emergent
Life Sciences Research

Review Article

The ecology, biology and aquaculture of *Channa* sp. with special emphasis on striped snakehead, *Channa striata*: A review

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Received: 7 February 2026
Accepted: 8 June 2026
Online: 12 June 2026

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Emer Life Sci Res (2026) 12(1): 45-67

E-ISSN: 2395-6658
P-ISSN: 2395-664X

DOI:
https://dx.doi.org/10.31783/ELSR.2026.1214567

Abstract

Snakeheads belong to the family Channidae and comprise 2 genera of which *Channa* spp represent an iconic genus of large-bodied species of the family. However, recently, a new family Aenigmachannidae, was erected as a sister group to Channidae. In general, snakeheads have a long, torpedo-shaped body with long, continuous dorsal and anal fins that run along their body upto the caudal fin. They are called snakeheads because of their body shape and the presence of eyes on top of their heads. If they are moist, they can survive out of water up to 4 days. Some species of snakehead can grow to over 4 feet long and weigh more than 40 pounds. Striped murrel is considered to be highly nutritious and is known to have medicinal values. It is also to be noted that some of the snakehead species are becoming invasive. The spread of the species is likely to continue due to illegal introductions, primarily for food, along with natural range extension due to climate change. The majority of species production is from capture fisheries due to a lack of standardized aquaculture production technology, which has led to habitat degradation and pressure on the ecosystem. Therefore, standardization of aquaculture technology is the need of the hour to conserve and enhance the natural stock of the species. However, recent reviews on the species have focussed mainly on aquaculture technologies available for the species. Hence, in this review, recent knowledge on the current distribution, trophic ecology of the species, genotypic characterisation, reproductive potential, commercial exploitation and medicinal value of the species, which is one of the major reasons for exploitation are discussed to facilitate conservationists to develop a suitable conservation strategy for the species.

Keywords distribution, ecology, genotypic characterization, medicinal value, murrel, snakehead

Introduction

Global aquaculture production reached 130.9 million tonnes in 2022 [1], with Asia as the leading contributor, particularly China, Indonesia, and India. For the first time, aquaculture surpassed capture fisheries in aquatic animal production, contributing 94.4 million tonnes (51% of total production) and 57% of production for human consumption [1]. Major contributors included carps, barbels, other cyprinids, tilapias, and cichlids. The fisheries sector has become increasingly dynamic in recent decades due to rising demand [1].

Aquaculture plays a vital role in food security, nutrition, and rural livelihoods [2]. Growing demand for nutraceutical-rich foods has highlighted the need for species diversification [3-4]. Snakeheads (*Channa* spp.) are promising candidates due to their accessory respiratory organs, which enable survival in low-oxygen environments [5-6].

Approximately 53 species of *Channa* (Table 1) are distributed across 24 countries (Table 2), with 96% occurring in Asia. IUCN Red List assessments are available for 20 species, of which 12 are classified as Least Concern, 3 as Near Threatened, 2 as Vulnerable, 1 as Critically Endangered, and 2 as Data Deficient (Table 3, Figure 1). Among them, the striped snakehead (*Channa striata* Bloch, 1793) is commercially important due to its high protein [7] and albumin content [8]. It inhabits swamps, rivers, streams, and lakes [9], and, as a top predator, regulates prey populations [10]. It is cultured in countries such as the Philippines, Thailand, Cambodia, and Vietnam [11], and contributes about 13% to India's marketable fish production [12-13].

Table 1. List of species available under the genus *Channa* spp.

