (Timmons et al. 2018). Since nitrification rate depends on the temperature, it is important to maintain proper temperature. Table 20.2 shows the effects of temperature on nitrification rate of nitrifying bacteria.

A healthy aquaponics system can be achieved if the water temperature is kept in the range that is safe for fishes, plants, and bacterial growth. There are many factors that affect water temperature; some of them are local climate, source of heat, material used for piping, insulation in the tanks, area of exposure of water to air, type of growing system, total volume of water, heating source, and backup systems. For cold-water aquaponics, these factors will have an effect in maintaining a consistent water temperature. It is important to minimize dependence on external energy sources to maintain the water temperature so that the costs and dependency are reduced. Hence, an efficient system design must take into account the factors that affect the temperature.

Fish-plant combination: Fishes have traditionally been grouped into three classes depending on their temperature preference: cold-water species (prefer water temperatures under 15 °C), cool-water species (between 15° and 20 °C), and warm-water species (above 20 °C). Cold-water fishes that may be reared in aquaponics are trout (*Oncorhynchus mykiss*), European eel (*Anguilla anguilla*), pike perch (*Stizostedion lucioperca*), Arctic char (*Salvelinus alpinus*), and sturgeon (Order Acipenseriformes). In cold-water systems, the selection of plants is limited. Since plants need appropriate light, temperature, and nutrition (macro- and micro-elements) for growth, providing ambient condition is necessary. Fruiting plants may need special nutritional requirements, based on growth characteristics. Large-size plant varieties may require larger, more nutrients and proper temperature (e.g., tomatoes and root plants). Buzby et al. (2016) have studied a wide variety of food crops, including lettuce, herbs, and Asian greens and vegetables in a flow-through aquaponics system. (For a list of plants (vegetables, fruits, herbs, and medicinal plants) that may be used in cold-water aquaponics, see Bakhsh et al. 2015).

20.9 Specific Parameter to Design Efficient Aquaponicss System

Apart from the general consideration, various specific technical parameters are also required. Some of them include design ratios (feed input-to-area ratio, volume ratio or component ratio, area ratio, and nitrogen ratio), water flow rates and hydrodynamic characteristic (flow rate, hydraulic loading rate, hydraulic residence time (plant and fish)), and finally the degree of coupling.

20.9.1 Aquaponics Design Ratio

To correctly design an aquaponics system, several design considerations are suggested. The most important aspect in designing an effective aquaponics system is to consider the nutrient or mass (nitrogen, carbon, phosphorous) balance and energy (involved in converting fish waste to nutrients) balance equation of all process involved in successfully operating an aquaponics system. An essential condition for successfully running an aquaponics system is by maintaining a dynamic equilibrium of nutrient generated from fish to nutrient assimilated by plants. Due consideration should be made to the relative size (in volume), area, and ratio of plants to fish in the system. Also, nutrient removal or recovery rates must be accounted while calculating overall nutrient balance in the system. Some of the important design ratio that must be understood while setting up an aquaponics unit includes (1) feed-to-area, (2) area to volume, (3) volume ratio, (4) area ratio, (5) plant-to-fish number or mass ratio, (6) nitrogen ratio, and (7) plant-to-fish feed ratio (Colt et al. 2022). It is also important to consider the rates of nutrient (nitrogen, phosphorous) utilization and removal in the system. All these parameters are directly

Table 20.4 Aquaponics design ratio with specific fish-plant combination (Colt et al. 2022)

Species used	Original parameter		FAR	Reference
	Parameter	Value		
Tilapia-lettuce	FAR	169	169	Al-Hafedh et al. (2008)
		84	84	
		56	56	
African catfish-water spinach	Fish-plant ratio (FPR)	2	n/a	Endut et al. (2010)
		4	n/a	
		6	n/a	
		7	n/a	
		8	15–42	
		9	n/a	
		10	n/a	
Tilapia-Laura tomato	Area-to-volume ratio (AVR)	0.67	97	McMurtry et al. (1997)
		1.00	65	
		1.50	43	
		2.25	28	
Tilapia-lettuce (Exp.#3)	Plant-fish ratio (PFR)	1.2	80	Rakocy et al. (1993)
		1.5	67	
		1.9	53	
		2.5	40	
		3.8	27	
		7.5	13	
Tilapia-lettuce	FAR	14.3	14.3	Rakocy (1988)
		28.7	28.7	
		43.0	43.0	
		57.4	57.4	
		71.7	71.7	
		86.0	86.0	

or indirectly related to the mass-balance equations involved in the flow of materials (Table 20.4).

Here

$$\begin{aligned}&\mathrm{FAR}=\mathrm{Feed\ input\,(g/day)/Plant\ growth\ area}\left(\mathrm{m}^2\right);\quad \mathrm{FPR}=\mathrm{No.of\ plants/No.of\ fish};\\&\mathrm{AVR}=\mathrm{Area\ of\ plants\ growing\ unit}\left(\mathrm{m}^2\right)/\mathrm{Area\ of\ fish\ rearing\ units}\left(\mathrm{m}^2\right);\\&\mathrm{PFR}=\mathrm{No.of\ Plants/No.of\ fish}\end{aligned}$$

20.9.2 Feed Input-to-Area Ratio (FAR)

The popular method to design any size and shape of aquaponics is by using the simple feed-to-area ratio (FAR). It is a ratio that accounts three important variables:

(1) the daily amount of fish feed in grams, (2) the plant type, and (3) the amount of fish feed fed daily per m^2 plant growing area. Amount of feed fed to fish (according to a particular stocking density of the fish) is related to the waste (nutrients) generated in the system. The amount of nutrient is related to the amount of waste produced and the effectiveness of the nitrification process in the aquaponics system. This decides the amount of plants that may be grown in the hydroponic unit. FAR is a simple ratio indicating how much feed is input in the system per plant growth area, which may be expressed as g feed/m^2/day, where g feed/day is the total gram of feed given to the fish daily and m^2 is the total hydroponic surface area (HAS) per square meters.

$$\mathrm{FAR} = \frac{\text{Feed Input}\,(\mathrm{g/day})}{\text{Plant growth area}\,(\mathrm{m}^2)} \tag{20.1}$$

However, it may be noted that FAR is not an efficient quantity in calculating the nutrient requirements of plants, as it will depend on composition of feed, digestibility, waste generated, and protein requirements of the fish species. The daily feed input may vary with the size of fish, time, and nature of production (sequential or batch) method. Further, the process of conversion of fish waste to plant nutrients is a complex process and not fully understood. Thus, using only FAR for aquaponics system design may not be the best way. An excellent discussion about the aquaponics system design employing FAR is given by Lennard (2012) included in (Table 20.5).

20.9.3 Volume Ratio (VR) or Component Ratio

The optimum ratio of daily fish feed input to plant growing area will maximize plant production while maintaining relatively stable levels of dissolved nutrients. It is important to match the volume of fish tank water to volume of hydroponic media also, known as component ratio (Diver 2006), for optimum functioning of aquaponics system. The volume ratio or component ratio is defined as:

$$\mathrm{VR} = \frac{\text{Volume of plant growing unit}\,(\mathrm{m}^3)}{\text{Volume of fish rearing unit}\,(\mathrm{m}^3)} \tag{20.2}$$

For DWC system, the water volume is the volume of plant growing unit; for media bed, it is the volume of entire media; for NFT, calculation based on VR is inappropriate, as it may occupy a large area compared with volume. Home-based small aquaponics systems were based on a ratio of 1:1 or 1:2. Further this ratio may be improved to 1:4 with improvement in design. The variation in range depends on type of hydroponic system (gravel vs. raft), fish species, fish density, feeding rate, plant species, etc. (Diver 2006). Rakocy et al. (1993) proposed the volume ratio as a parameter for designing the requirements of grow beds. A volume ratio of 1 m^3 of fish-rearing tank to 2 m^3 of pea gravel 3 to 6 cm (1/8 to 1/4 in.) in diameter as

Table 20.5 Feed-to-plant growth area ratio for coupled single-loop/coupled aquaponics systems

Input feed (g feed/m/day)	Type of fish	FCR	Feed protein (%)	Type of plant	Plant density (no. of plant /m^2)	Type of system	Temperature (°C)	References
40–50	Tilapia	1.4–1.8	32	Leafy green plants (lettuce)	20–25	Small single-loop coupled system	25	Somerville et al. (2014)
50–80	Tilapia	1.4–1.8	32	Fruiting vegetables	4–8	Small single-loop coupled system	25	Somerville et al. (2014)
60–100	Tilapia (Red Nile)	1.7–1.8	32	Leafy green plants (lettuce)	29.6	Coupled system	25	Rakocy (2012)
15–45	African catfish	1.2–1.39	34%	Water spinach			27.5–28.8	Endut et al. (2010)
25–35	Trout	–	–	Lettuce	n.a.	Coupled system	15–17	Southern and King (2017)
16	Tilapia	1.7–1.8		Lettuce	30	Coupled with aerobic digester	25	Lennard (2012)
13	Tilapia	1.7–1.8		Lettuce	25	Coupled with digester	25	Lennard (2012)

hydroponic media is recommended for reciprocating (flood and drain) gravel bed aquaponics systems. The value of VR depends on the surface area of the media used. It may be very large in systems with high surface area like sand (McMurtry et al. 1997). A volume ratio for fish tank/sedimentation tank/bio-filter/hydroponic unit = 2.25:1:0.075:0.6, with fixed fish tank/hydroponic unit = 3.75:1, was employed in the design of two identical closed ebb-flow substrate aquaponics systems at the University of Rostock (Palm et al. 2014).

20.9.4 Area Ratio (AR)

The area ratio defines the area of hydroponic (plant) units to area of the fish-rearing unit.

$$AR = \frac{\text{area of hydroponic unit}\,(m^2)}{\text{area of fish rearing unit}\,(m^2)} \tag{20.3}$$

In a commercial system, AR may range from 7.3:1 (low stocking density) to 11.5:1 (high stocking density), depending upon the aeration provided (Rakocy 2012). However, for small-scale home-based system, 3:1 may be used for designing the system (Somerville et al. 2014). Since the area for growth of plants depends on the type of plants and its exposure to sunlight, AR may not be an efficient parameter for system design.

20.10 Nitrogen Cycle, Concentration, and Ratio

The first process of introducing the nitrogen in an aquaponics system is the input of fish feed, where only 1/3 of feed nutrients are digested, absorbed, and utilized in the metabolic processes and retained in biomass, while the rest are excreted as non-fecal or fecal losses into the environment in the form of ammonia nitrogen (90%) (Timmons et al. 2018). The main aim in aquaponics is to use ammonia nitrogen excreted by fish to provide nitrogen source for plant growth. In aquaponics, this process of bioconversion of nitrogenous (ammonia, ionized ammonia, unionized ammonia, and urea) waste to usable nutrients (nitrites) for plants includes three major steps—(1) ammonification (conversion of leftover feed and non-fecal and fecal matter of fish to ammonia and other nitrogenous waste), (2) nitrification (conversion of ammonia and other nitrogenous waste to nitrate), and (3) assimilation of nitrites by plants. A major issue in designing an efficient aquaponics system is the lack of our understanding of mechanism and dynamics pertaining to nitrogen transformation or cycle and particularly the process of nitrification. The process of nitrogen transformation in an aquaponics system is quite complex, affected by various factors. The factors which affect the nitrogen transformation in aquaponics are pH, DO, flow rate of water, C/N ratio, and concentration of ammonia and nitrate (Wongkiew et al. 2021).

In an aquaponics system, the concentration of nitrogenous compound is dependent on the complex process of system design, mode of operation, and the nutrient balance between the nitrogenous waste produce and assimilation by plants. It is important to consider the quantity and rates of nitrogen input to outputs and its relation to ammonia nitrogen generation, nitrification, nitrate assimilation, and nitrogen loss. This information is critical to maintaining the mass balance in the system and to increase nutrient availability.

The first step to understanding the amount of nitrogen is the calculation of waste generated in the system and consequent quantity of ammonification. The amount of nitrogenous waste generated is used to calculate total ammonia nitrogen (TAN). The total amount of unionized ammonia (NH_3) and ionized ammonia (NH^{+3}) is termed as TAN generated in fish-rearing system and is related to feed input or feeding rate (kg/day) (F), protein content (PC) of the feed as (Timmons et al. 2018):

$$P_{\mathrm{TAN}} = F \times \frac{\mathrm{PC}}{100} \times 0.092 \tag{20.4}$$

where the constant 0.092 is the constant for TAN generation. This equation is based on the assumption that 80% of nitrogen from feed (nitrogen content is 16%) is assimilated by fish and the fish excreta waste constitutes 90% TAN and 10% urea. Although Eq. (20.4) accounts for the amount of nitrogen input and TAN generated in the system, there is no information on the loss of nitrogen by assimilated by plants, denitrification, and sludge removal. The removal of nitrogen must be accounted. It can occur by a variety of processes, and they are (Endut et al. 2014):

I. Nitrogen fixed in fish biomass as organic nitrogen.
II. Nitrogen fixed in dead fish biomass as organic nitrogen.
III. Dissolved inorganic nitrogen including TAN, NO_2^-, and NO_3^-.
IV. Total organic nitrogen in the effluent in water discharged and sludge discharge.
V. Nitrogen gas removed from the system by passive denitrification and by ammonia volatilization.

A mass balance for nitrogen in an aquaponics system may be written as (Endut et al. 2014; Wongkiew et al. 2017; Colt et al. 2022):

$$N_{\mathrm{feed}} + N_{\mathrm{MW}} + N_{\mathrm{added}} = \Delta N_{\mathrm{fish}} + \Delta N_{\mathrm{plant}} + \Delta N_{\mathrm{SW}} + \Delta N_{\mathrm{WD}} + \Delta N_{\mathrm{SD}} + N_{\mathrm{N_2}} + N_{\mathrm{H_2O}} + N_{\mathrm{NH_3}}$$

where N_{feed} is the amount of nitrogen in the input feed, N_{MW} is the amount of nitrogen in make water, N_{added} is the amount of nitrogen due to added fertilizer, ΔN_{fish} is the increase in amount of nitrogen content in fish, $\Delta N_{\mathrm{plant}}$ is the increase in amount of nitrogen content in plants, ΔN_{SW} is the amount of nitrogen in system water (due to TAN, NO_2^-, and NO_3^-), ΔN_{WD} is the amount of nitrogen in water discharged, ΔN_{SD} is the amount of nitrogen in sludge discharged, $N_{\mathrm{N_2}}$ is the amount of nitrogen gas removed from the system by passive denitrification and valorization,

N_{N_2O} is the amount of nitrous oxide lost due to denitrification, and N_{NH_3} is the amount of ammonia removed by valorization.

20.10.1 Nitrogen Ratio

A parameter which characterizes the nitrogen relationship in plants and fish is the nitrogen ratio (NR) defined as (Colt et al. 2022):

$$\mathrm{NR} = \frac{\text{Nitrogen produced by fish } (N_\mathrm{f})}{\text{Nitrogen uptake by plants } (N_\mathrm{p})} \tag{20.5}$$

Although NR may be affected by flow rate, mineralization process, and loss by denitrification, it can be a parameter to understand conditions in the system. Three conditions may be anticipated by the value of NR:

1. NR = 1 suggest a dynamic equilibrium. This represents an ideal condition in aquaponics system and may indicate the zero-waste condition.
2. NR < 1 indicates high uptake by plants or underproduction of nitrogen (due to larger no. of plants the system can support). Here, either the number of plants must be reduced or the number of fish must be increased. If this situation persists for a long time, the system plant production may be reduced. If increasing the stocking density of fish is not possible, then the addition of external organic fertilizer is suggested.
3. NR > 1 indicates the system is generating waste (ammonia) more than the plant assimilates. This condition is dangerous for the fishes. There will be increase in electrical conductivity and solid sludge accumulation. There is a need to increase the nitrification process through the use of larger effective biofilter and consequently increase the number of plants in the hydroponic system.

The NR is related to the FAR by the following relation (Colt et al. 2022):

$$\mathrm{NR} = \alpha \times \mathrm{FAR} \tag{20.6}$$

where $\alpha = \mathrm{PF}_n/(\rho_\mathrm{p} \times \mathrm{GR}_\mathrm{p} \times \mathrm{SC}_\mathrm{p}\,\% \times N\%)$ and $\mathrm{FAR} = \text{g feed}/(d \times A_\mathrm{p})$. Here PF_n is the production function for total nitrogen (g N/g feed), ρ_p is the density of plants (g/m^3), GR_p is the growth rate of plants (g/day), $\mathrm{SC}_\mathrm{p}\%$ is the solid content of plants, $N\%$ is the nitrogen in plants (%), g feed is the input feed in grams, d is the number of days, and A_p is the plant growth area.

Although various ratio parameters are reported in the literature, the most used design parameter is the FAR. This can be also understood from a number of variables affecting the value of the parameter considered as shown in Table 20.6.

Table 20.6 The number of variables required to obtain a criteria parameter for design of an aquaponics system (Colt et al. 2022)

Design parameter	Relationship with nitrogen ratio	No. of variables
FAR (feed area ratio)	$NR = \alpha \times FAR$	5
AVR (area volume ratio)	$NR = \alpha \times \left[\frac{\rho_f \times FR_f}{AVR}\right]$	7
VR (volume ratio)	$NR = \alpha \times \left[\frac{\rho_f \times FR_f \times \rho_p}{VR}\right]$	8
AR (area ratio)	$NR = \alpha \times \left[\frac{\rho_f \times FR_f \times \rho_p}{AR}\right]$	8
PFR# (plant fish ratio#)	$NR = \alpha \times \left[\frac{W_f \times FR_f \times \rho_p}{PFR}\right]$	9
PFRM (plant fish ratio-mass)	$NR = \alpha \times \left[\frac{FR_f}{PFRM \times \rho_f}\right]$	7

FR_f is the feeding rate of fish per day (% /day), ρ_f is the density of fish, W_f is the weight of fish (g/fish), PFR# is the number ratio of plant to fish, and PFRM is the mass ratio of plants to fish

20.11 Water Flow Rates and Hydrodynamic Characteristics

Aquaponics is a system under a flow of water. Usually, oversized pipes are used to promote sufficient flow of water, increase air-water contact, prevent blockage due to growth of biofilm, and reduce the effects of bio-fouling. For efficient water flow in the system, removing the solid built up via settling tank, bio-filter and sludge digester is very important in the system. Any inefficient components may block the flow of water and lead to system failure. The types of flow that are usually employed in aquaponics are constant flow-through, intermitted, semi-circulatory, and fully recirculatory. The water flow rate and the number of cycles influence the waste transfer for fish tank to sedimentation tank, contact time of the microbiome in roots with the water, distribution of nutrients, and oxygen dissolved. This in turn influences both the direct uptake of nutrients by plants and the transformations by the microbial community (Maucieri et al. 2018; Endut et al. 2010). The flow rates are found to have major influence in the performance of aquaponics system. Lennard and Leonard (2006) have compared a reciprocating flood/drain cycle (10 min flood every 70 min) to a constant flow in a hydroponic gravel bed (0.52 m^2) plated with lettuce during a 21-day cycle. In constant flow, systems performed better due to high water retention time, increasing the contact time with roots and organisms, resulting in higher nitrate and phosphate assimilation, better pH buffering, and higher dissolved oxygen concentrations. Also, it is important to consider the plant species-specific response, for example, studies of responses of *Lactuca sativa*, *Ipomoea aquatica*, *Brassica rapa* var. *chinensis*, and *Brassica rapa* var. *parachinensis* to three root flooding conditions (drained, half-flooded, and flooded) were done by Trang et al. (2010). They observed that the growth of *Brassica* varieties were best in the drained condition, while *Lactuca sativa* grew best in the half-flooded and *I. aquatica* in the flooded.

The hydrodynamic characteristics of water flow in aquaponics are less understood. Some important parameters that require due consideration while designing aquaponics system are water flow rate, hydraulic loading rate, hydraulic residence time, system residence time, fish and plant residence time, water velocity in the hydroponic unit, and loading rate in the fish-rearing units (Maucieri et al. 2018; Endut et al. 2010; Colt et al. 2022).

20.11.1 Water Flow Rate

It is the amount of water in liter (L) per minutes or volume of water per hour. Most of the papers suggest that between 2.3 and 18 fish tank water recirculations per day with a water flow from 0.8 L/min (0.048 m^3/h) to 8.0 L/min (0.48 m^3/h) should maximize aquaponics system performance in terms of fish growth, plant growth, and nutrient removal (Maucieri et al. 2018).

20.12 Hydraulic Loading Rate (HLR)

The rate at which wastes from the fish-rearing tank are discharged in the hydroponic unit, known as hydraulic loading rate, affects the growth rate of plants (Endut et al. 2010). The hydraulic loading rate is calculated as:

$$\mathrm{HLR} = \frac{Q}{A_{\mathrm{HP}}} \tag{20.7}$$

where $Q = L/t$Q = L/t (flow rate liters per unit time) and A_{HP}A$_{\mathrm{HP}}$ (surface area) of hydroponic trough.

20.12.1 Hydraulic Residence (Contact or Residence) Time

The hydraulic retention time is the amount of time a particular volume of water stays in a particular unit of aquaponics system. It is related to the volume of water in the subunit (*V* in litres) and the flow rate of water (*Q*) in the system:

$$\mathrm{HRT} = \frac{V}{Q} \tag{20.8}$$

It has a dimension of time. Since the contact time is important for the assimilation of nutrients in an aquaponics system, the size of volume of water in the system is an important factor that must be considered. pH buffering, amount of DO, and water quality also depend on the hydraulic retention time. The inverse of HRT is the exchange or turnover rate.

The residence time refers to the ratio of volume of the entire system to make up flow rate (L/m). For DWC, it is 89 ±69 days. For media, it is 4617 days. For NFT, it is 65±36 days (Colt et al. 2022). For a flow-through system, the residence time ranges from 4.5 to 112 (0.003 to 0.078 days) (Buzby and Lin 2014). However, the value of theoretical HRT and residence time (actual from the system) may be different due to the type of setup and coupling in the system.

20.13 Coupling Degree

The aspect of coupling and the degree of coupling are an important aspect in the design of an an aquaponics system. Usually, aquaponics are either coupled or decoupled. However, the amount of water/nutrient exchanges can affect nutrient availability and distribution. This is particularly important in terms of mass balance in the system. The type of coupling in aquaponics has influence in nutrient water flow, location and growth of bacteria in the system, mode of operation, number of cycle or loops, and processing of waste in the system. The criteria and degree of coupling may include water, nutrients, and energy and their exchange rates. The coupling degree may define a certain input or output relationship in nutrient and water flow. The coupling degree of water (CDW) is defined as the amount of water transferred in an aquaponics system to the aquaponics output water (AP Output water) (Baganz et al. 2022).

$$\text{CDW} = \text{Transfer water}/\text{AP Output water}$$

The CWD may be used as a criterion to size aquaponics units. Another criterion for the size of aquaponics is through the use of nutrient transferred to nutrient required for hydroponic plants. The coupling degree of nutrients input (CDNI) is defined as (Baganz et al. 2022):

$$\text{CDNI} = \text{Nutrient transferd}/\text{Nutrient required in Hydropic unit}$$

CDNI includes the solid waste as a part of nutrient transferred. However, only water-soluble dissolved nutrients are required by the hydroponic plants. The aquaculture coupling degree of nutrients output (CDNO) is more informative with regard to the nutrient utilization defined as (Baganz et al. 2022):

$$\text{CDNO} = \text{Nutrient transferd}/\text{Aq Ouptut Nutrient}$$

20.14 Hydroponics Unit Consideration

The three major types of plant-rearing unit used in aquaponics are (1) deep water culture (DWC), (2) media bed (MB), and (3) nutrient film technique (NFT).

20.14.1 Deep Water Culture (DWC)

In DWC system, also known as "deep flow system," the leafy vegetables are grown in rafts floating on water. The system is designed in rectangular furrows made of wood or bricks and lined with high-density polyethylene (HPDE) with 500–1000 GSM. The dimensions may vary according to system design. One of the most common dimensions of the DWC units is 1–10 m long, 50–80 cm wide, and 15–20 cm of water depth (Schwarz 1995). The floating rafts are made of polystyrene sheet with a square or circular opening (15 mm diameter) to put net pot for plant. The polystyrene rafts insulate the water from the sun's heat and prevents algal growth in the system. It is important to aerate the water in DWC and maintain a DO level of >5 mg/L. This is done to prevent root rot by formation of anaerobic zone. Thus, depth of water, distribution of nutrients, and quantity of DO are critical in the design of DWC. Usually, the nutrients are rich in regions around the inlet water and decrease as we go further down the length of the DWC. This gradient in nutrients and the nutrient uptake by the particular plant grown limit the length of DWC. This can result in nutrient deficiency in regions of DWC. To remove or mitigate this problem, a "conveyer production system" may be devised (Fig. 20.9).