S.N.	Snakehead species name	Common name(s)	Synonyms	References
1.	*Channa amari*	-	-	[14]
2.	*C. amphibeus*	Borna snakehead/ Chel snakehead	*Ophiocephalus amphibeus, C. amphibia, C. amphibius, C. amphibious*	[15]
3.	*C. andrao*	-	-	[16]
4.	C. argus	Northern snakehead	*O. pekinensis, O. argus warpachowskii, O. argus kimurai*	[17]
5.	*C. aristonei*	-	-	[18]
6.	*C. asiatica*	Small snakehead	*Gymnotus asiaticus, C. ocellata, C. sinensis, C. formosana*	[19]
7.	*C. aurantimaculata*	Orange-spotted snakehead	-	[20]
8.	*C. aurantipectoralis*	-	-	[21]
9.	*C. auroflammea*	-	-	[22]
10.	*C. aurolineata*	-	-	[23]
11.	*C. bankanensis*	Bangka Snakehead	O. bankanensis	[24]
12.	*C. baramensis*	Baram Snakehead	O. baramensis	[25]
13.	*C. barca*	Barca snakehead	*O. barca, O. nigricans*	[26]
14.	*C. bipuli*	Galaxy Blue Snakehead/ Meghalaya Leopard Snakehead	-	[27]
15.	*C. bleheri*	Rainbow snakehead	-	[25]
16.	*C. brahmacharyi*	-	-	[28]
17.	*C. brunnea*	-	-	[29]
18.	*C. burmanica*	Burmese Snakehead	-	[30]
19.	*C. cyanospilos*	Bluespotted Snakehead	*O. cyanospilos, O. striatus*	[24]
20.	*C. diplogramma*	Malabar snakehead	*O. diplogramma*	[31]
21.	*C. gachua*	Dwarf snakehead	*O. gachua, O. aurantiacus, O. marginatus, O. limbatus, C. limbate, O. apus*	[26]
22.	*C. harcourtbutleri*	Inle snakehead	*O. gachua, O. harcourtbutleri, C. orientalis, C. harcourtbutleri*	[32]
23.	*C. hoaluensis*	-	-	[33]

Continued Table 1.

24.	*C. kelaartii*	-	-	[34]
25.	*C. limbata*	-	-	[25]
26.	C. lipor	-	-	[35]
27.	*C. lucius*	Forest snakehead	*O. lucius, C. lucia, O. polylepis, O. siamensis, C. siamensis, O. spiritalis, O. bistriatus*	[25]
28.	*C. maculata*	Blotched snakehead	*O. guentheri, O. tadianus, O. marmoratus*	[25]
29.	*C. marulioides*	Emperor snakehead	-	[25]
30.	*C. marulius*	Great snakehead/ bullseye snakehead	*O. marulius, O. grandinosus, O. grandinosus, O. sowara, O. leucopunctatus, O. theophrasti, O. aurolineatus*	[26]
31.	*C. melanoptera*	-	-	[25]
32.	*C. melanostigma*	-	-	[36]
33.	*C. melasoma*	Black snakehead	*O. melasoma, O. mystax, O. rhodotaenia*	[25]
34.	*C. micropeltes*	Giant snakehead/ Giant mudfish	*O. micropeltes, O. serpentinus, O. bivittatus, O. stevensii, O. studeri*	[25]
35.	*C. ninhbinhensis*	-	-	[33]
36.	*C. nox*	Night snakehead	-	[37]
37.	*C. orientalis*	Ceylon snakehead	*O. auranticus, O. marginatus, O. coramota, O. fuscus, O. limbatus*	[38]
38.	*C. ornatipinnis*	-	-	[39]
39.	*C. panaw*	Panaw snakehead	-	[40]
40.	*C. pardalis*	-	-	[41]
41.	*C. pleurophthalma*	Ocellated Snakehead	*O. pleurophthalmus, O. urophthalmus, O. spiritalis*	[25]
42.	*C. pomanensis*	-	-	[42]
43.	*C. pseudomarulius*	-	-	[34]
44.	*C. pulchra*	Peacock Snakehead	-	[43]
45.	*C. punctata*	Spotted snakehead	*O. punctatus, O. karruwey, O. lata, O. indicus, O. affinis*	[25]
46.	*C. quinquefasciata*	-	-	[44]
47.	*C. rara*	-	-	[45]
48.	*C. royi*	Andaman emerald snakehead	-	[46]
49.	*C. shingon*	-	-	[47]
50.	*C. stewartii*	Assamese/ Golden Snakehead	*O. stewartia*	[48]
51.	*C. stiktos*	-	-	[49]
52.	*C. striata*	Striped/ Common/ Chevron snakehead	*O. striatus, O. wrahl, O. chena, O. planiceps, O. vagus, O. philippinus, O. melanopterus*	[25]
53.	*C. torsaensis*	Cobalt blue snakehead	-	[50]