20.14.2 Nutrient Film Technique (NFT)

In the NFT, long trough or narrow channels or pipes with holes on the topside for insertion plants are used. The holes should be large enough for easy insertion of plants and cleaning. The size of channels or pipes is usually 10 to 15 cm wide (4 to 6 in.). The nutrient solutions continuously flow inside the channels through the roots and finally drain back to the pump sump (Schwarz 1995). There is a small gap between the water flowing and the topside of the channel where the nutrient water comes in contact with the air and oxygen dissolves. The roots of plants under the moist condition inside the channels grow in the presence of dissolved oxygen from air. Various designs can be made to vertically mount troughs and maintain high plant density by adjusting the distance between troughs to provide optimum plant spacing during the growing cycle and utilize vertical greenhouse space. NFT requires solid removal regularly to prevent excess solid accumulation on roots, which can lead to root death and poor plant growth. However, the length of the channel is limited by

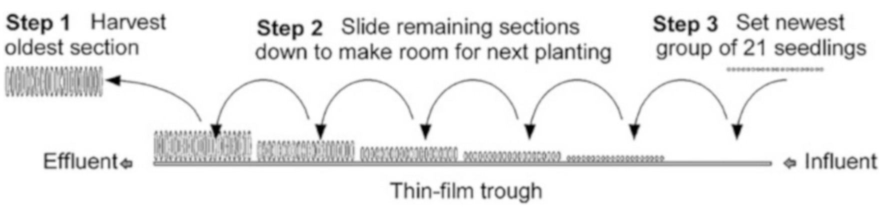

Fig. 20.9 Illustration showing the steps in a conveyer production system (Adler et al. 2003)

the nutrient uptake capacity of the plants. Due to small amount of water in contact with the roots, NFT is not effective when there is variation in temperature. It requires constant, uninterrupted supply of water and nutrients.

20.14.3 Media Bed

The media bed system is often used for larger fruiting plants. The main components of such a system are (a) inlet and outlet pipe line; (b) a growing bed filled with gravel (particle size of 1/2–3/4 cm), coarse sand, tuff, clay, sawdust, wood fiber, rice hull, and polyurethane; and (c) a mechanism of reciprocating flow regime (or ebb or flood) like a bell siphon. The chemical and biological characteristics of the medium in grow bed should be clearly known beforehand (Raviv and Lieth 2008). The size of bed may vary according to design. However, the depth of grow bed is around 11–12 in. Such systems are capital intensive and require water leakproof system and strong support. The design of the media bed is dependent on the type of media used (Schwarz 1995; Raviv and Lieth 2008).

20.15 Aquaponics in Cold Water: Toward Adaptation and System Designs

20.15.1 Flow-Through Aquaponics System

Much of the development and system design, discussed so far in an aquaponics system, has been for warm water. In this section, we discuss the various adaptations in design in fish culture system in cold water that is closely related to aquaponics. Flow-through aquaculture systems are mostly employed for the culture of cold-water fishes. Some fish species as trout (*O. mykiss*, *S. trutta*, and *S. fontinalis*), Arctic char (*S. alpinus*), yellow perch (*Perca flavescens*), hybrid striped bass (*Morone* hybrids), and sturgeon (*Acipenser* spp.) (Fornshell and Hinshaw 2008) are reared in a flow-through system. The flow-through system includes linear earthen and concrete raceways and tanks with various shapes and design. Raceways are elongated, narrow, and shallow tanks or ponds through which water flows continuously. The typical raceway production system consists of a tank (rearing unit) or a series of rectangular tanks in either series or parallel configuration. In an ideal raceway, water flows with uniform water velocity across the tank cross section, but in actual systems, friction losses cause water velocities to vary across the width and depth of the raceway; also, there is water-quality gradient from the inflow to the outflow of the rearing unit, with best environmental conditions at the inflow and deteriorating water quality along the length of the raceway (Fornshell and Hinshaw 2008).

The flow-through aquaculture systems require constant management of water supply and flow-control structures, aeration (oxygenation supply), tank design, and waste management systems. Since high biomasses of fish are reared in flow-through units, there may be fish loss within minutes of water flow cessation or problems with

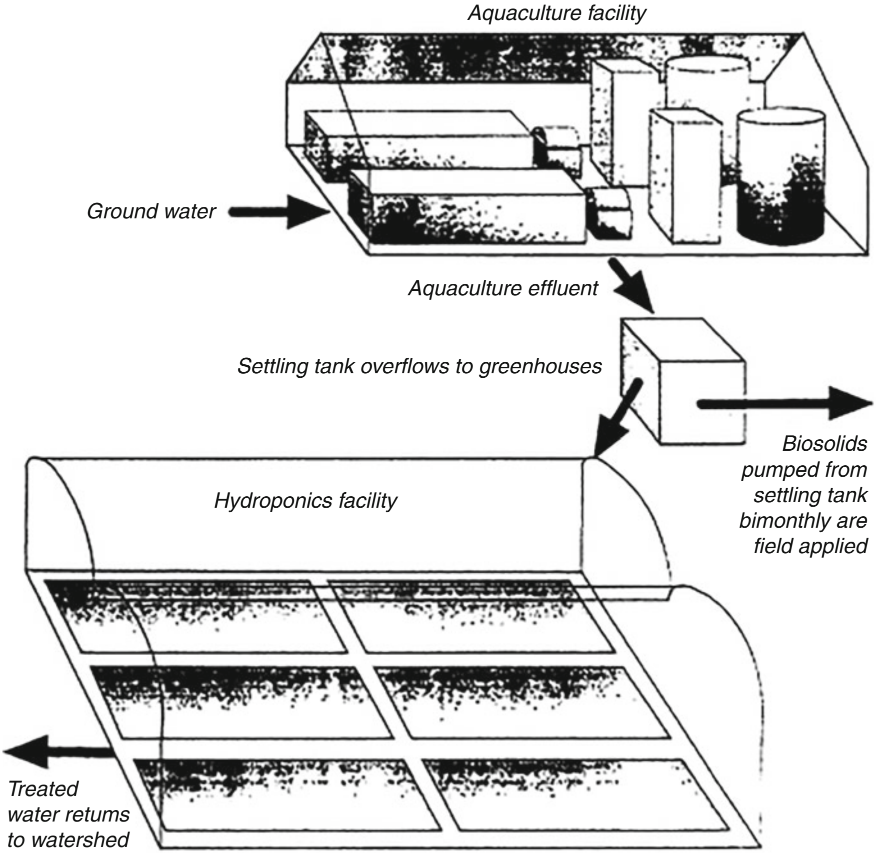

Fig. 20.10 Integrating the fish production unit to hydroponic plant production unit in housed in a greenhouse (Adler et al. 2000)

oxygen delivery. The farm effluents are characterized by low waste concentrations at high volumes and are difficult to treat (Cripps and Kelly 1995). The discharges may also exceed permitted limits if waste management structures and operations are not maintained. For this reason, integration with plant-based nutrients removal from cold-water rearing systems is most important. Flows and water temperatures can fluctuate widely throughout the year, and this may lead to changes in growth rates and water quality.

To mitigate the waste generated, increase nutrient concentration, and control temperature fluctuation, recirculatory cross flow raceways integrated with a greenhouse hydroponic system are developed (Adler et al. 2000). The production system (Fig. 20.10) consists of two independent trout fish-rearing systems composed of a single fish tank and filtration loop. The fish tanks are cross flow raceways. The filtration loops include drum filters, fluidized sand filters, carbon dioxide strippers, and low head oxygenators (Fig. 20.10). The system is a gravity flow design with the flow of water in one direction with no return. The ground water is allowed to flow into the aquacultural facility, and effluents from fish rearing then are allowed to settle in a settling tank, which overflows to the hydroponic facility housed in the greenhouse. Once the water flows through the hydroponic grow beds, it is returned to the watershed. The sizing of the hydroponic unit inside the green house is done with the view to reduce the waste concentration of nutrient to a desired level by plant assimilation.

20.15.2 Recirculatory Couple Single-Loop Aquaponics System

The outdoor aquaponics design of UVI by Rakocy is integrated with a greenhouse, and a modified UVI design in Alberta, Canada, was developed by Savidov et al. (2007). This was done with the view to control the climatic condition and maintain a consistent temperature through the year. The RAS unit was housed in the greenhouse. The cold fresh water was plumbed into the sump tank area via a heat exchanger and boiler system capable of keeping the water consistently warm (~24.8 °C as tilapia was reared in the system). The RAS is aerated using air blowers and diffusers and had a liquid oxygen backup. The system was constantly monitored through a computer-controlled system.

20.15.3 Wetland Aquaponics

Constructed wetlands (CWs) are cheap, efficient systems for treating large effluent wastewater. Integrating constructed wetlands with intensive fish culture is one of the most commonly practiced methods for environmental remediation (Lin et al. 2002). It may be an open-pond-type system (Palm et al. 2018) or recirculatory-wetland type (Zachritz et al. 2008). The factors influencing the efficiency of CWs for treatments of effluent are nutrient inflow concentration, hydraulic loading rate (HRL), hydraulic retention time (HRT), and accumulation of TSS within the CW (Sindilariu et al. 2009). Two major types of hydraulic water flow characteristics are devised in CWs for treatment of effluent from fish culture units—surface flow (SF) and subsurface or submerged surface flow (SSF) systems (Lee et al. 2009). Further, the SSF is classified into horizontal, vertical, and hybrid, according to flow direction of wastewater. The combination of subsurface vertical and horizontal flow wetlands is called the hybrid system. It is observed that at present there is no specific optimized value of HLR or HRT of SF, SSF, and hybrid system. Different values depending on various flow rates and system design are reported (Sindilariu et al. 2009; Zachritz et al. 2008; Lee et al. 2009).

The complex waste removal process constructed wetlands are similar to that in biofilter and in a hydroponic unit. The removal of nutrients and/or pollutants in wetland ecosystem is complex and depends on a variety of mechanisms, including sedimentation, filtration, precipitation, volatilization, adsorption, plant uptake, and various microbial processes (Vymazal 2007; Lee et al. 2009). The role of plants in constructed wetland is reviewed by Shelef et al. (2013). The potential use of *Salicornia* spp. in aquaponics has also been suggested (Turcios and Papenbrock 2014).

20.16 Need for Cold-Water Aquaponics

It may be noted that less than 2.5% of the total water reserves is fresh water and mostly locked in ice in cold and temperate regions of the world. This provides an opportunity for cold-water aquaculture. Since the ecosystem in this region is prone to climate change and pollution, there is a need to develop a climate-resilient and environment-friendly sustainable food production system. Aquaponics is an environment-friendly, sustainable food production technology that has the potential to address these issues. However, aquaponics is mainly confined to warm water, semiarid, and hot areas with water scarcity. Aquaponics in cold water is rather less developed, and this is due to differences in natural environmental conditions, with long low temperature periods, challenging intensive aquaculture production at high latitudes. Further access to unpolluted freshwater, environmental concerns of waste-water management and difficult geographic terrain makes it more challenging. These issues are highly relevant in the Indian context. In India, cold-water aquaculture is picking up recently. There is enormous potential for increase in the future due to the Himalayas. The Himalayan region is usually cold, occupying 16.2% of the total geographical area of India (Gangopadhyay et al. 2021), and 40% of the total utilizable waters are from the Himalayas (Mendiratta et al. 2019). Since the ecosystems of the Himalayas are fragile and prone to environmental pollution, developing cold water aquaponics for the Himalayan region has enormous potential.

20.17 Issues of Cold-Water Aquaponics and Challenges

In this chapter, we have discussed the principles of aquaponics, various system designs, and considerations for efficient maintenance and functioning. It may be noted that less information is available for cold-water aquaponics. One of the major issues in setting up aquaponics in cold water is its adaption to geo-climatic temperature fluctuations. Also, the issue of maintaining a consistent water temperature is critical of effective functioning of the system. Since there are different requirements for fish and plants, providing ambient conditions for both fish and plants separately is also a challenge. Cold-water fishes have lower optimum temperature requirement and more restrictive water quality. It is important to know that the growths of nitrifying bacteria are very low compared to heterotrophic bacteria and optimum temperature is above 30 °C (Gerardi 2006). Further slow rate of nitrifications due to low-temperature condition in cold water has to be addressed via smart efficient biofilter and sludge digester design (Kinyage and Pedersen 2016). Efficient nutrient recovery through standard sludge digester is still a challenge, but inclusion in a standard aquaponics system may further complicate the system design, leading to higher economic cost. Another aspect is the problem of slow growth rate of fish and plants in cold waters. All these issues coupled with high cost of setting a standard aquaponics unit limit the possibility of cold-water aquaponics. A potential solution to different optimum conditions for fish and plants is the (a) selection of fish-plant combination with compactable temperature requirements and (b) use of decoupled system that allows the adjustment of separate requirements (pH, temperature, DO, and other physicochemical parameters) of fish and plants (Goddek et al. 2015). Further, it is reported that "warm climates were four times as likely to be profitable than those in colder climates," considering the energy consumption in maintaining an optimum temperature in colder climates (Love et al. 2015).

20.18 Perspective and Conclusions

In the last decades, we have seen enormous increase in interest in aquaponics. Various types and sizes of aquaponics have been designed (Palm et al. 2018; Love et al. 2015). However, the main challenge for setting up an aquaponics unit is the local climatic condition and management of aquacultural waste. This is also true for cold-water aquaponics where maintaining a constant temperature range becomes a challenge. In this chapter, we also have reviewed the aquaponics, its principle, system design, and various physicochemical parameters required for an efficient system design for cold-water aquaponics. Various issues pertaining to designing a cold-water aquaponics system are also discussed. It is observed that less amount of work has been done in cold water compared to warm water and no standard system exists. At present, only small-scale and laboratory model systems are reported with few large flow-through systems. There is no standard biofilter design and management protocol. In spite of enormous potential of cold-water aquaculture, aquaponics in cold water and its development toward standard commercial scale system are lacking. Increasing the nutrient recovery via efficient design of sludge digester can increase size of hydroponic unit that may increase the commercial viability through increased production of vegetables. It is anticipated that integration of cold-water aquaponics system with passive greenhouse, use of solar energy, and use of thermal batteries are some of the means to control temperature and will be profitable in the long run. The possibility of using and integrating with photovoltaic and solar thermal modules, solar flat plate collector (FPC), wind turbine, hydropower, biomass plant, combined heat and power systems, and energy and heat storage systems to aquaponics may also be explored (Karimanzira and Rauschenbach 2018; Bundschuh et al. 2017).

Although flow-through aquaponics system exists and is applied in cold climates, their success is questionable. It is important to integrate such system with sludge digester and mineralization tank for enhanced nutrient decomposition and recovery through ambient temperature maintenance for effective growth of bacteria (Goddek et al. 2018). Wetland aquaponics is another option with ease of use and cheap cost, but maintaining consistent optimum water temperature for effective bacterial activity of nitrification is a challenge. Further, designing closed recirculatory raceway design system may increase nutrient availability due to more contact time and nutrient retention in the system but needs more study. A decoupled system is a potential system in cold water as it can provide optimum conditions for both the plants and fish individually, but it has its own limitations in nutrient availability. Further integration with renewable energy source like that of biogas unit from the fish sludge for combined power and heating may also reduce external power dependency and lower operational cost (Gigliona 2015).

Finally, we note that aquaponics has overcome the proof-of-concept stage and proceeds toward farming applications; however, due to the complex ecosystem involved, there are many challenges still to be overcome to make it a commercially viable technology. We anticipate that aquaponics has a lot more to offer in the coming years than just a simple method of integrative farming.

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21 Impact of Climate Change in Temperate Fisheries of the Himalayas and Possible Adaptation Approaches

Amit Pande and Ravindra Posti

Abstract

A persistent variation in temperature and distinct weather patterns in a particular area or planet can usually be observed, which is referred to as climate change. Anthropogenic activities are primarily responsible for climate change; however, other factors are also known to contribute. Burning fossil fuels, ocean acidification, air quality, temperature, water regulation, and solar forcing are causing profound alterations in our environment. Gaseous emissions in the form of CO_2, SO_2, and oxides of nitrogen (NOX) can alter the precipitation chemistry of water. Changes in pH and dissolved organic carbon effect the bioavailability of mercury at the bottom of the aquatic food chain, which can seriously harm fisheries and human health. Alterations in climatic conditions like changes in temperature and hydrological systems within the mineralized zones profoundly affect the watershed chemistry. Poor water quality and enhanced toxicity thresholds directly affect the aquatic ecosystem. Thus, fish and fisheries are also affected by the wrath of changing climate. The Himalayan region stretches the entire northern margin of the Indian subcontinent with a span of more than 2500 km. It is known for its lofty peaks, glaciers, and biodiversity that are under threat due to climate change. Receding glaciers are becoming a serious concern as life in the hills depends on the aquatic resources. Any alteration in the environmental conditions can be a severe threat to all forms of life. The chapter steers the reader through the causes and impact of climate change and the consequences of climate change on the temperate fisheries of the Himalayas and adaptation measures.

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21.1 Climate Change

Climate change denotes a persistent variation of temperature and discrete weather patterns in a precise area or the entire planet. It is a consequence of burning fossil fuels, like oil, gas, and coal, which results in deleterious effects on our environment. Fossil fuels liberate carbon dioxide into the atmosphere and are responsible for heating the earth. The Intergovernmental Panel on Climate Change (IPCC) has cautioned that if greenhouse gas emissions keep escalating, climate change can contribute to a global rising sea level (Rahmstorf 2007). By 2100, the global temperatures are expected to rise by 4 °C, with notable differences in precipitation patterns. Thus, assessing the costs of biodiversity and its mitigation remains a daunting task for ecologists (Thuiller 2007).

Assimilation of incoming solar energy and reflected radiant energy are the consequences of greenhouse gases. Alteration in the buildup of greenhouse and other atmospheric gases disturbs the overall radiation budget (Gribbin 1988), which results in escalation of atmospheric temperature. A rise in atmospheric temperature by a few degrees can result in hydrological changes that can disturb the physical and chemical properties of water. Further, minor temperature changes can have a significant influence on climate (Roessig et al. 2004), leading to changes in the aquatic environment with alterations in aquatic life, namely, fish, invertebrates, and plant species of marine and estuarine ecosystems (Kitaysky and Golubova 2000; Stevenson et al. 2002). Thus, with a relatively small rise in temperature, there is a change in distribution and shifts in marine and inland fish populations (Perry et al. 2005; reviewed by Myers et al. 2017).

A major contributor to climate change is carbon dioxide (CO_2), a greenhouse gas which promotes accumulation of more bicarbonate when it reaches increased levels in the atmosphere. Enhanced water temperatures and acidification of aquatic water bodies, including oceans, have altered the aquatic environment (Roessig et al. 2004; Nikinmaa 2013). Among different aquatic organisms, the distribution shifts in both inland and marine fishes can be altered due to an increase in water temperature and other factors (Roessig et al. 2005; Myers et al. 2017; Timoner et al. 2021; Whitfield 2021; Perry et al. 2005). Alterations in inland aquatic ecosystems due to changes in water quality and other pathways have also been predicted (Nikinmaa 2013; Chen et al. 2016). Expected climate change in the future is likely to harm inland aquatic ecosystems by means of different pathways, along with variations in water quality (Kitaysky and Golubova 2000; Winslow et al. 2003; Paukert et al. 2017). Thus, devastating effects can be well predicted for aquatic ecosystems.

Several factors bring in climate change. Increased sea levels, construction of dams, scarcity of food, temperature variations, gaseous emissions, and increased rate of evaporation are some crucial factors responsible for alteration in an aquatic environment. It is predicted that climate change will accelerate the melting of glaciers. The thermal expansion of seawater will raise the sea level by nearly half a meter by 2100, disturbing life in aquatic ecosystems to a great extent. An increase in temperatures and water levels would seriously affect aquatic organisms as their existence may be threatened, or they may become extinct by the end of the century (Williamson and Guinder 2021). Man-made dams can alter the local climatic conditions and are already harming ecological niches by disturbing the native biodiversity, including the migration patterns and breeding of aquatic organisms (Null et al. 2013; Kirkland et al. 2021; O'Mara et al. 2021). Anthropogenic activities like the expansion of cities, industrialization, deforestation, burning of wood, and agricultural activities contribute to greenhouse gases. Anthropogenic interventions have led to the increase in greenhouse gases that add to the atmosphere trapping the sun's heat reflected from the earth leading to the phenomenon of the greenhouse effect (Wallington et al. 2009; Kweku et al. 2017).

21.2 Impact of Climate Change on the Aquatic Environment

Quality of water in an aquatic environment can have a remarkable change in the aquatic habitat. Gaseous emissions in the form of CO_2, SO_2, and oxides of nitrogen (NOX) can alter the precipitation chemistry of water. An increase in the concentration of SO_2 results in more sulfate ions that enter water bodies, reducing their pH. Acidification and increased water temperatures directly affect dissolved organic carbon (Evans et al. 2005). It is known that pH and dissolved organic carbon affect the systemic availability of mercury at the bottom of the aquatic food chain (Adams 2009; Dittman and Driscoll 2009; Poesch et al. 2016). Bio-accumulated mercury in aquatic food chains can attain maximum concentrations in edible tissues of fish. Mercury absorbed from the diet gets distributed to all the tissues in the body. Thus, consuming such fish can introduce mercury in humans, which can easily cross the blood-brain and placental barriers, resulting in several neurological manifestations (Fitzgerald and Lamborg 2014; Clarkson 1993; Amap/UNEP 2015).

Alteration in precipitation patterns and increased air temperature can alter the patterns of discharge in streams and rivers (Clow 2010; Leppi et al. 2012). Rising air temperatures in ice- or snow-covered places will speed up the melting of snow, alter the hydrological system by increasing the flow of nearby streams, and create a water deficit in the following season (Stewart et al. 2004). These late-season losses leave reduced water in the watercourse to be warmed during the hottest months of the year. However, the concentrations of chemicals are fairly diluted amid high flows, and the overall contaminant load may increase (Novotny 2003; Grigas et al. 2015).

Likewise, wearing away of rocks and transportation of solute are influenced either directly or indirectly by the local climate. The native hydrology, directly related to the environment, guides the sub-surface flow of oxygen and water in addition to the surface and sub-surface transport of eroding products (Nordstrom 2011). Moreover, temperature and hydrology intensely impact watershed rates of geochemical reaction and sketch the resulting water chemistry in water bodies draining those watersheds. Substantial changes in climatic conditions, such as thermal and hydrological systems within mineralized areas, can alter the watershed chemistry (Rogora et al. 2003).

Numerous researches have supported surges in rock weathering solutes (e.g., dissolved sulfate) over the preceding decades ascribed to upsurges in warming of the climate (Lami et al. 2010; Mast et al. 2011). A recent study has authenticated those increased concentrations of dissolved metals, e.g., Zn, Cu, and Cd are the products of pyrite erosion and toxic to freshwater fishes (Todd et al. 2012). This study established that upsurges in concentrations of in-stream toxic metal were probably attributable to several climate-influenced aspects, as well as augmented rock weathering, new sub-surface runoff, and weathering pathways as a result of loss in frozen surface ground, and a declining groundwater table (Todd et al. 2012). Notably, changes in water chemistry lead to worsening of downstream water quality and might increase toxicity thresholds that directly affect fisheries.

21.3 Impact on Inland Ecosystem

Direct and indirect changes in the climate may lead to substantial alterations in species compositions. However, total productivity may be persistent due to the high diversity and resilience of tropical systems and several intrusive fish species. Climate change has continued to have a noticeable global influence on freshwater ecosystems, fish, and other aquatic taxa, besides providing goods and services, including fisheries (Myers et al. 2017). Temperature influences almost all biological and chemical processes in freshwater ecosystems. Critical chemical transformations, concentrations of dissolved oxygen, degradation, evaporation, the rate of biochemical processes in the aquatic organisms, threat of disease, parasite transmissions, and trophic exchanges between consumers and their prey are some of the effects that are influenced by temperature (Dell et al. 2014; Miller et al. 2014).

Climate change is causing alteration in the structure of species assemblies, abundance, biomass and distribution, and the efficiency of fishing methods, fish yields, and gears. Inland fisheries have a significant contribution to meeting the food and livelihood demands of the fishing community. Unfortunately, diverse anthropogenic interventions have resulted in climate change, affecting both fish and fishing communities. Injudicious use of water, overfishing, the introduction of exotic species, pollution, habitat degradation, and the rising human population have dented inland fisheries globally. Therefore, climate change will tip off changes in freshwater habitats and the fish assemblages they provide. However, a few of these effects may benefit inland fisheries based on inherent fish populations.