Table 2. Distribution details of *Channa* sp

Snakehead Scientific name	Distribution
Channa amari, C. amphibeus, C. andrao, C. aristonei, C. aurantimaculata, C. aurantipectoralis, C. bipuli, C. bleheri, C. brahmacharyi, C. brunnea, C. barca, C. marulius, C. diplogramma, C. lipor, C. melanostigma, C. kelaartii, C. pardalis, C. rara, C. pomanensis, C. pseudomarulius, C. micropeltes, C. royi, C. stiktos, C. quinquefasciata, C. striata, C. torsaensis, C. gachua	India
C. argus, C. asiatica, C. lucius, C. maculata, C. marulius, C. nox, C. shingon, C. torsaensis, C. gachua	China
C. kelaartii, C. marulius, C. orientalis, C. punctata, C. striata, C. gachua	Sri Lanka
C. auroflammea, C. gachua, C. lucius	SouthEast Asia
C. micropeltes, C. aurolineata, C. maculata, C. marulius, C. melasoma, C. striata	Thailand
C. micropeltes, C. ninhbinhensis, C. hoaluensis, C. maculata, C. striata	Vietnam
C. micropeltes, C. baramensis, C. cyanospilos, C. marulioides, C. melasoma, C. striata	Malaysia
C. micropeltes, C. pleurophthalma, C. bankanensis, C. baramensis, C. cyanospilos, C. marulioides, C. melanoptera, C. melasoma, C. striata, C. micropeltes	Indonesia (Sumatra, Kalimantan and Borneo)
C. argus	Korea
C. asiatica	Taiwan
C. asiatica	Southern Japan
C. marulius, C. striata	Cambodia
C. melasoma	Philippines
C. melasoma	Singapore
C. striata	Western Java
C. aurolineata	Florida, United States
C. marulius, C. punctata, C. striata, C. aurolineata, C. burmanica, C. panaw, C. pulchra, C. ornatipinnis, C. harcourtbutleri	Myanmar
C. burmanica	Burma
C. argus	Russia
C. barca, C. gachua, C. marulius, C. punctata, C. striata	Bangladesh
C. marulius, C. punctata, C. striata	Pakistan
C. marulius, C. punctata, C. striata, C. stewartii	Nepal
C. punctata	Tibet
C. punctata	Afghanistan

Table 3. IUCN Red List Status of *Channa* sp.

S.N.	Snakehead Scientific Name	IUCN Conservation Status
1.	*Channa amphibeus*	Least Concern
2.	*Channa asiatica*	Least Concern
3.	*Channa barca*	Critically endangered
4.	*Channa bleheri*	Near Threatened
5.	*Channa burmanica*	Least Concern
6.	*Channa diplogramma*	Vulnerable
7.	*Channa gachua*	Least Concern
8.	*Channa harcourtbutleri*	Near Threatened
9.	*Channa lucius*	Least Concern
10.	*Channa maculata*	Least Concern
11.	*Channa marulius*	Least Concern
12.	*Channa melasoma*	Least Concern

Continued Table 3.

13.	*Channa micropeltes*	Least Concern
14.	*Channa orientalis*	Vulnerable
15.	*Channa ornatipinnis*	Data Deficient
16.	*Channa pleurophthalma*	Near Threatened
17.	*Channa pulchra*	Data Deficient
18.	*Channa punctata*	Least Concern
19.	*Channa stewartii*	Least Concern
20.	*Channa striata*	Least Concern

Growth rates vary by region: individuals reach 30-36 cm in one year, while reports indicate 25-27 cm in 9.5 months in Kerala, 32 cm in two years in West Bengal, and 30.51 cm in two years in Tamil Nadu [51]. The proximate composition of the *Channa striata* is presented in Table 4. Market prices range from ₹ 300-400 (US$ 5-7) per kg in India [52]and US$ 4-6 per kg in Indonesia [53], reflecting its high demand and suitability for aquaculture [54].

Table 4. Proximate composition of *C. striata* [55]

Nutritional component	Content (%)
Crude protein	23.0±0.7
Crude fat	5.7±1.9
Crude ash	1.8±0.07
Moisture	83.5±6.7