Freshwater ecosystems have a reasonably low buffering capability and are comparatively sensitive to climate-related inconsistency. There can be a variety of physiological and ecological influences on fish and freshwater ecosystems supporting inland fisheries, related to water temperature, water availability, and flow, besides other environmental disturbances. Climate change is expected to impact inland fisheries due to cumulative deviations in water temperature, nutrient levels, and precipitation patterns. For example, in the Ganga River system, most fish breed during the monsoon because of their dependence on seasonal floods. During the breeding months, a fall in precipitation may alter the required flow of turbidity essential for breeding Indian major carps (IMCs). A shift in pattern of rainfall during the breeding season is accountable for the difficulties encountered in breeding and subsequent recruitment of the IMC juveniles in the river. There would be harmful effects at longer time scales on cold-water fish species compared with the ones inhabiting the warm water. The predicted response for cool water species would be beneficial (reviewed by Barange and Perry 2009).

Climate change, a threat to global food production, can damage the quality and quantity of fish production. Global fish production has progressed continuously, reaching 46% of the estimated figures (FAO 2020). Global fish production is expected to increase from 46% to 53% in 2030 (FAO 2020). However, the changing climate poses a challenge for the sector's fast, sustainable growth to meet the food requirements of the rapidly growing human population. Aquaculture, the fastest-growing global food-producing sector, has also been affected by climate change. The sector seems to be at risk because the predicted effects of climate change are alarming (reviewed by Maulu et al. 2021). The impact of climate change on aquaculture has been extensively reviewed (Maulu et al. 2021). Most of the studies on climate change have established adverse effects, overlooking the positive ones. There can be direct or indirect consequences of climate change on aquaculture production (Handisyde et al. 2006; De Silva and Soto 2009). The direct effects influence the physical and physiology of finfish and shellfish stocks in production systems. At the same time, the indirect effect may alter the primary and secondary productivity and framework of the ecosystems, input necessities, and services needed by fishers and aquaculture producers. Global climate change has significantly affected the growth rates, disease susceptibility, time of spawning, and mortality at certain life-cycle stages. It has economic impacts related to direct implications for the cultural process (Maulu et al. 2021).

Numerous effects of climate change have been observed on the ecosystem and fish production. There would be decreased ice cover, warmer water temperatures, and longer seasons due to augmented algal abundance and productivity in high-latitude/high-altitude lakes (McClanahan and Cinner 2012). It is expected that the intensification of hydrological cycles may substantially influence the limnological progressions. It would affect the productivity of all forms of aquatic life because of augmented runoff, discharge rates, flooding areas, and water levels during the dry season (McClanahan and Cinner 2012).

Analysis of the temperature and rainfall data and normalized difference vegetation index has revealed that the warming rate in the Himalayas is more than the global average, suggesting the vulnerability of the Himalayas to climate change (Shrestha et al. 2000). An increase in temperature and light intensification would result in differential responses between plankton components, suggesting an alteration in the environment of fishes to predator-prey mismatch (Barange and Perry 2009). Although there is a limited conformation supporting upsurge in occurrence of disease related to global warming, dissemination of pathogens to higher latitudes has been witnessed (Tewari et al. 2017). A classic example of change in climate is parasitism in aquatic animals. In a study evaluating the potential response of aquatic animal parasites to climate change, it was demonstrated that there is intricacy of host-parasite systems, suggesting precise predictions for biological systems (Marcogliese 2001). Parasites in aquatic systems react directly to variations in temperature but also indirectly to changes in other abiotic factors that are mediated indirectly through deviations in the dispersal and abundance of their hosts. The expected results are local destruction and introductions of different life forms. In the long term, climatic change may influence the selection of different life-history traits, affecting parasite transmission and, potentially, virulence. Moreover, an important consequence of climate change may invite some serious emerging diseases as well.

To sum up, in a rapid time scale within a few years, rising temperatures will negatively impact fish physiology, resulting in considerable limitations for aquaculture and alteration in the distribution of species, besides possible changes in abundance as recruitment processes may be impaired. The timings of important events like life history would diminish, particularly affecting short-lived species like plankton, squid, and small pelagic fishes.

21.4 Impact on Fisheries

The consequences of climate change on inland fisheries and aquaculture will be catastrophic in terms of poverty alleviation besides the reliance of different nations on fish and fishery resources (reviewed by Barange et al. 2018). It proposed that climate change will certainly prompt noteworthy deviations in the opportunity and fish trade and fish produces with serious geopolitical and economic concerns on countries that are reliant on this sector. Climate change impacts are expected to be greater at a regional scale as the catch potential can vary substantially between regions (Barange et al. 2018).

With fish being the most vulnerable to global warming, increased temperatures may demonstrate alterations in stress physiology (Alfonso et al. 2021). The enhanced temperature may change the capacity of fishes to survive with other stressors, compromising their health. Moreover, rapid temperature upsurges are known to tempt acute stress responses in fishes and might be of ecological significance in precise situations. High temperature causes stress to fishes, which triggers the release of catecholamines and cortisol. Elevated cortisol responses due to an acute rise in temperature have been reported in several fishes, with a few exceptions (reviewed by Alfonso et al. 2001). Temperature fluctuations may also alter blood osmolality besides hematological variables. Besides having an inhibitory effect on the fish immune system, acute thermal stress can also affect total protein and serum ion concentrations. It has been observed that short-term acute thermal exposure can also result in serum ionic imbalance in trout, with the restoration of homeostasis (Bard and Kieffer 2019; Balta et al. 2017). Further, thermal stress can alter the levels of heat shock protein (HSPs) at the cellular level by affecting the endocrine stress system. For instance, in red blood cells of rainbow trout *Oncorhynchus mykiss*

(Walbaum 1792), the adrenergic system can enhance the response of HSP, while cortisol inhibits heat stress-induced levels of HSPs (Alfonso et al. 2021). Chronic exposure to elevated temperature can lead to severe consequences for the resting stress physiology of fish because of alteration in the brain's noradrenergic and dopaminergic systems. Moreover, a warmer climate can also alter the stress-coping capacities of fish.

It has been demonstrated that cold-water habitat for fish species has been reduced by water regulation, construction of dams, and land-use change with a variation in stream temperatures. Climate change has consequences on hydroclimatic conditions, which impacts water temperatures downstream of the dams, affecting ecology as stream temperatures are sensitive to fluctuations. Thus, reservoir regulation affects stream temperatures and cold-water habitat with climate change (Null et al. 2013). A recent study conducted at 30 dam sites across various environmental settings throughout Massachusetts (USA) has shown that most dams warmed temperatures downstream with variable magnitudes. It was observed that cool headwater streams, having wide impoundments, faced maximum warming. It was intriguing to note that 75% of the cold/cool water sites shifted to warmer thermal classes downstream, with the thermal effects of dams being most significant during the lower flow periods (Zaidel et al. 2021). A similar phenomenon has been predicted for Indian cold-water fishes, as a variation in the pattern of the reproductive biology of golden mahseer from the lesser Himalayan region concerning regional climate change had consequences on breeding phenology (Joshi et al. 2018).

21.5 The Himalayan Region

The Himalayas, or abode of snow, is the youngest mountain chain and is often referred to as the third pole. The majestic bow-shaped range spreads the entire northern margin of the Indian subcontinent with a span of more than 2500 km from the south of the Indus Valley. The Himalayas stretch from Nanga Parbat (8114 m) in the west to Namcha Barwa (7755 m) in the east. Three parallel ranges—the Greater Himalayas, the Lesser Himalayas, and the Outer Himalayas—constitute the Himalayan range with some of the highest mountains on earth. The Himalayan region is geologically unique and the most vivid and evident creations that resulted due to the collision between two continental tectonic plates (Molnar 1984). The Himalayas, known for the world's highest peaks, soaring heights, valleys, alpine glaciers, and deep river gorges, present diverse ecological niches and climates.

The Himalayas, Hindu Kush, Karakorum Mountains, and the Tibetan Plateau constitute the Hindu Kush-Himalayan (HKH) region, which is abundant in snow and ice resources exceeding any other polar region (Fig. 21.1). The 3500 km HKH region stretches across eight countries from Afghanistan in the west to Myanmar in the east besides harboring a range of ecosystems. The HKH region is diverse and includes several native communities, high biodiversity and agro-diversity, and diversity in climatic systems. From the high-altitude mountains of the HKH region, ten river basins are known to originate, namely, the Amu Darya, Brahmaputra,

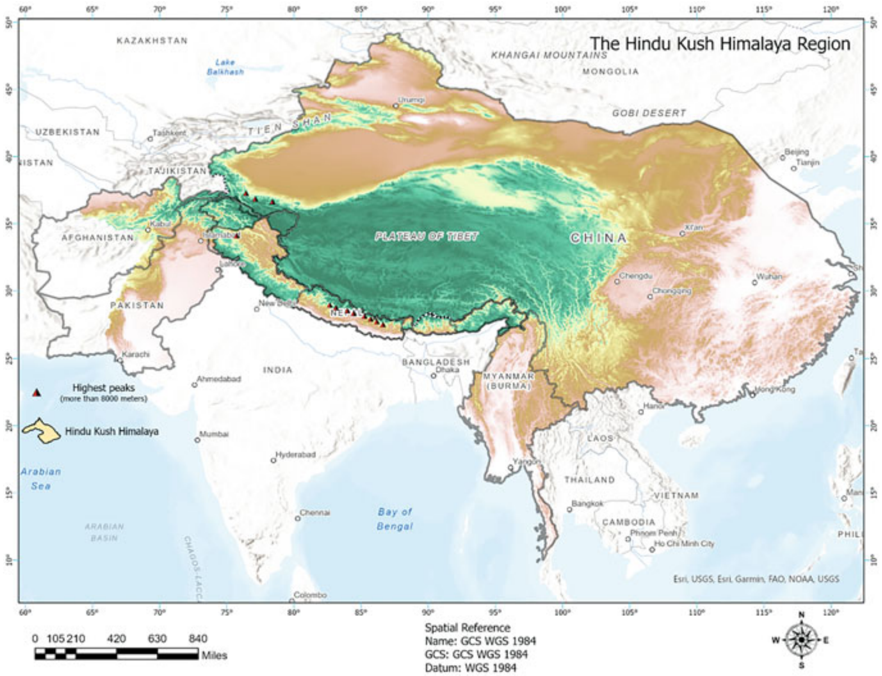

Fig. 21.1 The Hindu Kush-Himalaya region

Ganges, Indus, Irrawaddy, Mekong, Salween, Tarim, Yangtze, and Yellow (Eriksson et al. 2009) The Trans-Himalayas Karakoram Mountains spread from India into Pakistan, and China is the northernmost range, and to the south of the Karakoram Range lie the Zanskar and Ladakh ranges.

The Indian Himalayan region includes union territories of Jammu and Kashmir and Ladakh apart from Himachal Pradesh, Uttarakhand, Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura, Meghalaya, and parts of Assam and West Bengal. Geologically, the Indian Himalayan region is divided into three regions. The Trans-Himalaya begins from the foothills of south Shivaliks and extends up to the Tibetan plateau in the north. The greater Himalayas include Himadri, while the lesser Himalayas are the Himachal region; the Shivaliks constitute the outer Himalaya (Fig. 21.2). Many perennial, glacier-fed rivers flow from the Himalayas and provide water to a large part of the Indian subcontinent. The Himalayas are also known for their diverse flora and fauna.

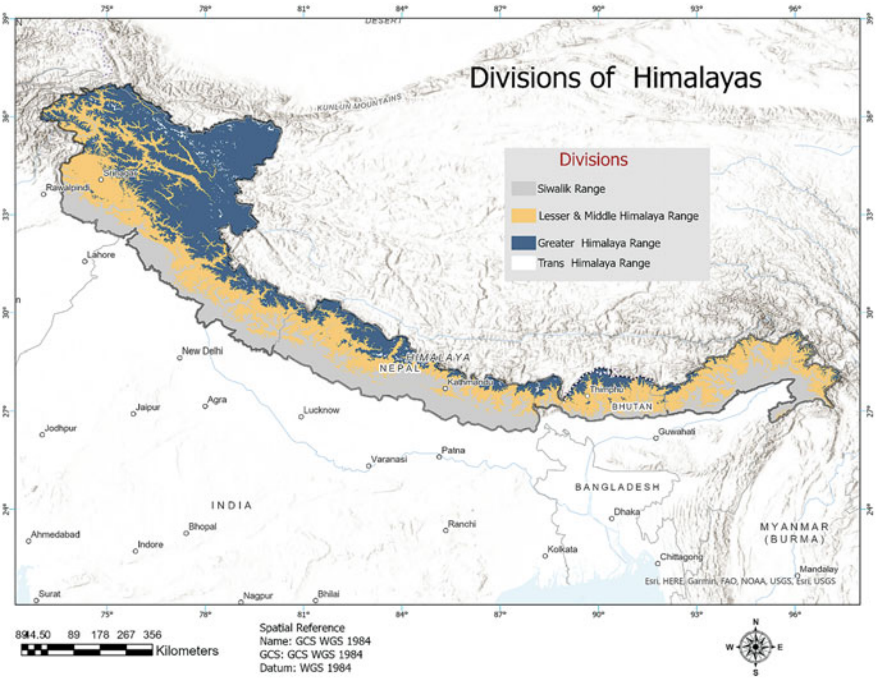

Fig. 21.2 Divisions of the Indian Himalayan region

21.6 Resources

The Himalayan region is rich in aquatic resources that range from brackish water lakes like the Pangong Tso lake (14,270 ft. above mean sea level), an endorheic lake spanning eastern Ladakh and western Tibet, and Tso Moriri, a lake in the Changthang plateau (14,836 ft., above mean sea level), to several fresh waters, for example, Lake Mansarovar (15,060 ft. above mean sea level), Gurudongmar Lake (17,500 ft. above mean sea level) in Sikkim, and several others. Several rivers originate from the Himalayan glaciers.

21.6.1 Rivers

Three river systems—the Indus, the Ganges, and the Brahmaputra—originate from the Himalayas that are classified as Trans-Himalayan and Himalayan. The Trans-Himalayan rivers originate beyond the Great Himalayas and include the rivers Indus, Sutlej, and Brahmaputra, whereas the Himalayan rivers originate in the Himalayas and find their course through the northern plains. The rivers Ganga, Yamuna, and their tributaries are examples of Himalayan rivers (Fig. 21.3). Further, the

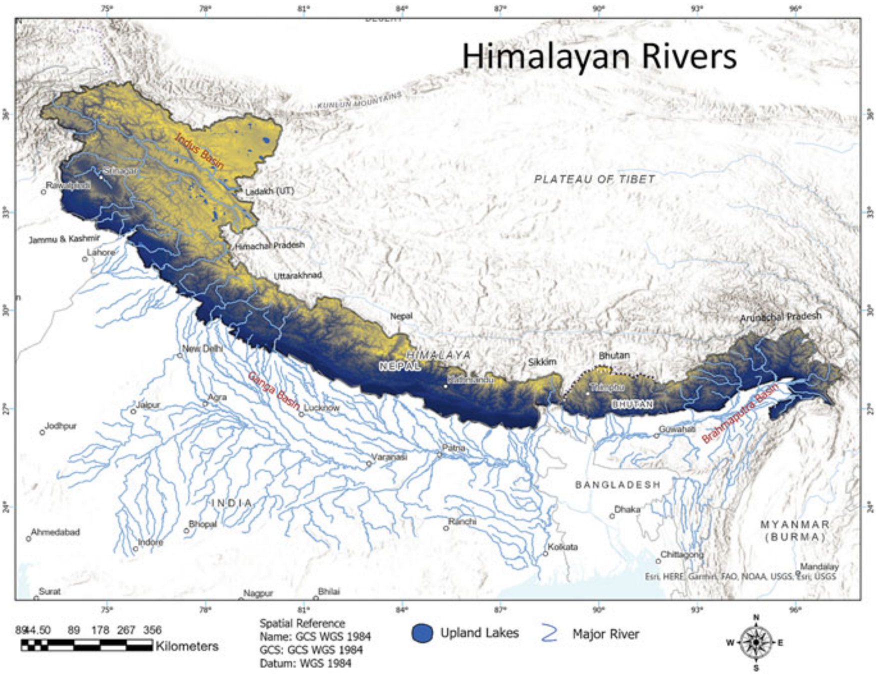

Fig. 21.3 Upland lakes and major river systems of the Himalayas

Table 21.1 The Himalayan rivers

Origin	River system	Major rivers	Tributaries
Trans- Himalayan (beyond the Himalayas)	Indus	Indus	Gartang, Zaskar, Dras, Shyok, Shigar, Nubra, Gilgit Huza Sutlej, Ravi, Beas, Chenab and Jhelum
	Brahmaputra	Brahmaputra	Dehang and Luhit, Subansiri, Kameng, Tista, Manas Burri Dihang, Disang, Kapila
Himalayan (Himalayas)	Ganges	Ganges	Yamuna, Son, Tons, Purpun, Ramganga, Gomati, Ghaghra, Gandak, Kosi, Mahananda

Himalayan rivers can be subdivided into the Indus System, the Brahmaputra System, and the Ganga System. The rivers of these systems are represented in Table 21.1.

21.6.2 Glaciers

Glaciers, the natural buffers of hydrological seasonality, free meltwater during summer and early autumn. They are water assets in the mountains and discharge the surplus water into lowland rivers besides recharging river-fed aquifers. Glaciers also contribute to global sea-level change due to the melting of ice (Bolch et al. 2012), a phenomenon that may be attributed to climate change. The Himalayas are often referred to as the "Third Pole" due to the vast glacier reserves besides Antarctica and the Arctic. The Indian Himalayan Region has nearly 9000 glaciers out of the world's 198,000 that are spread across the provinces of Sikkim, Jammu and Kashmir, Himachal Pradesh, Uttarakhand, and Arunachal Pradesh. The largest glacier outside the polar region, Siachen, is about 72 km long. It is located near the Indo-Tibet border on the northern slopes of Karakoram Range and feeds the rivers Mutzgah and Shaksgam. Baltoro, Biafo, Nubra, Hispur, Nun-Kun, Machoi, and Rimo are some other important glaciers in Jammu and Kashmir. Baltoro is the second largest glacier and feeds river Shigar, an important tributary of river Indus. Biafo feeds the tributaries of Shigar river, Nubra glacier to river Nubra, which connects the river Shyok, a tributary of Indus. Other important glaciers are Gangotri, Bandarpunch, Dokriani, and Doonagiri in Uttarakhand, Bara Shigri and Chhota Shigri in Himachal Pradesh, and Zemu, Rathong, and Lonak in Sikkim.

21.6.3 Lakes

An area greater than 10 hectares is occupied by 2028 glacial lakes and water bodies in the catchments of the Himalayan region from which some of the important rivers originate. There are 503 glacial lakes and 1525 water bodies. According to the Central Water Commission (CWC), more than half of the glacial lakes or water bodies (1169) are located at an elevation between 500 m to 4000 m above sea level (CWC 2011). However, the latest data reveal that out of the 1257 glacial lakes and water bodies studied during 2021, 607 have shown a decrease in water spread area, 340 have shown an increase, and 308 have not shown any significant change (Fig. 21.4).

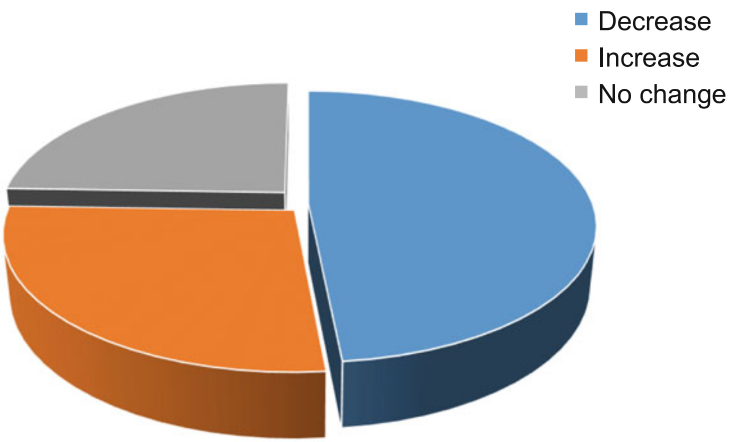

Fig. 21.4 Status of glacial lakes and water bodies in the Indian Himalayas (CWC 2021)

From Fig. 21.4, it is evident that the area of glacial lakes and water bodies is decreasing very fast, a matter of serious concern for the environmentalists as well as the general public by large. For the details, the readers are suggested to refer to the annual report of the CWC 2021. The alarming recession in water bodies may be attributed to the changing climatic conditions with serious consequences in the future, as evident from several studies (Kargel et al. 2011; Bolch et al. 2012; Kulkarni and Karyakatre 2014). The melting of Himalayan glaciers is a matter of grave concern, and several factors are responsible for the thawing of glaciers (Talib and Zulkifli 2022).

21.7 Fish Fauna of the Himalayan Region

There are several fish species that have been recorded in the Himalayan region, out of which 258 are from the Indian cold-water region. The distribution of fish species in the Himalayan streams builds upon factors like flow rate, water temperature, nature of substratum, and the availability of food. In torrential streams, three zones can be identified on the basis of dominant fish species and the hydrographical features, namely, the headwater zone, large stream zone, and slow-moving meandering zones (Sehgal 1988). Rheophilic species of loaches and catfishes (*Nemacheilus gracilis*, *N. stoliczkae*, and *Glyptosternum reticulatum*) inhabit the headwater zone, whereas the confluence of headwater streams or the large stream zone is inhabited by *Diptychus maculatus* and *Nemacheilus* spp. The upper or most torrential reaches of the large stream zone are known to be inhabited by rheophilic species of the snow trout species like *Schizothoraichthys esocinus*, *S. progastus*, *S. richardsonii*, and *S. stoliczkae.* Snow trout species, namely, *S. longipinnis*, *S. planifrons*, and *S. micropogon*, dwell in the intermediate reaches of the large stream zones. Species like *Garra gotyla*, *Crossocheilus diplochilus*, *Labeo dero*, and *L. dyocheilus* dwell in the least rapid zones. The meandering slow-moving zone is inhabited by a large number of eurythermal and cold-water species like *Tor* spp. *Barilius* spp., catfishes, homalopterid fish (*Homaloptera* spp.), and *Channa* spp. (snakeheads). However, based on the distribution pattern of Himalayan fish, six major groups were suggested by Menon (1954) (Table 21.2).

As of today, the schizothoracines are considered mainly Central Asiatic in distribution, with a few species distributed along the southern face of the Himalayas, which may be attributed to the Trans-Himalayan origin of the major rivers like the Indus, the Sutlej, and the Brahmaputra. The eastern Himalaya drained by the Brahmaputra has a greater diversity of fish fauna than the western Himalayan drainage. The important aspects that affect the life of fish in the Himalayan streams are current velocity, variation in water discharge, temperature, and dissolved oxygen level in the water, type of substratum, shelter from the water current, and availability of food. Fishes of the Himalayan region have adapted to live in fast water currents, and water temperature affects their geographical distribution and local occurrence. Some fishes have upper tolerance of around 20 °C and tolerate only a small range of temperature (endothermic species). The endemic schizothoracines (*S. esocinus* and

Table 21.2 The distribution pattern of Himalayan fish (Menon 1954)

Group	Habitat	Fish species
I	Fish inhabiting shallow, clear, cold waters in the foothills without any striking modifications to current	*Labeo*, *Tor*, *Barilius*, and *Puntius*
II	Fish inhabiting the bottom water layers in deep, fast current, with powerful muscular cylindrical bodies	Schizothoracines and the introduced trouts
III	Fish sheltering among pebbles and stones to ward off the strong current	*Crossocheilus diplochilus*
IV	Fish sheltering among pebbles and shingles in shallows, with special attachment devices	Loaches *Nemacheilus*, *Botia*, and *Amblyceps*
V	Fish which cling to exposed surfaces of bare rocks in slower current, with adhesive organs on their ventral surface for attachment to rocks	*Garra*, *Glyptothorax*, and *Glyptosternum*
V	Fish that cling to the exposed surfaces of bare rocks in fast current, with limpet-shaped bodies and mouths, gills, and fins highly modified to suit the habitat	*Balitora*

D. maculatus) and exotic brown trout are a few examples that survive best at temperatures below 20 °C, whereas water temperatures over 25 °C can be tolerated well by carps, mahseers, and lesser barils. It is intriguing to note that the schizothoracines and brown trout can survive in chilling cold streams of the Lesser and Greater Himalayan waters during December and January in near-zero temperatures. The schizothoracines migrate from headwaters to lower altitudes to cope with low temperatures in winters, thus constituting a substantial part of fish catches in rivers and tributaries.

S. richardsonii, *S. longipinnis*, and *S. curvifrons* are known to spawn with the rise in temperature in the streams of Kashmir from near freezing to 10–17 °C during May–June, whereas in the river Sutlej, upstream migration of *S. richardsonii* is induced during March when the water temperature rises. The stable inflow of snowmelt water at temperatures of 8.0–9.5 °C promotes the migration of the fish to spawn in side streams, where the water temperature is in a range of 17.5–21.5 °C. Likewise, in the Ravi river system, the fish spawns in May. On the contrary, in upper Beas, the fish spawns merely in July–August at a water temperature of 16.5–18.5 °C. Intriguingly, *S. richardsonii* migrate downstream to the lowest stretches of the same drainage for spawning from October to December at a temperature of 19.0 to 22.5 °C. Thus, in some schizothoracines, temperatures and flow rates determine multiple spawning for laying eggs.

Hailstorms and drought conditions in the Lesser Himalaya may cause adverse conditions. A drought in Kashmir in 1972 resulted in trout kill due to the sharp rise of temperature in the Vishav river, a tributary of the Jhelum in the Kashmir valley (Sehgal 1974).

Mahseer, trouts, and schizothoracines are fishes that spend most of their energy maintaining an upright position in fast and turbulent currents. The frequent occurrence of floods hampers their breeding, which is evident from the thin population in the upper reaches of some rivers that travel through deep and narrow gorges in cold glacial and snowmelt waters.

The fluctuating water discharge and drying streams can result in isolated pools or remnant pools of no water, the reason being annual variations in the winter and monsoon precipitation. Rapid streams turning into stagnant pools can have depleted dissolved oxygen concentrations. Moreover, fish in such pools can become susceptible to terrestrial predators. However, low temperatures in such streams may help maintain the level of dissolved oxygen to optimum levels required by cold-water fish (7.0–8.0 mg/L). Based on the water temperature, the rivers of the Himalayan region can be distinguished into two temperature zones, namely, the rhithron and potamon zones.

The rhithron zone is characterized by steep, narrow, and shallow riffles or rapids, with flat, wide, and deep reaches or pools. Riffles have a turbulent flow of highly oxygenated water, with rocks, boulders, or pebbles with coarse bottoms with partial vegetation. The monthly mean temperature of the rhithron zone is around 17–18 °C, dissolved oxygen concentrations are high (10.1 mg/L), and the currents are fast (0.9–1.8 m/s). Stenothermic fish like the brown trout and snow trouts (*S. richardsonii*, *Schizothoraichthys esocinus*, and *S. progastus*) inhabit this region. Potamon reaches wide, flat, meandering channels, mud bottoms, considerably rooted, and with floating vegetation. The dissolved oxygen concentrations of the water bodies fall in the dry season in the small pools, which may be completely oxygen depleted. The potamon zone has a higher mean water temperature (around 22–23 °C), with low dissolved oxygen concentration (8.0 mg/L), and much slow current velocity (0.5–0.7 m/s). Eurythermic or warm stenothermic fish fauna is prevalent, comprising fish species like *L. dero*, *T. putitora*, and *G. gotyla*.

During a study of rivers in the northwestern Himalayas, it was observed that a gradual increase in water temperature and pH is marked by a decrease in dissolved oxygen and reduced density of nymphs of mayflies and stoneflies. However, there is an increase in larval and adult aquatic beetles (Sehgal 1988).

21.8 Climate Change Impact on Rainfall and Temperature in IHR

Several studies suggest that the average temperature of the earth's surface has increased by 0.74 ± 0.18 °C from 1906 to 2005 (IPCC 2007). Moreover, the latest reports of the Intergovernmental Panel on Climate Change (IPCC) suggest that human activities have increased global temperatures by between 0.8 and 1.2 °C beyond their pre-industrial levels. The report claims that if present emission trends continue, global warming will raise the temperature of the earth by 1.5 °C between 2030 and 2052 (IPCC 2018). The rise in temperature would lead to an increase in atmospheric moisture that would likely result in a rise in global mean precipitation.

Over the period 1901–2005, global annual mean land precipitation showed a small but unclear rising trend. However, during the twentieth century, precipitation increased typically from 30° to 85°N over land. On the contrary, precipitation decreased significantly between 10°S and 30°N in the last 30–40 years. The linear trend in rainfall decline for the period 1900–2005 was 7.5% per 100 years in western Africa and southern Asia, whereas precipitation increased by more than 20% per century in much of northwest India during the same time period (IPCC 2007).

This correlation between rising global temperatures and shifting precipitation patterns has been the subject of a number of recent researches in India. It is evident from remote sensing interpolation that the precipitation pattern has enhanced during the period 2011–2015 as well as 2016–2020 when compared with the precipitation pattern of the year 2010 (Fig. 21.5). This conclusion has been arrived, by means of raster format for preparing the maps obtained from Climatic Research Unit, University of East Anglia.

Long-term trends in maximum, minimum, and mean temperatures over the northwestern Himalayas during the twentieth century indicate an enormous surge in air temperature in the northwestern Himalayas, with warm winters (Bhutiyani et al. 2007). Simulating the winters across the western Himalayas, Dimri and Ganju (2007) discovered that both the temperature and the amount of precipitation are consistently underestimated. There was an upward tendency in temperature and a downward trend in precipitation in some areas over the western Himalayas, according to an analysis of temperature and precipitation trends through time. For example, the rainfall patterns in the Koshi basin between eastern Nepal and Southern Tibet studied by Sharma et al. (2000) revealed varied results as there was more precipitation at some sites while lower at others. Kumar et al. (2005) discovered comparable patterns in precipitation for Himachal Pradesh. Rainfall patterns in the Indian Himalayas were studied by Basistha et al. (2009), and the data from 30 different sites were analyzed for a change throughout the course of the twentieth century. Changes were particularly pronounced over the Shivaliks and the southern section of the Lesser Himalayas, and they saw an upward trend from 1950 to 1964 before it began to decline over the years 1965–1980. A time series analysis of rainfall and wet days was conducted by Kumar and Jain (2010) at five sites in the Kashmir valley. Although yearly rainfall trends are reported to be falling at four locations and increasing at one, none of these trends are statistically significant. Umiam, a town in central Meghalaya at about mid-elevation, was studied for the precipitation pattern examined between 1983 and 2010 (Choudhury et al. (2012). The study revealed that the total annual rainfall increased at a rate of 3.72 mm/year, which was not statistically significant.

21.9 Impact of Climate Change on Temperate Fisheries

The consequences of climate change are going to be catastrophic as far as the fisheries sector of the temperate Himalayan region is concerned. The Himalayas have been undergoing record warming at a greater pace than earlier in the past (Shrestha et al. 2012; Mir et al. 2021). It is disturbing to note that over the past 100 years, the global mean temperature of the Himalayas has augmented at a rate of 0.74 °C, while the regional temperatures rose to an average of 0.6 °C every 25 years (Lamsal et al. 2017). The effects of climate change on the Hindu Kush Himalayan

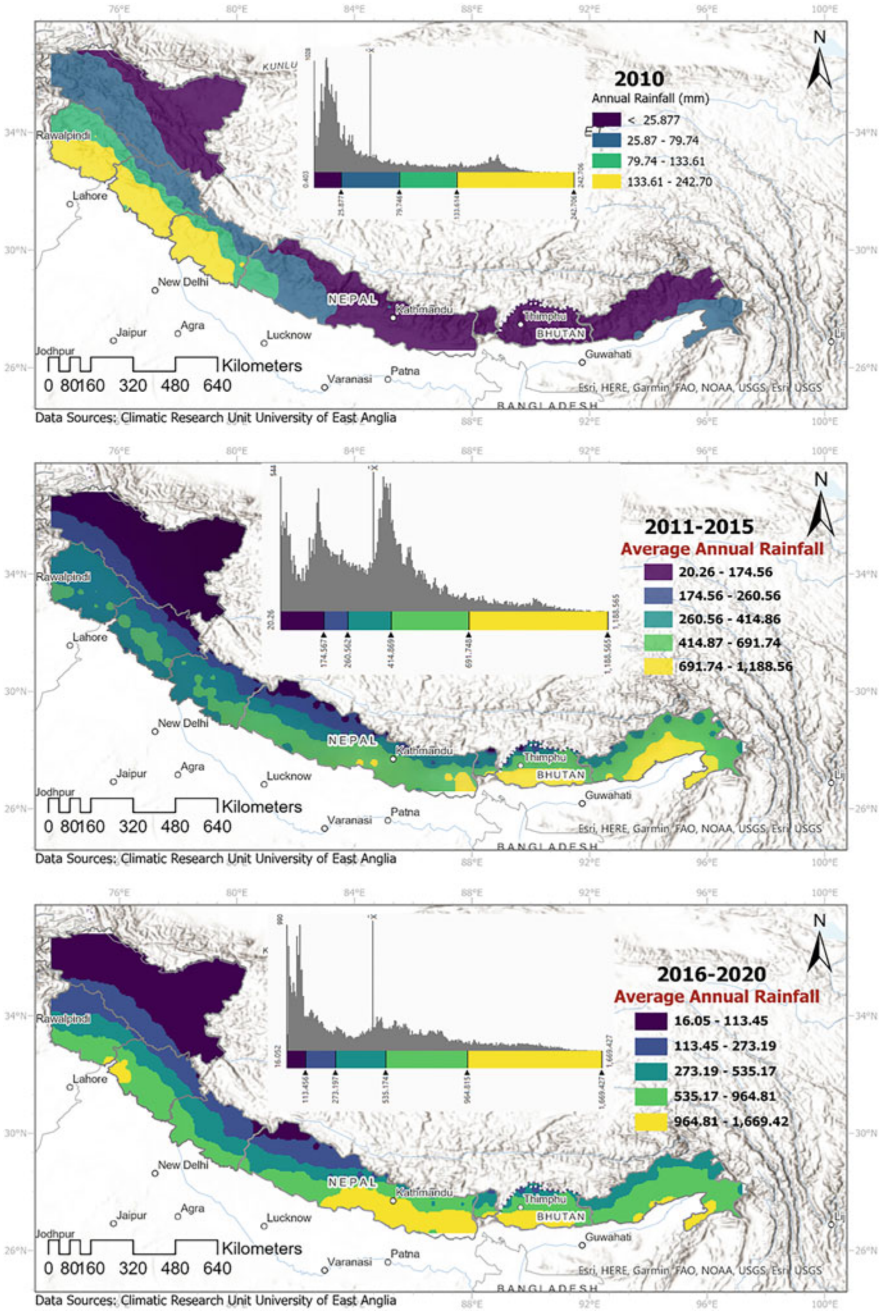

Fig. 21.5 Comparison of precipitation patterns in 2010 with 2011–2015 and 2016–2020

range have been well documented. The extraordinary rates of climate warming in HKH have endangered biodiversity, the functioning of the ecosystem and services, as well as the survival of mankind in the HKH region (Kattel 2022). Climate warming in HKH is leading to serious aspects with dire consequences on social, economic, political, ecological, and biodiversity. Impacts of climate warming due to natural and anthropogenic activities on biological diversity have resulted in rapidly changing life cycles, development of new physical traits, shifts in habitat ranges and species distribution, variations in abundance, and migration patterns in the HKH region (Kattel 2022). The severity of pests and disease outbreaks could be critical reasons for losses in biodiversity as a result of climate change, which in turn will have a serious effect on ecosystem function. Loss of biodiversity can wear away ecosystems' ability to withstand the effects of climate change, although nature has provided biodiversity the ability to stabilize ecosystems against climatic stressors (Pires et al. 2018). The interface between climate warming and biodiversity losses is intricate. Therefore, climate warming may lead to circumstances with extreme damage to the Himalayan biodiversity. It is suggested that climate warming could alter mechanisms that disturb the biodiversity of an ecosystem (Pires et al. 2018). Biodiversity losses disturb ecosystem processes and reduce the productivity of an ecosystem's productivity as well as its performance (Balvanera et al. 2006).

There would be serious implications of climate change on the fisheries of the Himalayan region. It is known that the Himalayan water bodies are rich in endothermic species that survive at a low-temperature regime of around 20 °C and cope with only slight fluctuations. Climate change could limit the distribution of endothermic species as the snow line would move to higher altitudes. The rise in temperature would also affect aquaculture production of both endemic schizothoracines and exotic trout. At the worst, climate change may lead to the complete wiping out of stenothermic species as the water quality and water levels would deteriorate at a great pace. Further, climate change would alter the winter and monsoon precipitation patterns leading to the reduction in the water levels of the Himalayan lakes and rivers, which may eventually dry. On the contrary, climate change would enhance the prevalence and intensity of flash floods. Moreover, the rapid melting of glaciers would destroy the fish habitat by sweeping the stenothermic species to regions with higher temperature regimes and finally killing them.

Another severe consequence would be the change in the spawning behavior of the temperate fish species. An alteration in their thermal regimes would compromise the breeding of fish, and it can be expected the breeding seasons would change. Climate change may also alter the developmental stages of fish with either slow or, at times, earlier development of fry. Such fry would be prone to environmental pressures and susceptible to diseases. Elevation in thermal regime would also lead to a change in the distribution of temperate fish species with the replacement of stenothermic species with euthermic ones like the carps and mahseer. Further, climate change would alter the temperature zones. Thus, the suitability of certain aquaculture species would see a drastic change. For example, areas presently suitable for trout farming would no longer be suitable. Under such circumstances, trout farming may get replaced with carp farming. This prediction is in accordance with that of Lamsal et al. (2017) who demonstrated that the climate suitability of tree-line species would expand toward higher elevations that are currently unsuitable. Further, the net climatic suitable areas will increase in the future compared with the present situation, and high elevation belts will become more climatically suitable (Lamsal et al. 2017).

Likewise, fish inhabiting the rhithron zones may face a sharp decline in their population due to reduced water flow caused by drying of rivers and streams, whereas in the potamon zone, pools of stagnant water may prevent fish survival due to heavy eutrophication. With a change in an ecological niche, the fish would face scarcity of food as certain plankton would be lost due to rising water temperature. Another serious impact of climate change will be eutrophication, a consequence of the gradual increase in the concentration of nutrients like phosphorus, nitrogen, etc. in an aquatic body. Eutrophication would contribute to drastic changes in dissolved oxygen content besides the production of blue-green algae that are harmful not only to fish but to humans too. Anthropogenic activities like the construction of dams would result in water scarcity in the rivers to affect the biodiversity of fish. It would lead to loss of breeding grounds for stenothermic fishes leading to a decline in population.

Adverse weather conditions like hailstorms and drought conditions in the Lesser Himalayas may frequently be encountered. It has been reported that in Kashmir, a drought in 1972 resulted in mass trout kill because of the sharp rise in temperature of the Vishav river, a tributary of the Jhelum (Sehgal 1974).

Fisheries ensure a nutritious supply of food and livelihood, directly or indirectly, to over 1.4 million people (FAO 2010). Warmer freshwater temperature and changes in the pattern of flows have reduced the abundance of trouts, mahseers, snow trouts, and other endemic species in hilly areas. These changes have affected the growth, survival, reproduction, and distribution of fish species besides aggravating predation and competition by exotic species. Thus, with a distributional shift in freshwater species, endemic species would run the risk of extinction.

Fishes inhabiting cold regimes have a slow metabolism. With the warming of surrounding water up to a certain temperature, the metabolism of fish speeds up. The food is digested well, and fish growth is rapid and better, which enables it to reproduce. If the food supply is limited, the growth of the fish is affected. However, warming of water over a certain threshold depletes dissolved oxygen leading to "oxygen squeeze," a phenomenon where less oxygen is available to support the increased metabolism, which, in turn, affects the survivability of fish. One of the well-known consequences of climate change is a rise in temperature, which will lead to oxygen squeeze and ultimately threaten aquatic life, including fish.

The physiology of fishes is intimately linked with temperature, due to which they have evolved to survive inexplicit hydrologic regimes and habitat niches. This adaptation may lead to genetic changes in fishes that do not migrate or get acclimatized to the surrounding environment. However, thermal changes in the aquatic environment enhance the possibility of parasites and microbes to thrive, thus leading to serious fish diseases. Under thermal stress, the immune status of the fish gets compromised, and it becomes susceptible to diseases. Since fishes tend to mature earlier in warm waters, they often have stunted growth or smaller body size.

Therefore, climate change could lead to a substantial drop in the abundance of a species.

Climate change will be the most prominent stress factor for fish in natural or artificial systems. Trout and salmon are among the most vulnerable fish species that will succumb to global warming because of their dependence on clean cold water. Warming of the habitats will have negative impacts on the entire life cycle starting from eggs, juveniles, and adults. According to the Natural Resources Defense Council (NRDC 2002), global warming will be one of the causes of the fading away of trout and salmon populations from 18 to 38% of their current habitat by the year 2090. Further, if emissions of heat-trapping pollutants such as carbon dioxide are not reduced, NRDC predicts that habitat loss for individual species could be as high as 17% by 2030, 34% by 2060, and 42% by 2090.

21.10 Possible Adaptation Approaches

Climate change, a serious threat to the earth, is not a yet-to-come problem. It is a continuous process going on for several decades. However, anthropogenic activities have facilitated it to a great extent, as evident from the reduction in snowpack and earlier spring runoff with dire consequences. All over the world, there have been changes in the distribution, abundance, and quality of water and fish. The temperate Himalayan region will face the scourge of climate change; therefore, mitigation is warranted before it is too late. Warming of the temperate Himalayan region will have serious consequences on cold-water fish, affecting livelihood, recreation, and regional culture.

Adaptation, the tuning in natural or human systems in response to an actual or an expected change, can moderate damage or exploit beneficial opportunities. Adaptation is necessary for living beings in order to survive climatic stimuli (IPCC 2007) and to cope with current and expected impacts. It is achieved by reducing risks and vulnerabilities, identifying opportunities, and capacity building at all geographical and social scales. Some broad adaptation strategies that can be kept going in the face of adversity with relevance to temperate fisheries and aquaculture systems are as follows:

- Monitoring, forecasting, early warning data systems, and adaptation could be helpful in generating as well as sharing information about climate change.
- Investigations should be conducted to find solutions on projections and impact assessments of regional and local climate.
- Ways to adapt to climate change in decision-making, policies, and procedures must be integrated.
- Circumventing obstructions in an adaptation by sustaining and augmenting the flexibility of natural and human systems.
- Firm response to societal inequality and broadcasting the effects of climate change.

- Evasion of undesirable effects of climate change, green taxes, or trading systems can be implemented as adaptive measures.
- Reducing stress factors like overfishing and pollution compounded by climate change.
- Continuous well-planned restocking program to reduce the vulnerability of important fish species like mahseer and snow trout.
- Protecting the resilience of the freshwater by avoiding habitat destruction and pollution that could further aggravate stress on the systems.
- De-silting of the natural water bodies (rivers, lakes, creeks, and reservoirs) to prevent drying up, which has already manifested in zones across the country.
- Controlled fishing to reduce overfishing as a way of protecting the water bodies and the resource-poor fishermen.
- Integration of aquaculture with agriculture and/or poultry for diversification.
- Development, adaptation, and adoption of appropriate fish post-harvest technology for reducing losses incurred by the rural fishers and make-up for reduced fish production due to the impact of climate change.
- Plan of action to protect fishing communities from the impact of climate change such as floods, displacement, and disease outbreaks.
- Promotion of fish culture in cages and irrigation canals.
- Promote the culture of planktonophagous and herbivorous fishes to sequester carbon.
- Support innovation by research on management systems and aquatic ecosystems.
- The political will to implement adaptation strategies.

The Food and Agriculture Organization (FAO) advocates for the control and management of fisheries to uphold healthy and productive ecosystems (FAO 2009, 2013). It ensures the upkeep of structure, practices, roles, and interfaces between the components of the ecosystem, strategically including and maintaining the biodiversity. Restoration of the habitat may be essential as a part of an ecosystem approach. Adaptive actions may assist in the conservation of climate-induced changes, particularly in species composition. Therefore, management requirements may be enforced to adjust and respond to climate-induced changes such as changes in distribution, species composition, or productivity (FAO 2009).

The ecosystem approach offers the chance to think about climate change in the sector's planning and in the refinement of management practices to effectively address climate inconsistency and drifts at scales ranging from individual to farm or a selected area under management. Several studies have identified possible adaptation strategies for people to use. These include creating awareness of the importance of such systems among local communities and leaders, identifying critical areas, and minimizing stress related to climate.

Several initiatives have been taken up by the Government of India to combat the impacts of climate changes in the Himalayas. Resolution of environmental concerns in the Himalayas, an original approach, is being proposed by the National Mission for the Sustainment of the Himalayan Ecosystem (NMSHE), which is part of the National Action Plan on Climate Change (NAPCC). For the purpose of ensuring the long-term viability of the Himalayan ecosystem, the Government of India (GoI) has launched a number of projects, including Governance for Sustaining Himalayan Ecosystem (G-SHE), Hill Area Development Programme (HADP), Indian Himalayas Climate Adaptation Programme (IHCAP), Climate Change Adaptation Project (CCAP), and National Mission on Himalayan Studies (NMHS). These programs offer a variety of approaches toward mitigating the effects of climate change and finding ways to adapt to it.

21.11 Conclusion

There are several studies and pieces of evidence that reveal the Himalayas are warming up. The warming of this important region is likely to have a catastrophic effect on both flora and fauna. Climate change has led to either drought conditions or weird flooding due to cloud bursts. Such situations are becoming frequently encountered in the temperate Himalayan region, affecting several species of fish. Such tendencies can possibly continue in the future and lead to significant changes in ecosystems. Threats due to climate change increase the collective impacts of other anthropogenic activities like over-exploitation, habitat degradation, pollution, eutrophication, and the introduction of species. Global warming could rapidly dry the water resources and even increase the salinity of groundwater, which will be detrimental to temperate fisheries and aquaculture.

Adverse impacts of climate change are also putting enormous stresses on the lives and livelihoods of the people engaged in fisheries. It is foreseen that changes in intensity and seasonality of climate patterns would have serious consequences on hill fisheries. Therefore, managing existing fisheries and utilizing best management practices should counterbalance negating impacts of climate change on the potential of fisheries under an ecosystem-based approach. It is evident from the information that changes due to global warming will potentially have both favorable and unfavorable impacts on aquaculture. However, data indicate that adverse changes are likely to outweigh favorable ones in the temperate Himalayan region countries in the absence of adaptive capacity. Adaptation to climate change must be undertaken within a multifaceted context. Communities could help adapt to climate change by developing policies and programs to improve the resilience of natural resources through assessments of risk and vulnerability by increasing awareness of the impacts of climate change and by strengthening key institutions that would help the communities' adaptation. In this context, adopting climate resilience as an adaptation strategy will help meet the livelihood security of stakeholders associated with fisheries and aquaculture. The ecosystem approach to aquaculture offers the opportunity to consider climate change in the sector's planning and the development of management measures. Social and economic aspects and resource productivity need to be adapted for the management of fisheries to mitigate climate change. Moreover, ecological and human well-being are also warranted for the sustainability of aquatic resources. Advanced techniques and protocols need to be implemented to combat the changing climatic conditions.

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Livelihood Opportunities with Recreational Fisheries and Ecotourism

22

Rabinder Singh Patiyal and Ann Pauline

Abstract

Sport fishing, usually referred to as recreational fishing, is fishing done for enjoyment or recreation. With a 5% global annual growth rate, it is the tourist industry segment that is expanding the fastest. Recreational angling is a very sustainable kind of fishing compared to other kinds of fishing. Recreational fishing generates considerable economic gains and provides the locals with a variety of livelihood options. This chapter briefly describes the recreational fisheries and their sustainable management in the temperate Himalayan region.

Keywords

Recreational fishing · Fish-based ecotourism · Mahseer · Sport fishing · Himalaya

22.1 Introduction

Sports fishing or recreational fishing captivates the colossal rate of humanity almost every day and is the most sought-after adventure tourism. Various wildlife sports propel the general disposition of wildlife visitors into the multitude of wildlife adventures. Wriggling the fish "off the hook" may alight the tourists not only into an ambience of "adventure of exploration" which tosses the swings of the mood of public into one of the most tantalising curiosities about nature and its diversity but also inquisitiveness galore. The idea of angling, popularly known as sport fishing, is to catch fish using a fish hook or an "angle". It is accomplished using a rod, reel, line,

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Fig. 22.1 Different types of bait fishing

and hooks using a variety of baits. A fishing rod with a fishing reel is equipped with a fishing line to which the hook is attached. The hook is adorned with a bait or lure to entice fish. Baits may be synthetic or natural. Natural baits are dead or live fish prey like worms, insects, earthworms, and maggots, whereas artificial bait can be a "lure" without having to resemble actual prey.