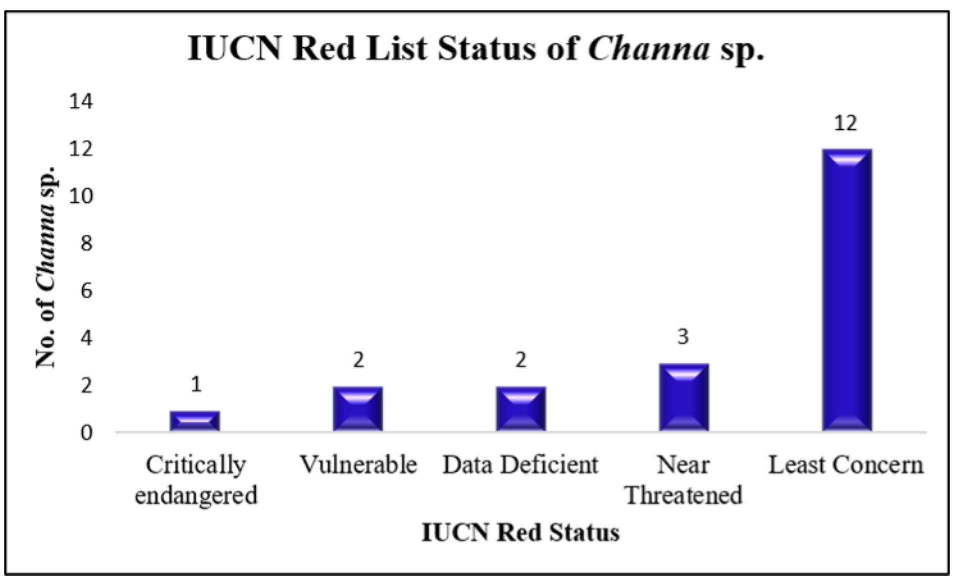

Figure 1. The number and status of *Channa* sp. listed in IUCN Red List

Sustainable production requires domestication and standardization of intensive breeding techniques. This review integrates available information on distribution, biology, trophic ecology, medicinal value, reproduction, and aquaculture of *C. striata*, and identifies key research gaps for future studies.

Morphological characteristics

Talwar and Jhingran [56] described key identification features of *C. striata*: the gular region is scaleless; the mouth is large, with 4-7 canines on the lower jaw behind a single row of villiform teeth that expand to six rows at the symphysis; villiform teeth are also present on the prevomer and palatines. The pectoral fin is about half the head length, and the dorsal, anal, pectoral, and pelvic fins have 37-46, 23-29, 15-17, and 6 rays, respectively; the caudal fin is rounded. Head scales are large, forming a rosette between the orbits with frontal scales as the central plate; there are 9 scale rows between the preopercular angle and posterior orbit, 18-20 predorsal scales, and 50-57 lateral line scales. The dorsal surface is dark brown to black with chevron markings and a dark stripe extending from above the maxilla to the operculum. Lee and Ng [57] reported morphometric proportions (as % of standard length) as follows: postorbital head length (28.6-37.2), interorbital width (5.1-8.9), preopercular length (6.2-26.4), pelvic–anal distance (3.5-8.8), and caudal length (11.9-23.3).

Juveniles differ from adults in that larvae lack black stripes and instead show a single broad orange lateral band [58]. Individuals above 40 mm develop a temporary pseudo-ocellus (a dark spot near the rear dorsal fin), which disappears in adults [59].

Phenotypic and genotypic characterization

Many *Channa* species are distributed worldwide, and they are differentiated using different morphometric characters. A report on the morphometric and meristic characters as phenotypes of wild *C. striata* from Mekong delta, Viet Nam has established a relationship of Head length (HL)- 33.1±1.1%, Body depth (BD)- 14.3±0.5%, Height of caudal fin (HCP)- 8.5±0.3% and Dorsal fin length (DL)- 59.1±1.7% with relative to standard length; Head depth (HD)- 42.5±2.1%, Small head width (SHW)- 33.0±1.7%, Large head width (LHW)- 52.5±2.1%, Distance of two eyes (DE)- 27.2±1.3%, Eyes diameter (ED)- 11.6±0.7%, Upper jaw length (UJ)- 38.3±1.5%, Lower jaw length (LJ)- 41.6±1.9%, Mouth width (MW)- 42.7±1.9% with relative to head length; Small head width (SHW)- 63.0±2.9% with relative to large head width; Upper jaw length (UJ)- 92.1±3.8%,

Mouth width (MW)- 102.7 ± 1.6% with relative to Lower jaw length [60]. Analyses on the geometric morphometrics of *C. striata* populations of Laguna de Bay regarding shape variation provided interesting results. High variation in the cranial region was reported from populations of the lake region, Binangonan and Tanay, whereas the highest morphometric values were noted from populations of the lake region, Calamba. The results further provided an insight that shape variation in the cranial region correlated with differences in dissolved oxygen and pH content of the lake, while the weight and length of fish were inversely correlated to the levels of ammonium-nitrogen and total dissolved solids [61]. A comparative study on the morphometric variation of *C. striata* from 9 populations in Sumatra Island of Indonesia was conducted based on 14 morphometric and 21 Truss network measurement characters, which revealed that the female had a higher percentage of head and body backbone compared to the male, and the fish population from the river had relatively similar morphometric characters when compared to the population from the floodplain [62].