The most popular techniques include fly, spoon, and bait fishing (Fig. 22.1). Fly fishing or fly casting method uses artificial fly to hook the fish with the help of rod and line. In spoon fishing, spoon-like artificial metallic shining lures are basically used to fish "heavier" waters where mahseer occurs. Bait fishing or bait casting is performed using both natural and artificial lures. The natural baits are earthworms, minnows, and insects.

22.2 History of Recreational Fisheries

Angling is an old sport which dates back to the ancient world. It started primitive in the fifteenth century. Individuals have been getting fish for food since fishes were found in streams and oceans. The sport of angling was promoted by the Greek philosophers Aristotle and Pluto, while the historian Plutarch gave guidance on the fishing line. Sport fishing dates back to the late fifteenth century, and angling did not fully take off until Izzak Walton's publishing of "The Compleat Angler" in 1653.

22.3 Recreational Fisheries in Indian Himalayas and Other Uplands

The golden mahseer (*Tor putitora*, Hamilton 1842) is frequently known in Asia as the king of the rivers and offers anglers from all over the world recreation that is unrivalled by salmon. Mahseer is located amid pristine freshwaters, which are often compared to wild, undeveloped areas and are described as signs of robust freshwater ecosystems that extend from the Himalayan ranges (Fig. 22.2). Some mahseer species are already threatened with extinction, and others are at risk due to indiscriminate fishing techniques like dynamiting and poisoning. Trivial concerns arise as a result of the establishment of multi-purpose reservoirs, which fragments habitat and reduces migratory routes. A significant issue is the extensive sand mining in spawning zones. These problems are prevalent throughout the majority of Mahseer habitats in the nation, including the Vindhya-Satpura, the Western Ghats, and the foothills of the Himalayas. The majority of mahseer species could eventually reach a point beyond which they cannot be saved if none of these are handled quickly and efficiently (Babu et al. 2014). Besides mahseer, the fish species that is found in plenty are gargantuan gooch (catfish) and trout species (rainbow trout, brown trout). The lower Himalayas are deemed to be the perfect spot for recreational fishing, i.e. mahseer, goonch, and trout are abundant in Ramganga and Kali river. The Godavari, Kaveri, Krishna and Mahanadi rivers all year round contain a significant amount of mahseer. Brown trout can be found in the Indus, Jhelum, and Lidder rivers

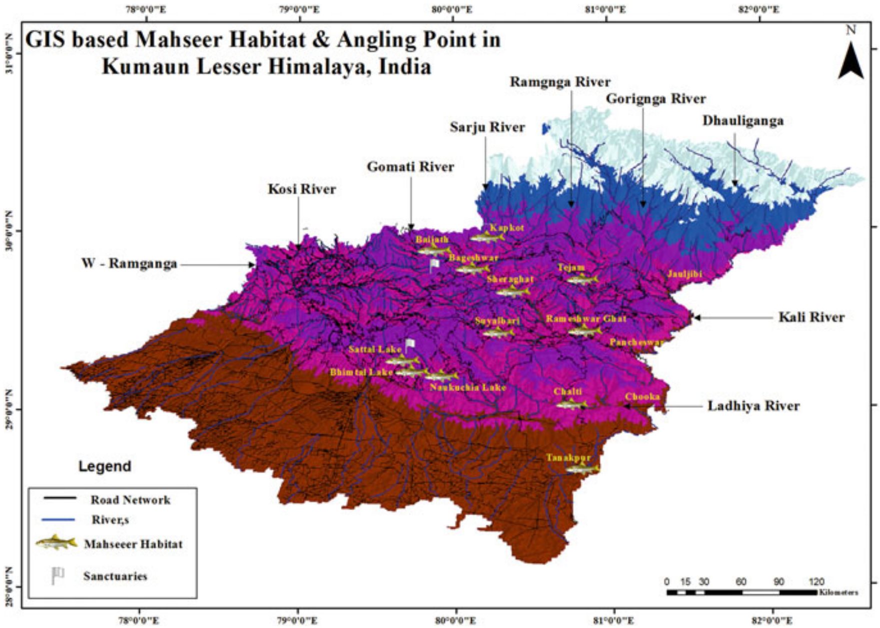

Fig. 22.2 Mahseer habitat and angling points in Lesser Himalaya, India

in northern India. Trout can also be found in the streams and rivers of Kerala and the Nilgiri hills in the South states of India.

Angling can be done year round. Due to diverse agro-climatic conditions, the best seasons, for the Himalayan rivers, are from October to November and April to June when the streams and rivers are well stocked with different species of fishes.

22.4 Angling Sites in India

Pancheshwar, located at the confluence of the rivers Kali and Sarayu, is one of the many excellent getaways for anglers in Uttarakhand. It provides a perfect location with beautiful mahseer species, such as golden mahseer, red fin mahseer, copper mahseer, and chocolate mahseer. The tranquil upper stream of the Ramganga river flows through the lush Jim Corbett National Park (Uttarakhand, India), which has an abundant supply of goonch, trout, and the highly sought-after mahseer fish. The Divisional Forest Officer (DFO) grants his or her consent for angling. The Mahanadi, Yamuna, Cauvery, Ganges, Brahmaputra, Sutlej, and other smaller Himalayan rivers and streams are only a few of the major rivers and their tributaries where sport fishing is permitted. Inland waters typically have a broad variety of fish, including mahseer, trout, and carps. In Himachal Pradesh's Sangla Valley, Manali, trout can be found. Brown trout are spotted in Gulmarg, Kashmir. The Kaveri river in Karnataka, the Andaman and Lakshadweep Islands, the Yamuna River, North Sikkim, Meghalaya (Fig. 22.3), Assam, and Arunachal Pradesh are a few other spots for recreational fisheries.

22.5 Sport Fishing as a Form of Regional Run Ecotourism

Traditionally, sports fishing has been done with a rod and line, primarily for enjoyment and with a focus on a particular species. The sport lasts until the fish is landed or lost depending on the gear used and the fighting abilities of the target species. Sport fishing abides by a specific set of guidelines established by governing organisations like the International Game Fish Association (IGFA) (Whitelaw 2003) Sport fishing can be classified as ecotourism if it satisfies certain requirements,

Fig. 22.3 An angling site in Meghalaya, India

including those that apply to catch-and-release fishing: (1) Fishing methods should mitigate fish stress and catch mortality; (2) tourism contributes significantly to biodiversity conservation and poverty alleviation by offering alternative livelihoods with better income to support the local communities.

22.6 Co-Management of Ecotourism

Community-based ecotourism initiatives are developed in regions that have high regard for the environment and have a lot of potential for nature-based tourism. These regions are typically isolated and underdeveloped, having little access to services, education, and other resources (Coria and Calfucura 2012). The development of rural areas is significantly impacted by their remoteness from markets as well as hard physical and climatic circumstances. In the past, projects including ecotourism had trouble getting access to tourist markets (Zeppel 2006).

Remote populations frequently provide essential skills and expertise to ecotourism endeavours. They are given a wide range of abilities to develop as sports fishing tour guides due to their traditional ecological knowledge (TEK). Tourist guides can use local knowledge of the environment, such as study of the behaviour and distribution of the target species (King and Faasili 1999). The creation of numerous alliances and the co-management of systems through the fusion of expert knowledge from the fields of science, business, and local knowledge can all help to allay these concerns. Training local tour and sport fishing guides could build community capacity and result in local knowledge that can empower others.

22.7 Role of Governance in Promoting Recreational Fisheries

Fair distribution of benefits is a prime feature of successful ecotourism activities. A challenge in community-based natural resource management is power dynamics. Cases have reported corruption and misappropriation of benefits by locals and nationals. As a result, community people are compelled to embrace alternative means of subsistence that enable higher and more consistent revenue than tourism. This may have a detrimental effect on the preservation of biodiversity, resulting in a drop in visitor numbers and the failure of the ecotourism endeavour as a whole. The establishment of profit sharing and local community accountability can be guaranteed by transparent governance systems.

22.8 Benefits of Biodiversity and Ecotourism

The ecotourism should function based on some principles and indicators (Table 22.1). Ecotourism projects with a community focus should create opportunities for the target species and the local population to make a living. There hasn't been enough data and comprehensive evidence in the field. Reduction

Table 22.1 Principles and their indicators for ecotourism functioning

Principles	Indicators
1. Local capacity	Number of training initiatives to enhance local capacity Number of local workers employed by tourism-related businesses Participation rate in ecotourism pursuits Societal agreement with local laws
2. Governance	Local democracy level Locals' potential to influence projects Local opinion on ecotourism development Benefits are equitably distributed
3. Social outcomes	Locals' nutritional status Development of infrastructure, such as schools and hospitals The number of educational awareness initiatives offered in nearby schools
4. Biodiversity outcomes	Target fish species biomass Finding new hazards to the target species and their habitat Hooking and release mortality rate Perceived changes in risks to the habitat of non-target species Extent of stock enhancement of selected fish species
5. Ecosystem service benefits	Ecosystem services' quality in relation to fish species' habitat

in local harvesting of sports fish leads to nutrition deficiency, which should be backed up by alternative sources of protein. Evidence suggests that tourism may be a factor in local site price increases (Wunder 2000). Although ecotourism increases household income, total dependence should be avoided because it is extremely susceptible to shocks to the world market (Allison and Ellis 2001). Environmental changes result in habitat modification that benefits fishing but decrease the overall ecosystem's flexibility. Stocking farmed fish to increase natural sport fish populations is a popular practice.

22.9 Recreational Fishing: A New Economic Opportunity in the Temperate Himalayan Region

Economic gains from recreational fisheries are significant. Recreational fisheries produce orders of magnitude of higher economic value per kilogram of fish. They also contribute greatly to employment. Studies show that recreational fisheries give additional non-market values to the society (Toivonen et al. 2004). Rising incomes in developing nations offer opportunities to develop and sustain these fisheries and strengthen the connections to tourism and other aquatic recreational activities, despite the fact that recreational fisheries contribute to having a relatively greater importance in developed countries. By their very nature, commercial and subsistence fisheries coexist with recreational fisheries. They put a lot of pressure on the fishing resources, which leads to disputes and policy problems. It implies that all three activities must be managed responsibly and that the governance structure and allocation procedures must strike a balance between the conflicting demands of various interest groups and society as a whole. A recent estimate of the global loss of rents in marine capture fisheries does not account for the rents created by recreational fishing, which can be substantial (Arnason et al. 2017). Recreational fisheries offer a broad array of fisheries governance mitigation strategies that are applicable outside of these fisheries. These agreements cover a variety of topics, such as the management of these fisheries by indigenous peoples, the separation of angling and land rights, community leasing of water bodies, stock enhancement, licensing and levies, catch reporting, approaches to recovering management costs, and payments for ecosystem services.

For the residents, recreational fisheries offer a different means of subsistence. The ecology of the target fish species, such as spawning and seasonality, needs to be better studied. The requirement for good governance and dispute resolution methods is made simpler by the equitable distribution of rewards. It is necessary to comprehend population dynamics, life cycle traits, food webs, and ecological interactions from a broad perspective. Healthy, productive, and resilient ecosystems are maintained by effective management of sports fisheries. Multi-stakeholder collaborations, resourcing, knowledge integration, and innovation can all be used to effectively implement adaptive co-management concepts.

22.10 Conservation Approach and Concluding Remarks

Conservation and tourism have worked in tandem since the earliest twentieth century. To boost up the fisheries and aquaculture activities, the Directorate of Coldwater Fisheries Research (DCFR) conducts awareness programs to facilitate interaction with the anglers. It has developed breeding protocols and subsequently conducts training to farmers. The institute is also involved in seed ranching programs to replenish and maintain the river stocks. It conducts capacity building programs with the angling operators and conducts angling competition in collaboration with the tourism departments. All these endeavours will help conserve and rehabilitate recreational fisheries in the natural water sources, augmenting the livelihood security of the people in the hilly terrains.

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23 Design and Operational Principle of Recirculatory Aquaponic System in the Himalayas: Prospects and Challenges

Abhay Kumar Giri and Nityanand Pandey

Abstract

In modern scientific soil-less cultivation, aquaponics/integrated agri-aquaculture farming (IAAF) is gaining wide popularity, especially in urban and hilly areas with water and space constraints. Following the concept "waste to wealth," this hi-tech natural/organic by-product utilization strategy produces fish and plants for human consumption and use without any external input. It requires only 10% of water as compared to the traditional farming. The recirculatory aquaponic system (RAS) has the benefit of solving problems like waste management headaches and unwanted weed infestation, including soil-borne pests and diseases, hence, providing optimum space for the growth of much healthier plants. In an optimized system, the fish, plant, and microbial (bio-filter) components technically co-exist in symbiotic equilibrium, where the ammonia- and nitrite-oxidizing bacteria convert the toxic ammonia to nitrate for utilization by plants. However, some proportions of nitrite and ammonia are also utilized by the plants, depending on their species and varieties. The varieties with hardy nature and giving better production are chosen. Selection of fish and plant species varies according to the type, locality, and aquaponics method for the grow-out cultivation. Based on the material compatibility and type of plants to be cultivated, several categories of organic and inorganic media bed substrates can be used to cater the needs. are a good number of aquaponic techniques such as nutrient film technique (NFT), media bed, deep water culture (DWC)/raft, drip and wick system, Verti Stack, Dutch bucket, Vertigrow, ebb and flow (flood and drain), aeroponics, etc. are practiced in small scale to commercial farming, each bearing its benefits. These systems can be installed in the form of mini, small, semi, hobby, open pond,

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domestic, backyard, demonstration, or commercial way as per their purpose, area confinement, and scale of operation. As a primary food source, aquaponics may not fully replace the long-established conventional farming. Still, it can suffice as a much-warranted solution for the area/country without possessing adequate space, water, and fertile soil for the fisheries and agriculture to promote further.

Keywords

Aquaponics · Integrated agri-aquaculture farming · Soil-less farming · Media bed · Organic produce

23.1 Introduction

In recent times, aquaponics has been one among the safer food production units that produce chemical-free food of good quality in a confined space. With the application of this kind of high-tech techniques, relatively nontoxic quality of food is produced by natural means with no or limited external inputs. This self-sustained integrated food production system has the potential to produce two diversified groups of crops such as fish and plants in a limited space or area for human consumption and/or use, hence also referred as "Integrated Agri-Aquaculture Farming" (IAAF). The term "aquaponics" is the amalgamation of two words, i.e., "*aqua"* (aquaculture- raising fish in a controlled environment) and "*ponics"* (growing in soil-less media). This is an integrated fish and plant production technology, which basically unites two sub-units like "aquaculture" and "hydroponics," but for fruitful operational functioning of the unit, it is scientifically comprised of three components such as fish, plant, and microbes. It is basically a futuristic production system, more preferably equipped for urban places including temperate Himalayan hills, where there is limitation for both space and water. According to Palm et al. (2018), aquaponics is a type of production system that produces both aquatic organisms and plants in an integrated manner where majority of the nutrients required by the plants for their optimal growth and survival were being obtained from the effluents generated by the aquatic organisms under cultivation. This technique is quite effective in growing wide varieties of crops and requires only 10% of water with no use of chemical fertilizers in contrast to traditional farming method in soil (Duarte et al. 2015). As the system produced good-quality chemical-free foods that are safe for human consumption, hence, it got organic certification in developed countries such as the USA. But to make the system viable, it should be scientifically designed, keeping eye on several intrinsic factors such as the types of fish and plant to be cultivated, their ratio, solid waste removal and biofiltration system, etc.

The system can be based on the stocking of single fish species or polyponics with the mixture diversified aquatic organisms or following the concept of freshwater Integrated Multi-trophic Aquaculture (IMTA), where the plants are being grown in the fish culture pond itself with the help of some floating rafts. In a basic recirculation aquaponic system (RAS), the feed loss and fish waste can be reused within the system to convert these into valuable plant biomass, and also the water is replaced only to compensate the plant-mediated evapo-transpiration loss (Lennard and Leonard 2006). The effluents, generated from fish farming units, are difficult to treat because of large volume, carrying fairly dilute nutrients (Adler et al. 1996c; Heinen et al. 1996). There are a number of methods to lessen nutrient discharge of aquaculture effluents such as reduction of excess phosphorus in fish diet (Heinen et al. 1996; Jacobsen and Børresen 1995; Ketola and Harland 1993), decrease of uneaten feed (Asgard et al. 1991; Summerfelt et al. 1995), aggressive separation of uneaten feed and feces from the system (Summerfelt 1996), and application of various biological, chemical, physical (Adler et al. 2000; Metcalf and Eddy Inc. 1991), and plant-based mechanisms for the removal of nutrients (Adler et al. 1996b, c; Adler 1998; Rakocy and Hargreaves 1993). Of these solutions, plant-based removal of nutrients not only has the potential to offset the treatment costs but also fetch additional revenues (Adler et al. 2000) to the growers. This system is capable enough as relief from waste management headache and follows the concept "waste to wealth" as by-product utilization is an important strategy to uphold both the economic and environmental sustainability of aquaculture (Adler et al. 1996a). In general, status of aquaponics as a food production mean in temperate climates of the country is in infant state, but this integrated food production system will definitely be a step forward for the production of safe chemical-free food for the livelihood and income generation of hill communities with limited land holdings and water source, residing at difficult upland terrains of Indian Himalayan Region (IHR).

23.2 Principles

For the success of any kind of aquaponic system, the microbial communities play a vital role in the maintenance of optimal water quality, including the transformation and bioavailability of nutrients for the wellbeing of both animal and plants. The fundamental underneath principle for the operational functioning of the system is the efficient management of both waste and water to produce two crops rather than one, along with the partition and share nutrient resources between cultivated animals and plants. The waste produced from one biological system acts as nutrients for another biological system, and the fresh nutrient-rich water can also be re-used through recirculation process with the intervention of microbes (biological filtration). The maximum proportion of the aquatic animal waste contains ammonia, which is utilized basically by a group of ammonia-oxidizing bacteria to produce nitrite, which is again acted by another group of bacteria, i.e., nitrite-oxidizing bacteria so that finally nitrate is produced (Fig. 23.1). In lower thermal climates like the Himalayas, the major representatives of ammonia-oxidizing genera in the recirculatory system are *Nitrosomonas*, *Nitrososphaera*, and *Nitrosospira* (Moschos et al. 2022), including some ammonia-oxidizing archaea and *Nitrotoga* species (Bagchi et al. 2014; Hüpeden et al. 2016). However, among various nitrifying bacteria genera, the *Nitrobacter* group is generally more sensitive to lower water temperature than the *Nitrosomonas* group; hence, harmful accumulation of nitrites may be taken care of judiciously especially during colder seasons.

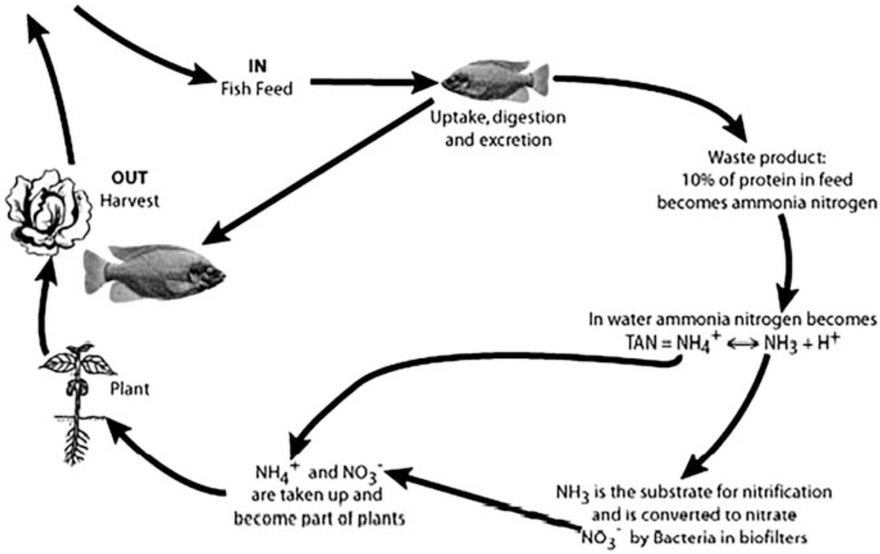

Fig. 23.1 Nitrogen cycle in aquaponics. (Source: Tyson et al. 2011)

Nitrates, including other nutrient elements produced as a final output by the nitrifying bacteria, are utilized by growing vegetables and plants to meet the nutrient make-up for their better growth and production, although some percentage of nitrite and ammonia are also utilized by the plants depending on the species and varieties. In an aquaponic system, the proper functioning of nitrogen cycle and efficient conversion of nutrients are mainly dependent on the composition and performance of beneficial microbial communities of the system, which are again regulated by several intrinsic water parameters like temperature, pH, dissolved oxygen (DO), alkalinity, and so on (Junge et al. 2017). Most of the biofilter bacteria perform optimally at 17–34 °C water temperature, and their growth rate becomes double at every 10 °C increase in water temperature within the biokinetic zone (BKZ). The DO, particularly for low thermal Himalayan uplands, also need to be maintained at least 60–70% of the saturation level as the beneficial bacteria become literally unproductive below the dissolved oxygen concentration of 2 mg/L (Masser et al. 1999). Similarly, fish and the microbial population require slightly alkaline pH, whereas plants need slightly acidic pH; hence, a pH range of 6.8–7.2 may be maintained in the system to benefit all the partners optimally (Tyson et al. 2004).

Aquatic animals and plants grown in the aquaponic system are generally safe as they are devoid of external fertilizer inputs. For cold-water climates of the Himalayan region, a wide varieties of fish and plants like trout, Murray cod, tilapia, koi, gold fish, crappie, red ear sunfish, bluegill, yabbies, silver/golden perch, salmon, jade perch, salmon, yellow perch, largemouth bass, arctic char, pike perch, sturgeon, walleye, catfish, and pacu along with leafy greens such as kale, Swiss chard, celery, parsley, dill, lettuce, pak choi, and sage, including a number of medicinal and culinary herbs may be advocated to the aquaponic growers that can perform optimally within the thermal regime range of 10–22 °C. For long-term sustainability with optimal output of the system, golden ratio among aquatic animal, plant, and microbial components has to be maintained and balanced with each other in a symbiotic equilibrium. In the context of cold-water Himalayan aquaponic system, in particular, there is dearth of information regarding the specific system design and principle of operation, rather similar strains of nitrifying bacteria are generally colonized in cold-water biofilter as that of tropical system but may not comparably with parallel kind of proficiency. For improved biofilter performance and efficient nutrient conversion in cold-water aquaponics, several kinds of biofilters such as bead filter, sand filter, trickling filter, and moving bed bioreactors (MBBR) may also be used in addition to swirl separator. In order to further strengthen the waste conversion process in low thermal regimes, the ebb-and-flow/flood-and-drain media bed method with bell siphon (among several aquaponic techniques) may be advocated to the growers, as it not only provides cushion for additional biofiltration but also makes the system more resilient to lethal accumulations due to further oxygenation. The prime aim of setting up of an aquaponic system in cold climatic hilly areas of Himalayan region is to strengthen the local economy with the production of high-valued chemical-free healthy foods in locality with the use of pricey imported crop and fish varieties.

23.3 Design of Aquaponic Systems

Basically, the aquaponic system is the hybrid of RAS for fish culture and hydroponic for plant cultivation (Goddek et al. 2015). The basic components of the system are fish-rearing tanks, solid removals (mechanical filters such as clarifier and microscreen), biofilter, hydroponic component, and sump (Rakocy 2012; Somerville et al. 2014). For aquaponics in cold-water Himalayas, the standardization of filtration units, especially the quality and volume of biofilter media, may be optimized well as the beneficial nitrifying bacteria may not perform efficiently at lower water temperature. The system can be grouped into mini, small, semi, hobby, open pond, domestic, backyard, demonstration, and commercial system (Fig. 23.2) based on their purpose, nature, function, installation, area confinement, and scale of production (Rakocy et al. 2010; Somerville et al. 2014). As the functionality of each kind of system is based on their adaptations to the geo-climatic variations of that particular site, therefore, the cold-water aquaponics in Himalayan uplands may not render that much impressive result as compared to tropical models.

The open pond aquaponics is a very cost-effective model and was developed long back primarily for catfish and tilapia. Now, this kind of system is being practiced for different types of carps, tench, pike, catfish, etc. and plants like water spinach, okra, tomato, and brinjal. The total pond area may be covered by 4–10% with plant grow-out raft for sustainable production without affecting fish growth. The carnivorous fish varieties could be more suitable for this kind of system as these will not temper the root of the plants unlike some of the herbivorous fish species.

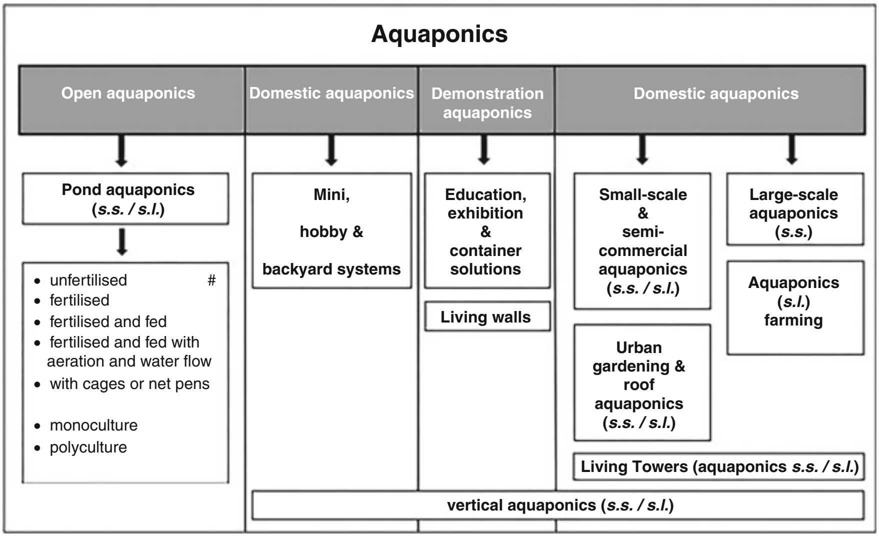

Fig. 23.2 Four main categories of aquaponic system: open, domestic, demonstration, and commercial (s.s. sensu stricto, s.l. sensu lato). (#Adapted from Stickney (1994) and Horváth et al. (2002) (Source: Palm et al. 2018))

The domestic aquaponics is a kind of coupled classical system where the fish and the plants are generally grown in close vicinity. There are different categories of domestic aquaponic systems (Fig. 23.3) such as mini (<2 m^2), hobby (2–10 m^2), and backyard system (<50 m^2), based on the area coverage, design, and component use. The type of fish, plant, and filtration systems vary according to the kind of domestic system being installed. The mini and hobby kind of systems are basically characterized by less hydroponic area and single small fish tank or aquarium with lower fish stocking density (preferably ornamental fish), where the growing plants float directly on the fish culture water. While the improved models may have separate aquaculture and hydroponic components with internal filters, sedimentation unit, and sump, the nutrient-enriched water is being supplied to the plant bed through the provision of internal or external pump. The gravity-driven fish tank water flows in the direction of filtration units-plant system-sump and then pumped to the fish tank. This kind of indoor systems is generally meant for fish keeping round the year rather than targeting production, but additional aeration facilities may be provided for better growth and well-being of the cultivated animals.

On the other hand, the backyard kind of domestic aquaponic system generally comprised of large fish tanks with more water holding capacity (Malcolm 2007) and improved filtration mechanisms (sedimentation and biofiltration units) with different types of hydroponic units spread over larger area. The airlift pumps may be used, if necessary, in order to target higher yield for human consumption. The backward systems can be installed in urban or cold climatic hilly areas, but a water heating system may be used to maximize the production in low thermal areas of northern

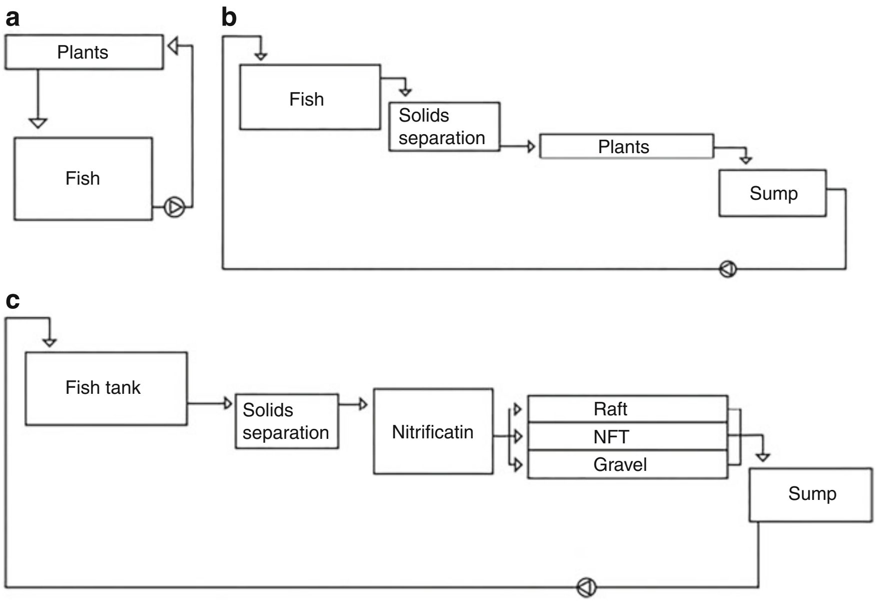

Fig. 23.3 Design of domestic aquaponic systems. (**a**) Mini-system. (**b**) Hobby system. (**c**) Backyard system. (Source: Palm et al. 2018)

hemisphere. For sustainability and enhanced productivity of the system, it can be integrated with vermiponics using tiger worms, i.e., *Eisenia fetida* in flood-and-drain mechanism, which not only encourage added fertilization for plants but also can act as food for the direct consumption by fish. But during cultivation process, the model requires higher degree of management (Somerville et al. 2014) due to the formation of anaerobic zones, hence limited in commercial application.

The design and operating principle of demonstration aquaponics are more or less similar to domestic form but generally installed in schools, colleges, universities, and industries for education and exhibition purposes. The basic motto is to educate the learners regarding the principles of food chain use with sustainable yield in higher scale. Models like vertical aquaponics and living walls (Wilson 2015) may be categorized under demonstration aquaponics and can be exhibited in organizations/industries to educate the people about waste-to-wealth principle.

On the basis of area and scale of production, commercial aquaponic systems are basically categorized (Fig. 23.4) into various groups such as small-scale (50–100 m^2), semi-commercial (100–500 m^2), and large-scale (<500 m^2) systems. Small-scale aquaponics can use one or more fish and plant units based on the demand of the produce as are generally meant for retail market. The mechanical and biological filters with different hydroponic subsystems such as DWC (raft), NFT, or ebb-and-flow techniques can be used to optimize fish and plant production. A minimum of one pump with backup option (in case of any failure) is needed for better sustainability of the system. For media bed substrates, a wide variety of

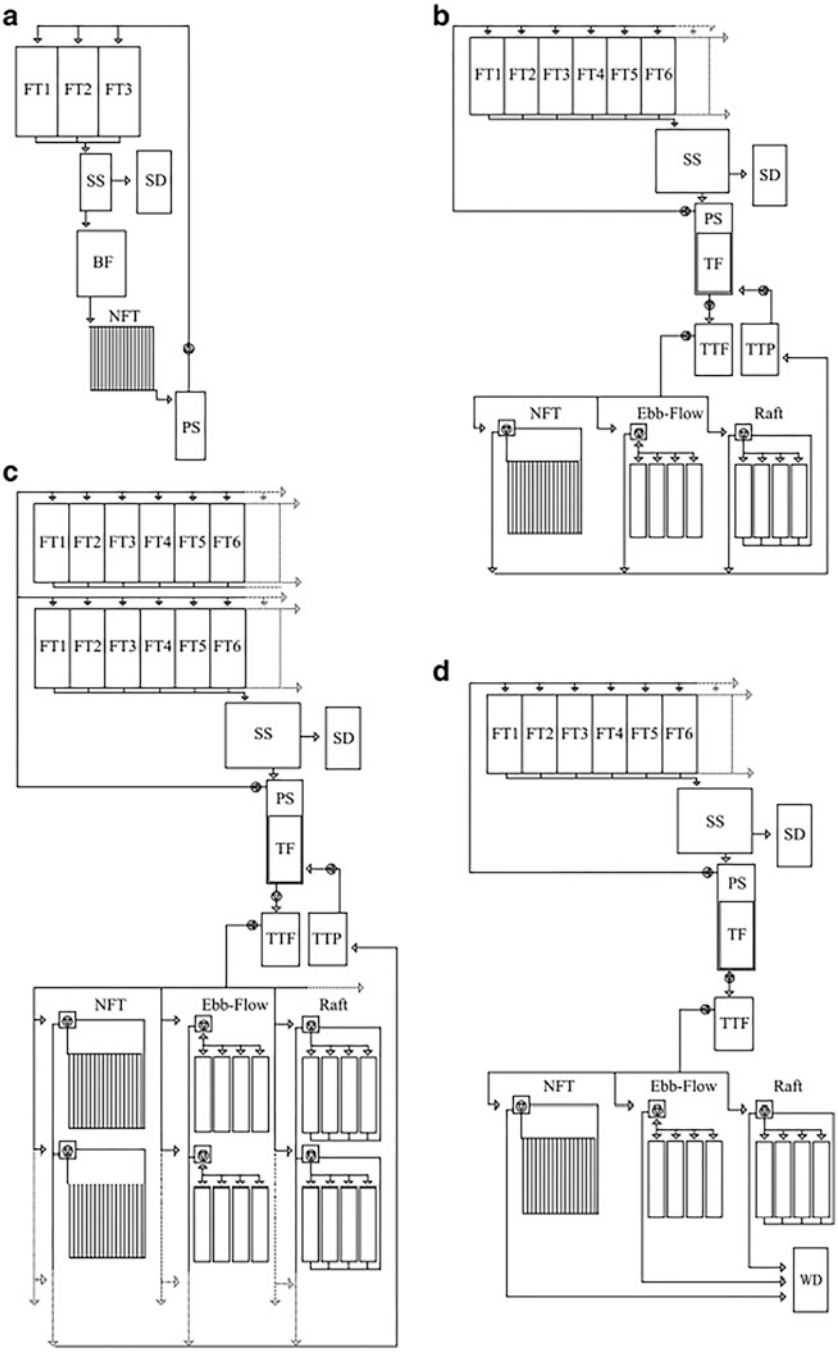

Fig. 23.4 Scale of aquaponic systems. (**a**) Small scale. (**b**) Semi-commercial. (**c**) Large scale. (**d**) Decoupled. *FT* fish tank, *SS* solids separation, *SD* solids disposal, *PS* pump sump, *BF* biofiltration, *TF* trickling filter, *NFT* nutrient film technique, *TTF* transfer tank fish process water, *TTP* transfer tank plant process water, *WD* water discard. (Source: Palm et al. 2018)

materials such as coarse sand, perlite (Rakocy et al. 2006), LECA (light expanded clay aggregate) (Graber and Junge 2009), volcanic gravel/pumice, limestone gravel, river and crushed stone, and recycled plastics (e.g., plastic bottle caps) can be used, but the prospects of biodegradable organic materials like coconut fiber, cocopeat, sawdust, peat moss, rice hulls, etc. (Somerville et al. 2014) could not be overlooked. Among different kinds of hydroponic media beds, gravel is more effective in the accumulation of nutrients, e.g., phosphorus (Palm et al. 2015). Some of the benefits of the small-scale system are of gravity-driven water flow, low energy consumption (single pump), and very low rate of water exchange unlike large-scale commercial system with higher degree of mechanization. These kinds of systems are quite used for the development of roof gardens in urban areas (Somerville et al. 2014), adding value to the rooftops and urban areas as well. With further customization, according to the specific geographical locations particularly for cold climatic Himalayan stretches, this model can cater the needs of hill populations in terms of livelihood security and socioeconomic upliftment.

The yield of semi-commercial aquaponics is higher than the small-scale system, and the produce may be supplied to both retail and wholesale markets. This system requires more than one pump with additional gravity flow to circulate the water, but there will be higher investment costs if the system includes multi-loop (bypass systems). The numbers of fish tanks and the stocking rate of fish may be increased in this semi-commercial model, but the wastewater containing higher nitrate concentrations needs to be oxygenated inside the biofilter. The treated nutrient-enriched water is then channelized through hydroponic units, which may be of DWC, NFT, ebb-flow, aeroponics, or combination of various subsystems. This semi-commercial system may be of coupled or decoupled with additional drip irrigation (Raviv and Lieth 2008) facility, and the design can be modified as per the specificity of the location and site. For smart farming with higher plant output, technologies such as CO_2 greenhouse enrichment (environmental control), potent water monitoring tools, power backup systems, efficient solids removal and biofiltration devices, biosecurity, and pest management including waste and sludge management systems are needed with alternative energy supplies.

In large-scale aquaponics, utmost yield of fish and plants can be obtained with effective management, using fully mechanized appliances and even computer-based facilities for the monitoring of water quality parameters. The fish and plants are chosen judiciously for better productivity within a confined area. In addition to the fish and plant selection, the stocking rate of fish and planting interval including the type of hydroponic system to be used are well taken care of. The system requires high investment cost with high degree of power consumption and, hence, generally operated with alternate energy sources. For better control of the climatic conditions, especially when cold thermal Himalayan belts are in target, these units are generally installed within the polyhouses or greenhouses with water heating appliances and the produce mainly targeted for indirect markets such as grocery stores, hotels, and wholesalers including private and government organizations like colleges, universities, etc. (Love et al. 2015). The system is generally equipped with multiple rearing units, rearing fish of different age or size groups, and staggered harvesting principles for both fish and plants are followed not only to maximize the production but also to get better price as per the market demand (Rakocy et al. 2006; Rakocy 2012). For a highly engineered system, special units such as cold traps, biogas, and photovoltaic systems may be arranged for better sustainability, particularly for temperate climates (Kloas et al. 2012). To maximize the plant output in large-scale aquaponics, intercropping method may be adopted with short-cycle plants like herbs, leafy vegetables, salad greens, etc. in addition to year-round producers like mint, basil, or other woody herbs with the latter bearing the advantage to be regrown by cutting at regular period of time (Rakocy 2012). The addition of biodigester unit or anaerobic nutrient remineralization component (ANRC) with an upflow anaerobic sludge blanket (UASB) reactor following the removal of sludge improves the water quality of the system (Goddek et al. 2016; Junge et al. 2017). The system generally does not encourage the cultivation of plants with media bed due to the need for higher degree of management, but the disease of both fish and plants can be managed better by adopting decoupling principle in large-scale systems.

In decoupled system, the fish culture and hydroponic components are physically disconnected from each other (Thorarinsdottir et al. 2015) for better control on nutrient supplementation, disease management, and water quality parameters. As the main focus of these kinds of systems is horticulture with higher rate of production (Delaide et al. 2016), hence, proper nutrient management can be achieved by not circulating the fish tank wastewater to all the components, rather may be channelized through plant production units after optimal supplementation with hydroponic fertilizing solutions specific to the plants under cultivation. Large-scale decoupled models are generally highly mechanized setups with multi-loop operation using a number of water pumps. In addition, as the system literally comprised of two subunits, hence, maintenance of optimal water quality in two subsystems definitely needs higher rate of investments.

23.4 Prospects and Challenges

The type and stocking rate of fish are the prime decisive factors for the growth and well-being of cultivated plants in any kind of aquaponics. Among the wide varieties of fish and plants sorted out for aquaponic farming, a fruitful combination of cold tolerant compatible farming materials may be selected for optimal output in low thermal Himalayan expanses. The better plant performance will be achieved when the selected fish have better dietary consumption rate, and also their waste is enriched with fair amount of plant growth nutrients. For example, low and high nutrient demand plants with less or more planting density may be chosen accordingly for respective carp and trout aquaponics. The nutrient requirement by the plants or in other words the effluent/nutrient removal from the system will depend on the type of plants under cultivation and its growth stages, i.e., the better the plant growth, the better will be the nutrient removal. Among some of the leafy greens advocated for cold-water Himalayan aquaponics, lettuce claims better efficiency in maintaining optimal water quality as it bears the capacity of utilizing ammonia nitrogen directly from the system. The cold-water aquaponic system with trout as a fish component can promote the farming of wide varieties of salad vegetables and medicinal plants. However, among various types and designs of aquaponic systems, the performance of DWC/raft system is quite impressive in cold thermal areas as it keeps the total suspended solids (TSS) in acceptable level by removing soluble nitrogen even at low concentrations.

On the other hand, the intensive production of fish and plants, particularly in cold climatic areas, will certainly attract some of the disease or deficiency symptoms in cultivated species, which should be addressed with organic agents (rather than chemical means) so as to avoid any harmful impact on the system environment. For small-scale production, indigenous solid separator with multifunctional biofilter-cum-media bed unit may be installed to cut short the space including investment cost for a DIY domestic cold-water aquaponics in particular. As one among the active farming techniques, the aquaponic system to be installed in remote terrains of temperate uplands needs continuous energy supply and, hence, may be operated with minimal mechanical equipment with power backup to avoid system collapse. Plant-based waste utilization/removal systems are principally based on the principle of "waste to wealth," i.e., compensate treatment expenditure, along with the provision of extra income for the marginal hill growers as well. Unlike soil farming, the health and growth of the plants are better in aquaponics because of the efficient water flow across plant roots for mass transfer of nutrients along with the omission of unwanted weeds and soil-borne diseases. These kinds of modern scientific natural farming systems are best suitable for small land holding hill farmers of Himalayas, including vertical and urban rooftop farming, but need proper technical know-how for its design, fabrication, and operation.

In order to extract optimal benefit from a cold-water aquaponic system, it may be designed and fabricated scientifically using efficient substrate media with better surface area for effective nutrient transformation to keep away from any kind of plant diseases/symptoms like chlorosis, rotting, leaf burn, drying, etc. The parameters, especially the macro- and micronutrients may be checked regularly and supplied with organic supplements, if needed. Among several water quality parameters, dissolved oxygen is one of the most critical parameters that determine the output of the system in terms of fish and plant biomass, and hence, its supplementation into water may be done through venture and airlift means besides the main aeration/oxygenation system. In DWC or raft aquaponics, most of the plants (transplanted plantlets/saplings) show drying symptoms during their early growth stages as shorter plant root fails to assess the underlying water, and hence, wick/cotton thread may be provided in each plant net pot for their better survival and growth. The NFT (nutrient film technique) is one of the most successful methods for soil-less plant cultivation, but plant selection including the height and diameter of NFT channel is vital for its success. For aquaponic farming in cold-water Himalayas, the NFT is one of the most suitable methods as the temperature of the channel water can be controlled in a better way with customized adjustments and is much efficient for the cultivation of leafy greens, but the system may not be as competent in growing root vegetables, including larger fruiting plants.

23.5 Conclusion

In order to get better yield from any of the aquaponic systems, the staggered/partial/multiple harvesting principle may be opted both for fish and plants, while periodic harvesting with restocking strategy shall be practiced for fish, especially in cold thermal Himalayan region. Climate control indoor setups like greenhouse or polyhouse with the provision for lighting and heating may be installed in temperate areas (northern hemisphere) for year-round production of diverse crop varieties (Knaus and Palm 2017a, b). The recirculation aquaponic system could be a fruitful model for better productivity within a limited space, especially in the upland terrains of Indian Himalayas, rooftops, and urban area farming, but the fish-plant combination, their cultivation area proportion, and the quality and sizing of the biofilter are needed to be standardized. New form of technologies may be researched and adopted in this line with efficient effluent removal, nutrient availability, and disease or pest control potential for better growth and well-being of cultivated varieties.

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Farm Design and Layout for Aquaculture Operations in the Temperate Himalayas

24

Ajit Kumar Verma and Chandrakant Mallikarjun Hittinahalli

Abstract

The success of an aquaculture project mainly depends on the fish farm layout plan and design. A well-designed and constructed aquafarm is a foundation for successful aquaculture operations and eventually for high fish production from a given area. There are basically three types of aquaculture farming systems: extensive, semi-intensive, and intensive. Streams, springs, lakes, rivers, reservoirs, and groundwater are some of the important water sources for inland aquaculture. Based on the sources of water and their dependability, aquafarms in the Himalayan region can be classified as spring water ponds, seepage ponds, bore-well and open-well water-fed ponds, rainwater-fed ponds, neighboring water body-fed ponds, gravity flow, and pump-fed ponds. Design of dikes, berm, slope, side slope, free board, allowance for wave action, flood allowance, settlement allowance, pond size, pond shape, etc. are important design parameters. This chapter provides a brief overview of different types of fish farms, layout planning for a fish farm, design, and construction of dikes and fish ponds in inland and in the Himalayan regions.

Keywords

Aquafarm · Construction · Dike · Ponds · Side slope · Water supply

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24.1 Introduction

Fish is an important component for fulfilling the human population's diet, and the fish caught worldwide is insufficient to meet the needs of the people (Merino et al. 2012; Jennings et al. 2016). There is tremendous pressure to enhance fish production in inland areas by using inland ground water or inland poor-quality water (Verma et al. 2010, 2014; Patel et al. 2022). For fish culture, it is essential to construct a well-designed fish farm (Ngugi et al. 2007). Fish farming can be done in the backyard as well as in a large-scale industrial pattern. For successful aquaculture practices, the first and foremost step is to make a proper layout plan with well-designed facilities so that an economical aquafarm can be constructed at a given site (Carballo et al. 2008). Fish farmers should take all necessary steps for high production, which is economically positive (Verma and Chandrakant 2017). Thus, it is very imperative to raise awareness among the fish farmers and entrepreneurs about the importance of preparing an appropriate layout plan and design of various components and facilities of a fish farm before commencing the construction.

24.2 Types of Fish Farming

Based on the stocking density of fish, inputs provided during the culture, facilities, and targeted level of fish production, there are three methods of fish farming: extensive, semi-intensive, and intensive (Baluyut 1989; Carballo et al. 2008).

Extensive system: In an extensive system, fish production is low in comparison to semi-intensive and intensive farming systems, as fish production mainly depends on natural food production in pond ecosystem. The input costs are usually low in this system. However, fertilizers may be used to increase the system's fertility and fish production.

Semi-intensive system: In a semi-intensive system, fish production is higher than in an extensive farming system due to supplementary feed and application of fertilizers. Aquaculture practices in a semi-intensive system require a well-designed farm layout and facilities for regular water exchange.

Intensive system: In an intensive farming system, owing to high stocking density; regular water exchange; round-the-clock aeration; better feed management; constant monitoring of water quality, health, and growth parameters; and constant supervision, fish production is higher compared to extensive and semi-intensive systems. Fish production in this system is entirely dependent on supplementary feeds. Due to high stocking density, management issues may arise. Further, there is an increased risk of decline in dissolved oxygen levels and increased susceptibility to diseases. High input costs force one to get a high market rate so that fish farming can be economically viable.

24.3 Layout Planning for a Fish Farm

The following factors are considered while planning the layout of a fish farm.

24.3.1 Land Area

- Land area (where a fish farm is to be constructed) prone to floods should be avoided. Information pertaining to the intensity of rainfall, surface runoff, floods in recent years, and land sliding are to be obtained from the nearest government department (meteorological department) and local residents for actual evidence.
- The site proposed for the construction of a fish farm should be free from pollution. Information regarding use of fertilizers, chemicals, and pesticides in the vicinity of the proposed site need to be obtained from the neighborhood farmers and local people (Saha and Gopalkrishnan 1975).
- The site is considered good if the land is at a low level than the water source so that the water can be drawn into the fish farm and supplied to different ponds under gravity; thus, pumping costs can be saved.
- Neighboring areas and any causes of concern should be assessed before considering the development plans.
- In general, a steep slope of the land is not suitable for construction of fish ponds. The land having a slope of about 1–2% can be considered for construction of an aquafarm (Bhakat 2018).

24.3.2 Water Supply

- Streams, springs, lakes, rivers, reservoirs, and groundwater (wells, aquifers) are the most common sources of water for inland aquaculture.
- Adequate quantity of good quality water should be available for fish production throughout the culture period.
- There should not be much seasonal change in the water quality parameters.
- Site selection can be finalized after ensuring the availability of quality water in adequate quantity throughout the culture period.
- Culturing cold-water fish (trout) needs huge quantity of water as they need a continuous supply of clean water with high dissolved oxygen concentrations.
- Tilapia (warm water species) can be cultured in static water with low dissolved oxygen levels.
- Need two to three times more water if the selected site has too much sandy soil stratum. The site having sand content more than 30% is not considered for fish farming as such sites leads to seepage.

24.3.3 Soil

- Land should be free from gravel or rocks.
- Good-quality soil should be available at least up to 1 m below the ground surface.
- To prevent seepage loss, clay layers of soil should be available in the site proposed for construction of an aqua farm.
- For building impervious dikes, the soil must contain a minimum of 20% clay diameter, below 0.002 mm (Lekang 2007).
- Higher clay content (up to 40%) should be available in the vicinity of proposed site, which can be used for packing core trenches in the dikes.
- Coefficient of permeability (K) should not be more than 5×10^{-6} m/s (Coche et al. 1992).

24.3.4 Proximity to a Market

- Existing physical infrastructure should meet the farmers' needs for marketing the fish.
- Sufficient demand for fish is needed.
- It would be better if the product could be sold out at farmers' doorstep or have a permanent buyer who can buy all the produce.

24.3.5 Availability of Infrastructure

- Roads should be good enough for bringing supplies (i.e., seed, feed, fertilizer, etc.) to the farm and selling the product to the market.
- Power supply should be available.
- Telephone/mobile connectivity is required for contacting suppliers, marketing, and technical assistance.
- Availability of needed inputs.
- Seed of fish should be available at a reasonable cost.
- Fish feeds and other required ingredients should be easily available in the vicinity of the location of fish farm.

24.3.6 Access to Technical Advice

- For any successful project, the technical guidance is very much essential. Therefore, a technical person who can provide technical guidance should be readily available in the nearby area.

24.3.7 Legal Issues

Legal issues can affect the entire fish farming project plan. Hence, one should have thorough knowledge of the following Acts and issues before starting the project:

- Water Act.
- Land Use Act.
- Environmental management.
- Other related acts like electricity, use of public water, coordination, etc.

24.4 Layout Planning of an Aquafarm

Land topography, water source, and drainage are very important aspects to be considered for preparation of layout plan of the fish farm and other farm facilities. It is better if there is a scope for expansion of the fish farm in the future. In such situation, the underground pipes for drainage, water supply, and other facilities may be laid out so that additional ponds, if required at a later stage, can be easily constructed (Lawson 1995). A well-designed and constructed pond is easier for operation and maintenance without affecting the environment.

24.4.1 Factors Influencing the Design of an Aquafarm

Layout planning is a process of distribution of total area of an aquafarm for construction of different types of ponds and facilities. Distribution of fish farm area mainly depends upon the purpose for which the farm is being constructed. Topographical features play a vital role in the design and orientation of various farm facilities, viz., ponds, dike, feeder canal, drainage canal, inlets, outlets, etc. Important points to be considered while designing an aquafarm and fish ponds are narrated below:

- The direction of the prevailing wind in the locality is one of the important considerations in orientation of farm facilities. In case of rectangular ponds, the longer side should be aligned parallel to the direction of predominant winds to maximize the dissolved oxygen concentration through diffusion. The winds help in increasing the turbulence of the water surface, which in turn increase the intensity of diffusion leading to increased aeration.
- The source of water should be located at a higher elevation to have gravitational flow pattern. The source of water should be well protected against floods, waves, cyclones, etc.
- In order to have smooth flow of water in feeder channels, the water distribution system should be short and straight and free from bends.

- The dikes and channels should be designed and constructed in accordance with the slope of the ground so as to have water distribution system to supply water under gravity.
- In order to avoid the discharge of used water back into the water intake system, especially in the river water intake system, the pond outlets should be located on the downstream side of the water intake system.
- The design and orientation of various farm facilities should be done so as to allow complete drainage of pond water for drying of the pond bottom.
- Freshwater sources should be located at sufficient distance from saline or brackish water sources to avoid salinization of freshwater resources due to the mixing of the large volume of seawater.
- The pond size should be manageable, as large ponds often pose problems in smooth operation and maintenance of ponds.
- The pond bottom should be smooth with sufficient slope for quick and complete discharge of water. It should be remembered that too much slope leads to erosion of the pond bottom and creation of cavities or depressions on the pond bottom. The harvesting will not be efficient and complete if depressions are formed on the pond bottom where fish take shelter during the process of harvesting.
- The central platform and peripheral trenches (not more than 20% of the total productive area) in shrimp ponds provide shelter during high temperatures. The bottom of the trench should be designated to facilitate complete drainage of water for the purpose of drying of ponds.

24.5 Design of Fish Ponds

- Fish ponds are designed and constructed to retain required volume of water for facilitating culture of desired species. Design of a fish farm is an art of building an environment-friendly ecosystem, taking advantage of the natural conditions and topographical features prevailing at the site. Design of a fish pond mainly depends upon the purpose of its construction and culture technology. The following factors influence the design and construction of fish farms:
  - Topographical features
  - Type and quality of soil
  - Water resources
  - Species to be cultured
  - Targeted production level
  - Type of water distribution and drainage system
  - Method of harvesting
  - Individual size of ponds
  - Fish culture techniques
  - Management practices

The design of fish pond depends upon the following aspects:

- Utility of pond (nursery, rearing, stocking, grow-out, etc.)
- Species to be cultured
- Water distribution system
- Culture technique (i.e., extensive, semi-intensive, intensive, etc.)
- Level of management
- Harvesting techniques

24.6 Fish Pond Design Parameters

24.6.1 Size

The size of a fish pond should be in accordance with the targeted production level and marketing strategies. Ponds should be easy to construct and economical for maintenance. From a management point of view, small ponds are better; however, the dikes and drainage ditches occupy more area, leading to wastage of productive land. Large ponds are economical (as the area occupied by dikes will be less); however, very large ponds are difficult to manage (Verma and Chandrakant 2017).

24.6.2 Shape

Earthen fish ponds are generally constructed in rectangular and square shape. It is difficult to construct circular earthen ponds as it becomes difficult to retain its shape. However, circular ponds can be constructed using strong and solid materials like concrete, stones, bricks, FRP, ferro-cement, etc. The circular tanks or ponds are generally used in hatchery, nursery management systems, and intensive culture systems. The following factors influence while deciding the shape of a fish pond:

- Site conditions
- Harvesting technique
- Cost of construction
- Aeration requirement
- Construction material

Earlier, the width of a fish pond was decided in accordance with the width of the fishnet used for harvesting. Generally, pond width is not more than 100 m if harvesting is done by netting. However, at places where harvesting is done by total dewatering, the shape of the pond is decided, taking into consideration the practical feasibility and site conditions. For a given area, square-shaped ponds prove to be economical, as the perimeter is minimum in a square-shaped pond when compared to a rectangular pond of the same area. For rectangular ponds, the ideal ratio of length and breadth is 1.5–2:1 (length/breadth).

In rectangular ponds, the longer side of the pond is designated parallel to the direction of predominant winds to maximize aeration. However, at locations of high wind velocities, soil erosion may take place. Therefore, at places where wind velocities are very high, the longer side should be kept perpendicular to the direction of the predominant wind to reduce soil erosion.

The corners of rectangular ponds are made round to avoid formation of the dead zone where uneaten feed, fecal matter, and other metabolic wastes of fish accumulate. Further, round corners facilitate smooth circulation of water.

Square ponds are economical with a high ratio of water area to the length of a dike. Square ponds are the best choice in places where there are no restrictions of property lines and topographical features and harvesting is done by total dewatering.

Round tanks are generally used in hatcheries for nursery and rearing activities. Compared to all other shapes, the water flow pattern is excellent in circular tanks.

24.6.3 Depth

The following factors influence in deciding the depth of fish ponds:

- Species to be cultured
- Culture techniques (mono-, polyculture, etc.)
- Slope of the ground
- Source of water
- Climatic conditions

The depth requirement of some important species is as follows (Verma and Chandrakant 2017):

Indian major carps, trout: 1.2–2.0 m
Catfish: 0.9–1.5 m
Shrimps: 0.75–0.9 m
Freshwater prawn: 0.75–1.0 m
Crawfish: 0.5–0.6 m

Shallow ponds are easier to manage but get too hot and enhance the production of rooted aquatic plants and impede seining. Deeper ponds are difficult to manage. At places where water availability is seasonal, deep ponds are ideal for storing more water during the rainy season; however, harvesting is difficult in deeper ponds.

Due to a suitable temperature regime and dilution of metabolic wastes released by aquatic animals, yields are generally high in deeper ponds.

24.6.4 Pond Bottom

For efficient harvesting and quick discharge of water, the bottom slope (i.e., pond bed slope) should be designed carefully. A minimum bottom slope of 0.1–0.2% is sufficient (Coche et al. 1992). Steep slope may lead to formation of depressions on the pond bottom where the culture species take shelter during the process of harvesting. To the extent possible, the outlet of a fish pond should be constructed in the deepest part of the pond. From all parts of the ponds, the bed slope should be aligned toward the pond outlet to ensure smooth and quick discharge of water. Steep slope in small ponds and gentle slope in large ponds may result in a wide range of water depths throughout the pond, which will lead to an undesirable thermal and chemical stratification in deeper water areas and aquatic plants on the bottom of the shallow regions.

24.7 Types of Ponds

Basically, there are three types of ponds.

24.7.1 Watershed Ponds

Watershed ponds are also known as embankment or hill ponds. Watershed ponds are constructed by raising bund around a natural water course. The main source of water for these ponds is rainfall and surface runoff. No separate water inlet or outlet is constructed in watershed ponds. These ponds are used for traditional cultural systems and fee fishing. Watershed ponds are not suitable for commercial aquaculture due to lack of facilities for regular water exchange. Harvesting is done by total dewatering.

24.7.2 Excavated Ponds

Excavated ponds are constructed by excavating earth from swampy or low-lying areas. These ponds are generally undrainable ponds. Like watershed ponds, these ponds are also not used for commercial aquaculture, as no facilities are available for regular water exchange.

24.7.3 Levee Ponds

These ponds are also known as cut and fill ponds. Levee ponds are constructed scientifically with proper design and layout plan for culture of specific aquatic species. These ponds are constructed partly by excavation and partly by raising the dike with the excavated earth. Levee ponds are ideal for commercial fish farming. The facilities required for regular water exchange like inlet, outlet, monk, drainage channel, etc. are provided in levee ponds. For economy, excavation from ground level should not be more than 50% of the total depth of pond.

24.8 Ponds of the Himalayan Region

Based on various considerations, listed below, the Himalayan ponds are classified into various groups.

24.8.1 Based on Source of Water

24.8.1.1 Groundwater-Fed Ponds

Spring water ponds: Spring water ponds are very common in hilly areas where springs with assured quantity of water are available. Spring water is supplied under gravity either directly into the pond or in nearby areas. Spring is a dependable source of water; however, its yield should be assessed before starting pond construction. The quantity of water from springs may vary throughout the year, but the quality remains constant and is usually better than the surface waters.

Seepage ponds: Water in these ponds are supplied from a water table by seepage. The water level in seepage ponds varies with the water table. One cannot depend upon seepage water for commercial aquaculture.

24.8.1.2 Bore-Well and Open-Well Water-Fed Ponds

Bore well and open wells are dependable sources of water supply for commercial aquaculture.

24.8.1.3 Rainwater-Fed Ponds

Rain and surface runoff are the main sources of water for these ponds. No water is supplied during dry seasons. These ponds are small depressions in impermeable soil with a dike built on the lower side. Basically, rain-fed ponds are watershed ponds (village ponds) and not suitable for commercial fish farming due to lack of water exchange structures and other required facilities.

24.8.1.4 Neighboring Water Body-Fed Pond

Gravity flow: Water in these ponds is supplied from nearby water bodies like streams, rivers, reservoirs, lakes, and irrigation canals under gravity (water source is at higher elevation). It can be fed either directly (into the ponds) or indirectly through a supply canal. Water control devices are to be constructed for regulation of water supply into canals and ponds.

Pump-fed ponds: Source of water is neighboring water body. These ponds are constructed at places where pond level is higher than the source of water. Since water supply under gravitational flow system is not feasible, pumps are used for supply of water to different ponds.

24.8.2 Based on Methods of Draining

Based on the method of draining, the ponds are classified as follows:

Drainable ponds: The bottom of the drainable pond is located at a higher elevation than the point where water is to be drained. Depending upon the location, drainable ponds could be either gravity draining or pump draining type. These ponds are usually fed by surface runoff, streams, etc.

Undrainable ponds: Undrainable ponds cannot be drained by gravity. Generally, the source of water is groundwater or surface runoff. The elevation of the surrounding area is higher than the pond bottom. Hence, gravity draining is not possible. Their origin may be either swampy area (groundwater is source) or ponds dug in the ground having clay, sand, gravel, etc.

24.8.3 Based on Construction Material

Based on the materials used for construction, the ponds are classified as follows:

Earthen ponds: Earthen ponds are constructed with good-quality soil/earth. Earthen ponds are the most used unit for fish production worldwide. More than 40% of the world's aquaculture production is performed in earthen ponds.

Walled ponds: At places where good earth is not available, ponds are created by constructing partition walls. The walls are constructed with variety of materials like brick, stone, concrete blocks, etc. Generally, small nursery ponds are constructed with bricks or concrete.

Lined ponds: Lined ponds are generally earthen ponds with PVC or plastic lining done on slopes and bottom. Impervious materials like rubber, plastic, stone slab, concrete slab, etc. can be used as a lining material.

24.8.4 Based on Construction Method

Based on the method of construction, the ponds are classified as follows:

Dugout: Also known as excavated ponds, these ponds are constructed by excavating soil and are filled with groundwater, surface runoff, rainfall, etc. Generally, these ponds are undrainable by gravity, and not suitable for higher technology farming systems.

Embankment ponds: These ponds are also known as watershed ponds and are constructed by building a dike around a watercourse or a low-lying area. These ponds are filled by rainwater, surface runoff, and other groundwater resources and are usually drainable and fed by gravity or pumping.

Cut and fill ponds: These ponds are scientifically constructed ponds. Construction of these ponds is done partly by excavation and partly by raising the dike. The excavated earth is used for raising the dikes. Good design is one where the cut is equal to fill. Such ponds are economically viable. These ponds are fed by gravity or pumping and are drainable. These ponds are suitable for semi-intensive and intensive culture systems as all required facilities are available in these ponds.

24.8.5 Based on Landscaping Features

Based on the features of the landscaping, the ponds are classified as follows:

Sunken ponds: Sunken ponds are similar to dugout ponds and are undrainable. The pond floor level is generally below the level of the surrounding land. These ponds are directly fed by rainwater, surface runoff, and groundwater. They can be built as dugout ponds or to utilize the depression in the ground, or sometimes even additional dikes are constructed to increase the water depth.

Barrage ponds: Barrage ponds are created by constructing a barrage or dam across the lower end of the bottom of a valley. These ponds are drainable. In flood-prone areas, a diversion canal is constructed on the side of the barrage pond to dispose of excess water. The diversion canals are provided with water control or intake gate (sluice) to regulate the flow of water. The source of water may be spring, stream, or reservoir. The barrage ponds are provided with inlet and the outlet. Spillways are constructed to safeguard the barrage/dams.

Diversion ponds: Diversion ponds are basically earthen ponds constructed either on plain ground or sloping ground in accordance with the topography of the land. Water is supplied to these ponds from a diversion canal (which acts as a feeder canal) of spring, stream, river, reservoir, lake, etc. under gravity or by pumping (as per the site conditions). The water flow is controlled through regulators (i.e., sluices), inlets, and outlets. These ponds are generally drainable. The diversion ponds can be constructed on sloping ground as cut and fill-type pond or on a flat ground.

24.8.6 Based on Usage of Fish Ponds

Based on the utility or function, the ponds are classified as follows:

1. Spawning pond (for the production of eggs and small fry)
2. Nursery pond (for the production of larger juveniles/fingerlings)
3. Rearing pond (for the rearing of fingerlings)
4. Grow-out pond (for the rearing of fingerlings/yearlings to marketable size)
5. Storage pond (for holding fish temporarily, often prior to marketing)
6. Brooder pond (for the rearing of brood stock)
7. Fattening pond (for the production of food fish)
8. Wintering pond (holding fish during cold season; covered with poly-film as in the case of a poly-house)
9. Quarantine pond (for keeping infected fish)
10. Integrated pond (ponds which have crops, animals, or other fish ponds around them to supply waste materials to the pond as feed or fertilizer)

24.9 Design and Construction of Dike

Dike is a trapezoidal-shaped earthen structure constructed along the boundary of an aquafarm; sides of feeder and drainage canal; and in between the ponds for various purposes.

Based on the purpose of construction, the dikes are classified as follows:

- Primary dike
- Secondary dike
- Tertiary dike

24.9.1 Primary Dike

The primary dike, which is also known as the main dike or peripheral dike, is constructed along the boundary or periphery of the fish farm to protect the farm from floods and storm surges. The height of primary dike should be kept above the high flood level (HFL) of the locality to prevent the entry of flood water into the fish farm. For design of primary dike, knowledge of environmental factors like rainfall, surface runoff, HFL, etc. is essentially required.

24.9.2 Secondary Dike

The secondary dike is constructed by the sides of the feeder and drainage channels. The design process of the secondary dike is similar to that of the primary dike. The depth of flow in the water channel is an important factor considered in designing the height of the secondary dike. The secondary dike provides much required stability to the feeder or drainage channel for smooth passage of water.

24.9.3 Tertiary Dike

The tertiary dike which is also known as partition dike is constructed in between the ponds to prevent the interplay of water from one pond to the other. The top of the dike, which is also known as crest (Fig. 24.1), acts as a roadway for the movement of men and materials for supply of feed and fertilizers; monitoring water quality and health of fish; and ease in harvesting.

The top width of the dike is also known as crest and is normally denoted by letter "B". The overall height of the dike is a function of high flood level (HFL) of the locality, water level to be maintained in ponds, depth of flow of water in feeder channels, freeboard, settlement allowance, fetch of the wave, wave up-rush, flood allowance, etc. The top width (i.e., crest) depends upon the type of vehicular load expected on the dike. The side slope, which is expressed as the ratio of horizontal to

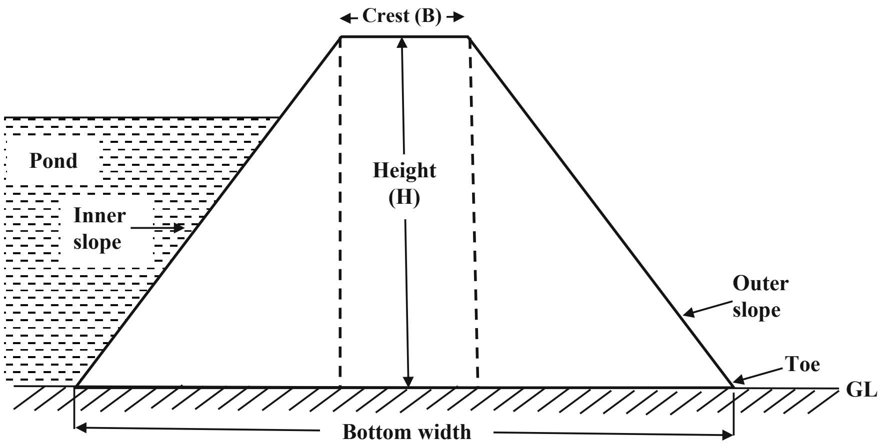

Fig. 24.1 Cross-sectional view of a dike

vertical side (H:V), mainly depends upon the type of soil used for construction of the dike.

24.9.4 Design of Dike

Design of a dike depends upon various factors, viz., the purpose of construction, water level to be maintained in ponds, type of soil, vehicular load expected on crest, topographical features of the site, method of construction, etc. The important design parameters of a dike are:

- Height
- Crest (top width)
- Side slope

24.9.4.1 Height

The overall height of a dike mainly depends upon the purpose for which the dike is constructed. The high flood level of the locality (HFL) is the most important consideration in designing a primary dike as the main function of a primary dike is to protect the aquafarm against floods. Hence, the data pertaining to floods which occurred in the past 15–20 years should be collected.

The depth of flow of water is considered in finalizing the height of a secondary dike. In order to design a tertiary dike (i.e., partition dike), the water level (i.e., storage level) to be maintained in the ponds is taken into consideration. While calculating the height of a dike, the following factors are to be taken into consideration.

24.9.4.2 Free Board (FB)

The free board can be defined as the vertical distance between the crest after settlement and the designed maximum water level of the pond. The free board acts as a factor of safety against overtopping of a dike. Generally, a free board of 0.6 m is considered in designing a periphery dike and 0.3 m for secondary and tertiary dikes.

24.9.4.3 Allowance for Wave Action (Hwa)

Erosion of dike takes place due to strong winds and waves. Therefore, allowance for wave action (Hwa) is taken into consideration while fixing the height of a dike. The allowance for wave action is calculated by using the following equation:

$$\mathrm{Hwa} = 0.014\ (\mathrm{F})^{1/2}$$

where Hwa = Allowance for wave action, F = Fetch of the wave.

24.9.4.4 Flood Allowance (Hf)

In flood-prone areas, due to frequent floods, the height of a dike gets reduced over a period of time. Hence, a provision for flood allowance should be made in the design of height for flood allowance so that the designed height of the dike remains unaffected for at least 15 years after the construction of the dike.

24.9.4.5 Settlement Allowance

Settlement allowance is also known as shrinkage allowance. Due to self-weight of the dike and vertical loads (like vehicular load) acting on the dike, poor soils settle after construction of the dike. Hence, a provision for settlement allowance should be made in the design of height. The amount of settlement depends upon the type of soil available at the site, method of construction, the optimum moisture content (OMC) at the time of compaction, etc. (Pillay and Kutty 2005).

24.9.4.6 Calculation of Height of the Dike

Considering the HFL of the locality, free board, flood allowance, settlement allowance, etc., the height of a dike can be calculated (Fig. 24.2) using the following equation (Verma and Chandrakant 2017):

$$\mathrm{Hm} = (\mathrm{HFL} + \mathrm{FB} + \mathrm{Hf} + \mathrm{Hwa}) / \{1 - (\%\mathrm{S}/100)\}$$

where:

Hm = maximum height of a dike
HFL = high flood level of the locality
Hf = flood allowance
Hwa = allowance for wave action
%S = settlement allowance

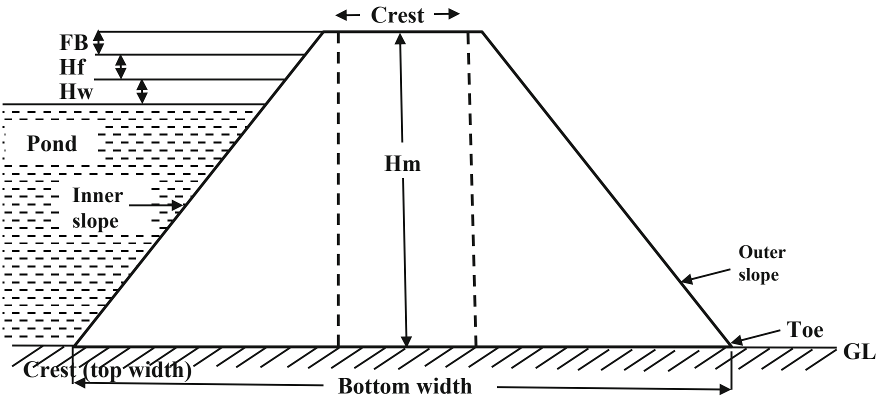

Fig. 24.2 Height of a dike, comprising different components

Table 24.1 Different types of vehicular load

Sr. no.	Type of vehicle	Top width (m)
1	Low vehicular load (cars, jeep, etc.)	3.0–4.0
2	Medium vehicular load (tractor, dumper, etc.)	3.5–4.5
3	Heavy vehicular load (trucks, bus, etc.)	4.0–5.0

Table 24.2 Soil conservation service recommendations for the minimum width of the dike

Sr. no.	Height of dike (m)	Top width (m)
1	Under 3.0	2.4
2	3.0–4.5	3.0
3	4.5–6.0	3.7
4	6.0–7.5	4.3

24.9.5 Crest (Top Width)

The top width of a dike mainly depends upon the type of vehicular load expected on the crest. The value of the top width for different types of vehicular load is given in Table 24.1 (Bhakat 2018).

The top width can also be calculated by using Frevert's equation given below:

$$B = 1.1\ (H)^{1/2} + 0.91$$

where:

B = top width (crest)

H = height of dike

Soil conservation service recommendations for the minimum width of the dike are given in Table 24.2 (Coche et al. 1992).

24.9.6 Side Slope

For an earthen dike, side slope is essentially required for stability. The side slope depends upon the type and quality of soil (Table 24.3). The flatter the slope, the more stable is the dike. However, it should be remembered that a flat slope involves huge quantity of earthwork. At places where good soils are available, from a construction and management point of view, the ideal slope is 1.5:1–2:1 (H:V) (Coche et al. 1992).

24.9.7 Berm

Berm is a step-like structure constructed in between the crest and toe (Fig. 24.3) to protect the slope of the dike against soil erosion due to surface runoff. Berms are constructed at places where surface runoff is more. Berms act like barriers to prevent the direct flow of surface runoff into the ponds. Berms act like a platform in between the crest and toe and thus help in netting, inspection of water quality, monitoring of the health and growth of fish, etc.

Table 24.3 Different types of soil and their optimum slope ratio

Sr. no.	Type of soil	Side slope (H:V)
1	Clayey soil	1:1
2	Loamy soil	1.5:1
3	Sandy sol	2:1
4	Homogenous with graded soil	2:1
5	Homogenous coarse silts	2.5:1
6	Homogenous clay	2:1
7	Loamy soil	2.5:1

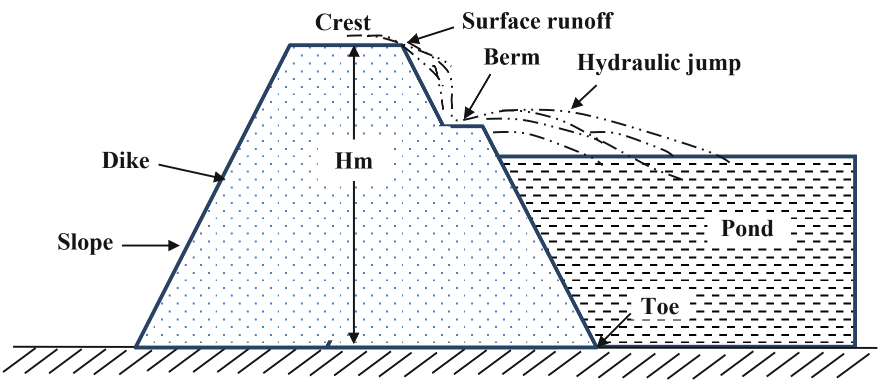

Fig. 24.3 Cross-sectional view of a dike showing berm

24.9.8 Calculation of Cost of Construction

An embankment has to be constructed around a fish pond as per the dimensions given below:

1. Top width = 2.0 m
2. Outer slope = 2.5:1 (H:V)
3. Inner slope = 1.5:1
4. Height = 2.5 m
5. Overall length = 500 m
6. Packing coefficient = 12%
7. Rate of earthwork in the locality = Rs. 150/m^3

Calculate the cost of construction, and draw the plan and cross-sectional views also.

24.9.9 Solution

Since inner and outer slopes are different, the cross-sectional area is calculated by dividing into three geometrical shapes as shown in Fig. 24.4.

Let A_1, A_2, and A_3 be three components of the dike

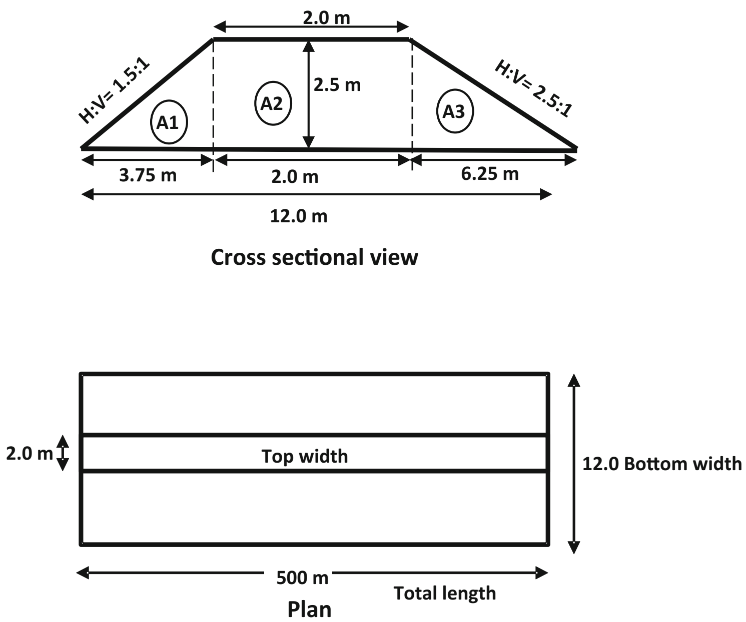

Fig. 24.4 Calculation of the cross-sectional area of a dike

so that $A = A_1 + A_2 + A_3$
(a) A_1 = area of the first triangle:

$$A_1 = 1/2 \text{ base} \times \text{height} = 1/2 \times 3.75 \times 2.50 = 4.69 \ \text{m}^2$$

(b) A_2 = area of rectangle:

$$A_2 = 1 \times b = 2.0 \times 2.5 = 5.0 \ \text{m}^2$$

(c) A_3 = area of second triangle:

$$A_3 = 1/2 \text{ base} \times \text{height} = 1/2 \times 6.25 \times 2.5 = 7.81 \ \text{m}^2$$

Total area:

$$\begin{aligned} A &= A_1 + A_2 + A_3 \\ &= 4.69 + 5.00 + 7.81 = 17.50 \ \text{m}^3 \\ Q_{th} &= L \times A = 500 \times 17.50 = 8750 \ \text{m}^3 \end{aligned}$$

Since Q_{pc} = 12 % of Q_{th} = (12/100) × 8750 = 1050 m^3

$$Q_{act} = Q_{th} + Q_{pc} = 8750 + 1050 = 9800 \ \text{m}^3$$

Cost of construction = Quantity of earthwork × Rate.

$$= 9800 \times \text{Rs.}150 = \text{Rs.}1{,}470{,}000.00$$

The cost of construction of the dike as per given data is Rs. 1,470,000.00 (approx. US$ 18,375).

24.10 Conclusion

Since ancient time, traditional aquaculture has been practiced in earthen fish ponds. Although considerable advancements were made in the last two decades in terms of pond design and construction, the basic concept of fish farm design has not changed much. Selection of an appropriate site is the first and foremost step in successful and profitable aquaculture venture. Consequent to selecting site and completing engineering surveys to gather requisite data for establishing an aquafarm, layout planning (Fig. 24.5) and design of fish ponds and other support facilities assume significant importance. The ultimate success of aquafarming mainly depends upon the best utilization of available area and preparation of a layout plan, taking advantage of natural and environmental conditions prevailing at the site. The construction and maintenance of an aquafarm become easier and economical if

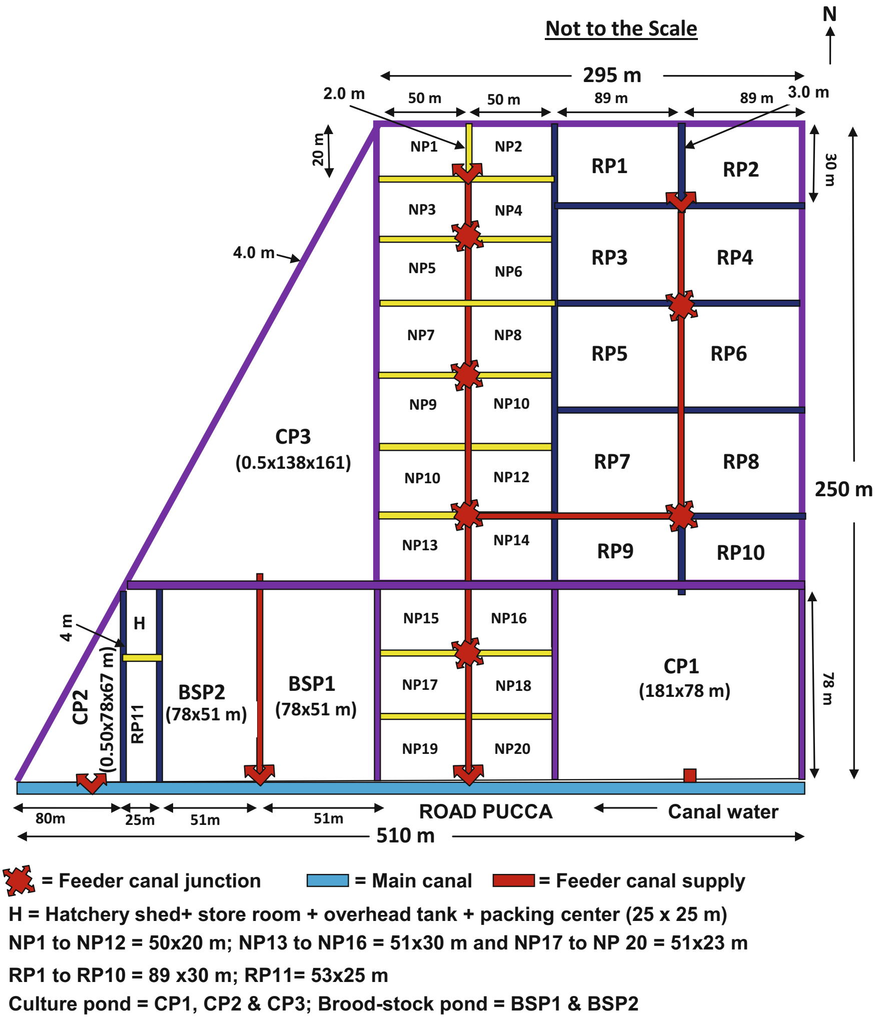

Fig. 24.5 Layout of an aquafarm

ponds and other facilities are designed properly. Depending upon the nature of work and activities involved, there are three types of planning—layout planning, manpower planning, and material planning—involved in the entire process of design and construction. The layout plan, design, cost estimation, construction, and maintenance of fish ponds and aquafarm depend upon many engineering aspects like topography, type of soil, water resources and quality, the orientation of the farm, and the best utilization of space. Therefore, basic knowledge of these engineering parameters and technical know-how, coupled with scientific expertise and experience, are important in successful aquaculture projects. Hence, it is essential and important to create awareness among fish farmers and entrepreneurs about the planning, design, and construction of scientific aquafarms in the Himalayan region.

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Hydroelectric Projects: An Inevitable Challenge in Fisheries of the Temperate Himalaya

25

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Abstract

The vast Indian Himalayan Region (IHR) and myriads of rivers make the region one of the opulent hotspots of the world in terms of potential hydropower energy. These hydropower projects usually break the continuum of a river, causing drastic changes in the physico-chemical and biological properties of water. In addition to the ecological impacts, socio-economic and livelihood concerns of the native people equally emerge. Many workers have assessed both negative and positive impacts of hydropower projects in the IHR, but data related to the fish and fisheries is quite limited. Therefore, it is imperial to understand the consequences of these irreversible ecological changes in the temperate rivers and frame suitable mitigation measures to minimize the risks to fish and fisheries, caused due to the construction of dams, barriers and water impoundments in the IHR.

Keywords

Coldwater fisheries · Hydroelectric projects · Dams · Fisheries · Migration

25.1 Introduction

Hydropower projects in the Indian Himalayan region have an increasing demand for generating an enormous amount of electric energy with the growing urbanization and industrial activities. This need has recently led to a boom in the construction of numerous dams and man-made reservoirs of huge hydropower capacities on the rivers. Many of these projects are in operation; some are either under the

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Fig. 25.1 A river in the Indian Himalayan region at Pancheshwar, Uttarakhand, India

developmental phase or planned to be commissioned in the coming years. The existence of extensive river drainage systems (Fig. 25.1) in the country, especially in the Indian Himalayan Region (IHR), makes them the most preferred resources for the contrivance of these large hydropower projects. However, on the contrary, these lotic water bodies are home to several commercially important fish species and many other prized fishes of sports and ornamental values (Fig. 25.2), sustaining livelihood and food security for the riverside dwellers and fishing communities at the rural front. Therefore, a barrier over a river can seriously change the socio-economic status and livelihood pattern of human lives, thriving profoundly on the fish fauna and the health of the rivers. Temperate rivers and streams in the IHR, in particular,

Fig. 25.2 Important hill stream fishes of the Indian Himalayan Region

sustain a rich fish faunal diversity with more than 258 species belonging to 26 families and 76 genera (Mahanta et al. 2011).

The dams exemplify a severe threat to these fish stocks, causing a major impact on the fish dynamics in terms of their movement, fish assemblage, fish reproduction and propagation, synergistically with altered water flow regimes, water and soil characteristics and invasion of alien and exotic fish species. Hence, it is imperative to understand the reflexes of the fish population in response to the ecological changes, caused by the construction of hydroelectric dams. In addition, the inland fisheries sector supports livelihood, nutritional security and income for thousands in the temperate Himalayan region, and therefore, it is imperative to assess impacts and their mitigation to overcome the socio-economic and ecological impacts of these projects.

25.2 The Hydropower Projects

India has more than 4000 large dams. The Tehri Dam (Fig. 25.3) in Uttarakhand, being the highest (261 m), is built on the river Bhagirathi. It is reported that about 58,000 large dams (elevation above 15 m) and 800,000 small dams have been constructed in the entire world (WCD 2000), and 73% of them have been built within the last 50 years. The highest number of dams is registered in China, followed by the USA and India. Nilsson and Berggren (2000) reported that the dams have regulated over 65% of the world’s freshwater discharges to the ocean. The Hirakud

Fig. 25.3 The Tehri dam in Uttarakhand, India

Fig. 25.4 The upcoming 2000 MW hydropower project in Subansiri, Arunachal Pradesh, India

Dam on the Mahanadi river is the longest in India, covering 26 km in length. Some of the major dams in the country are on the Sutlej, Beas and Ravi rivers in Himachal Pradesh; Chenab and Jhelum in Jammu and Kashmir; Rangeet and Teesta in Sikkim; Bhagirathi in Uttarakhand; and upcoming dams on Kameng, Subansiri and Dibang rivers in Arunachal Pradesh (Fig. 25.4). Shah (1993) cited these dams as Modern Temples of India as aptly referred by the Indian economy. The dams are considered to have significant social and economic benefits to the nation due to the revenue generated from tourism and recreation (Arain et al. 2008). India has followed similar lines and has constructed a large number of dams over the major rivers of the country for generating power and for indispensable benefits like irrigation in drought areas, supply of drinking water, flood control, transport through navigation, aquaculture avenues and recreation. The construction of dams has also given rise to numerous reservoirs, which are highly potential aquatic resources for fisheries development in the country. At present, there are 56 large reservoirs (>5000 hectares area), 180 medium reservoirs (1001–5000 hectares) and 19,134 small reservoirs (<1000 hectares) in the country, with a total reservoir area of 3.15 m hectares. Consequently, the construction of hydropower projects in India has become highly debatable, and severe resistance was imparted to each new dam proposal, particularly from the riverside dwellers and environmental groups. However, a certain fragment of society considers such hydroelectric power as a clean source of energy. This hydropower energy is environment-friendly as the energy is produced without any effluent like other energy sources from petroleum and coal. These hydroelectric projects may generate extreme and irreversible environmental impacts, especially when large reservoirs are built in temperate regions in hills and mountains where flora and fauna are in the highest density. There are many such negative impacts of impoundments on the fish fauna, and the impacts have been well documented by researchers in the country. The predicted changes in fish composition, distribution and assemblage structure and consequences for fisheries sustenance are challenging because of the diverse nature of the flow regime, the substratum, the meteorological variance and the complexity of temperate rivers. Impacts from hydrological alteration are unevenly observed in the fish distribution and assemblages in the reservoirs. Specific types of fish species are severely impacted, while others flourish well in reservoirs created by dams. In many cases, the functional trait of a fish in terms of their adaptation to the environmental cues, including those related to morphometric features of the body for feeding (mouth pattern, mouth size and position), habitat usage (body size and shape, fin size and position), metabolism (thermoregulation, salinity tolerance, hypoxia tolerance), reproductive behaviour (reproductive effort, secondary sexual characteristics, spawning nature, parental care, etc.) and defence tactics (guarding, crypsis, presence of armour or spines), is affected due to a change in the aquatic ecosystem.

25.3 The Major Impacts

Hydroelectric dams have been built on many rivers across the Indian Himalayan Region. The impact of a dam followed by impoundment in a free-flowing river leads to many physical, chemical and biological changes in the stream ecosystems. The major changes observed are (1) alteration of the lotic (riverine) environment into a lentic (lacustrine) environment, (2) habitat fragmentation, (3) fish fauna homogenization and (4) introduction of invasive or non-native fish species.

Large hydropower projects in IHR may develop synergistic environmental impacts on temperate river water and the reservoirs. This can be attributed to a change in abiotic and biotic water quality parameters, viz. temperature, dissolved oxygen, water pH, alkalinity and hardness, nutrients, plankton diversity, insect biomass, etc. An impoundment in the form of a reservoir can lead to eutrophication due to decomposed submerged vegetation, retention of sediments and nutrients in the reservoir. The hypolimnion may experience the decay of organic substrate, leading to anaerobic conditions. It is observed that the water in the reservoir has very different physico-chemical parameters as compared to a free-flowing river. The elevation of the outflow channels is the determining factor in the quality of tail water downstream. The water released from the epilimnion is usually well oxygenated and warm, whereas the water released from the hypolimnion is low in dissolved oxygen and cold. A reservoir influences the water temperature regime to a great extent, which can be seasonal as well as temporal. The water retained in the reservoirs for a longer duration may become stratified. The epilimnion layer of water may remain warm, whereas the hypolimnion layer may be cold. The release of the stratified cold water from the reservoirs may have an impact on the biota of the river, both downstream and upstream. The construction of a dam reduces the water velocity immensely, and henceforth the reservoir acts as a sediment sink. The quality and quantity of sediments deposited in the reservoirs depend on the runoff from the catchment areas, adjoining agricultural practices, human habitation, etc. Usage of profuse pesticides in the agricultural crops usually can be drained into a reservoir with surface runoff, and this may result in contamination in the fish flesh and finally cause a human health hazard.

The creation of a hydropower impoundment on a river leads to a barrier between the upstream and downstream movement of organisms and nutrients, causing fragmentation of stream fish habitats and populations (Fig. 25.5). Habitat fragmentation experiences reduced gene flow in fish populations, resulting in lower effective population sizes and eventually deleterious effects of inbreeding.

Fish fauna homogenization is the process by which ecosystems lose their biological uniqueness. In the IHR, there is a high probability of decreasing rheophilic fish species and increasing limnophilic species. The spread of alien species is a leading contributor to the global homogenization of freshwater communities, resulting in decreased local and regional fish faunal diversity (Poff et al. 2007). The disturbances and alteration of ecology habitually favour exotic or invasive fish species because they often have broad environmental tolerances or can out-compete native fishes (Pringle et al. 2000). In contrast, indigenous and endemic fishes tend to be adapted for unmodified local environmental and climatic conditions (Poff and Allan 1995). The most extreme habitat modification occurs in the reservoirs, created by dams, where the outside fish species comprise a greater composition of the fish population. This results from the artificial stocking of the reservoirs with the hatchery producing young fish species suitable for thriving in the impoundments. When the dams are fully commissioned, the reservoirs gradually fill in, and the fish habitat changes from riverine to lacustrine (Fig. 25.6), and there is generally a corresponding shift in the fish communities towards those species specialized for lentic habitats (Gao et al. 2010). Several studies showed an increase in non-native species, hence, escalating the total species richness in reservoirs. However, the population of the native fish species (Fig. 25.7) may decline or even

Fig. 25.5 Habitat fragmentation between the upper and lower reaches of the river across a dam

Fig. 25.6 Creation of a lacustrine environment due to construction of dam

Fig. 25.7 A haul of snow trout from a fast-flowing river of Arunachal Pradesh

vanish from the environment. Indigenous fish species, viz. *Schizothorax*, *Garra*, *Glyptothorax and Pseudecheneis* spp., are bottom feeders and have special adaptive features for scraping periphyton or algae as their food items from the substratum in the form of pebble, cobble, stones and boulders in the fast-flowing rivers of IHR (Baruah et al. 2019). This substratum also forms breeding grounds for the above fishes in many rivers. The construction of dams on the free-flowing fast water has resulted into a reduced flow regime, rise in water column and deposition of high silt. The deposition of silt or sediment over the natural substrata can adversely affect the foraging of fish and their spawning behaviour. Such a changed habitat compels the fish to migrate further upstream in search of food and suitable ground for breeding

Fig. 25.8 A large migratory fish golden mahseer (*Tor putitora*) affected by the dams

and propagation. The Himalayan snow trout, loaches and catfishes are some of the major groups affected due to the construction of dam over the temperate rivers.

One of the main consequences of dams on fish stocks is a remarkable reduction or even regional extinction of large migratory fish species like mahseer (Fig. 25.8) after the formation of an impoundment in the form of a reservoir due to changes in the fish ecosystems. Tehri Dam on Bhagirathi is one such example of the loss of mahseer due to dams (Sarkar et al. 2015). The dam restricts the upstream or downstream migrations of matured and gravid fishes to reach their conducive spawning grounds for reproduction. These fishes usually congregate in certain pockets and gullies downstream of the dam, which makes them prone to being heavily exploited by fishermen. Dams significantly act as a barrier to migratory fish moving upstream and downstream, and hence, the species diversity, richness and fish composition differ in the head water and tail of dams. It is very likely that due to the change in the water flow and the environment, the native fast-flowing and migratory fish may be replaced with slow-moving non-native fishes gradually in the upstream. The inundation of the catchment in the upstream also damages the fish nursery sites. Similar is the case in downstream, where the lack of water may dry up the floodplains for fish larval development. Further, retention of sediments and nutrients by the reservoir may hamper the water quality and quantity, reduce fish food organisms and promote the propagation of alien and invasive fishes. The floodplains forming a downstream portion of a large river are seasonally flooded by the main river. These inundated catchment areas adjacent to lowland forests and lakes are one of the most productive and important ecosystems for the foothill fisheries where several fishes spawn and propagate. The reservoirs are also infested with severe macrophytes in many cases, which can deteriorate the water quality and, hence, the survival of the fishes therein. Air-breathing fishes and catfishes may proliferate in those conditions, replacing the indigenous cold water fish species. The construction of a dam creates a lacustrine environment in the form of a reservoir from a free-flowing river environment. Therefore, it is very likely that the lake-like environment will be inhabited by different forms of fish species, which are mostly non-native and did not exist naturally in that river. Furthermore, the variation in the river flow also leads to lack of biological cues responsible for natural spawning and migration. The conducive aquatic environment for breeding and propagation is not present so the riverine fish species often fail to reproduce.

25.4 Mitigation Measures

Each hydropower project essentially undergoes an Environmental Impact Assessment (EIA) to minimize the negative impacts of the dam. However, it is not necessary that all the mitigation measures can be counted prior to the construction of a dam, and hence, periodical assessment is necessary throughout the life span of a dam to reduce the errors with time. Most of these mitigation measures are applicable to upstream and downstream of the river and in the reservoir itself. Efforts are made to keep control on the water quality parameters of the reservoir, viz. using mechanisms of water column mixing to prevent thermal stratification and enriching dissolved oxygen in deep water. Further, all the discharges from adjoining industries, agricultural lands, domestic water and sewage, etc. essentially are treated in water treatment plants before releasing into the water. Many important advances and amendments in management approaches and engineering of mitigation measures have resulted in new hydroelectric projects becoming more environment-friendly than in the past. It can be referred that the environment-related mitigation measures for a single-purpose dam might be easier to resolve than a multi-purpose dam. However, this may not be the case everywhere as the hydropower dams usually have greater height, which is an insurmountable height for migrating fish. Efforts must be made to improve the water quality level in tail water downstream, construction of suitable fish passes, fish lifts, etc. and maintenance of adequate water flow regime to protect the downstream aquatic ecology. Some of the fisheries information to be procured with time and database to be prepared in a hydropower project site are listed herewith:

1. Evaluation of the area under the impact of the hydropower dam, both upstream and downstream from an ecological view point.
2. Characterization of commercially important indigenous and endemic fish species in the region.

3. Studies on the habitats of important fishes/ecological modelling of the river under concern, viz. spawning grounds, feeding grounds, winter shelters, etc.
4. Evaluation of migratory fishes of the region and their pathways.
5. Knowledge on the human settlement in the region and their probable association with the river and the fishes.
6. Studies on the status of the hydropower project area, which includes the production, processing, income, marketing and trade, etc. of the people.
7. Policy development in mitigating the shortfalls and demerits of the hydropower projects in relevance to fish and fisheries.
8. Detailed assessment of the fisheries enhancement programmes in the hydropower project area.

25.5 Fisheries Enhancement Programmes

The following are several successful approaches for enhancing and intensifying reservoir fisheries production at the hydropower project sites:

1. Stocking the reservoirs with hatchery-produced young ones of indigenous and commercially important fish species. The introduction of rainbow trout for enhancing fish production and brown trout for recreational fishing is one option in temperate waters.
2. The reservoirs can be installed with Fish Aggregating Devices (FADs) for enhancing fish production and ease of harvest.
3. Excessive infestation of the hydrophytes can be eliminated from the reservoirs with the usage of environment-friendly herbicides and the introduction of weed-eating fishes.
4. Cage culture is another successful aquaculture model in practice for enhancing fish production in reservoirs.
5. The reservoirs in temperate regions can be suitably utilized for recreational purposes by stocking with brown trout, mahseer, minor carps, etc. Angling can be allowed by issuing a license to the angler and with the fishing policy of catch and release.
6. Enactment of laws to prohibit fishing during the spawning season in the upstream or head waters.

25.6 Conclusion

Although hydroelectric projects are inevitable for human development indices, a comprehensive and holistic fisheries management plan, linked to every hydroelectric project, must be in place to safeguard the indigenous fish diversity.

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