Cytogenetic studies in *C. striata* have revealed that the number of chromosomes in the species varies from 36-42 [63]. It is to be noted that if the genetic distance is more than 3.5%, then the samples are different species [64]. A report has mentioned that the genetic distance between *C. striata* from Southeast Asia and India was 3.6%, revealing cryptic diversity of *C. striata* in the world [65]. High level of within-species divergence was reported in *C. striata* collected from the wild in five locations in Southeast Asian countries [66]. However, the within-species genetic difference of *C. striata* from Malaysia was lower than that of other species and did not correlate with morphological variation [67]. Evidence states that the genetic distance among *C. striata* morphotypes in the Mekong Delta, Viet Nam, is like the snakeheads from Malaysia, Cambodia and Thailand [60]. It has been reported that *C. striata* originated from the Himalayan region [68], which distributed itself to different places of Southeast Asia during the wet climate when the species can take overland movement [66]. This was supported by the cytochrome b, which showed similar phylogenetic relationships of *C. striata* in Asian regions [66]. Bhat et al., [69] analysed the genetic variation of *C. striata* collected from four different geographical locations of India, namely the river Tamirabarani, the river Periyar, Kolleru lake and the river Brahmani using Random amplified polymorphic DNA (RAPD) markers and concluded that populations from the river Tamirabarani, the river Periyar, and Kolleru lake are genetically closer while the population from the river Brahmani was genetically distant due to its geographical distance from other rivers. Nguyen and Duong [60] concluded that *C. striata* exhibits high within-species variation in morphology and COI sequence diversity, even over small geographic scales with different environmental conditions, which they attributed to differences in living environments and feeding types between cultured and wild conditions. They also mentioned that the most variable characteristics, affected by degrees of movement, are the shapes of their head and body. This fact was also vouched by Yen et al., [70], who reported higher morphological differences within and among populations of wild snakehead compared to cultured ones from the Mekong Delta.

Robert et al., [71] quantified the intra-specific diversity and characterized the population structure of *C. striata* in Sabah, North Borneo, Malaysia by determining the variability at six microsatellite loci. They collected samples from nine locations representing the western, northern and eastern regions of North Borneo. Based on the genetic distance-based relationships and model-based clustering, they separated the overall Sabah population into two well-differentiated genodemes and mentioned that the route by which ancestral *C. striata* populations colonized the northeastern region of Borneo is unknown. Genetic diversity estimates of the species from different places are given in Table 5.

Table 5. Genetic diversity estimates of *C. striata* population from different regions

Population	Overall average allelic richness	Range of Average allelic richness	Overall Average expected heterozygosity	Range of Average expected heterozygosity	References
North Borneo	4.23	3.00-5.20	0.53	0.43-0.67	[71]
Mekong River Basin	4.04	2.04-4.94	0.67	0.34-0.77	[72]
Malaysia	4.76	3.00-7.63	0.58	0.3-0.76	[73]

Geographical distribution

C. striata is known to be native of southeast Asia. It is reported in Pakistan, India, Myanmar, Sri Lanka, Vietnam, Nepal, Bhutan, Bangladesh, southern China, Thailand, Cambodia, Sumatra, Borneo, and Java. It is known to be introduced to the eastern islands of Indonesia, New Caledonia, New Guinea, Fiji, the Philippines, South Korea and southeastern Russia [74-76]as it is shown in Figure 2.

Taxonomy

Snakeheads comprise 2 genus such as *Channa* spp. and *Parachanna* spp. There are only 3 species under the genus *Parachanna*, namely, *Parachanna africana*, P. insignis and *P. obscura*, which are distributed only in tropical Africa. Britz et al., [77] conducted a detailed osteological analysis of *Aenigmachanna gollum* based on high-resolution nano-CT scans from subterranean waters of Kerala in South India and reported that *Aenigmachanna* has several characters that are not found in the family Channidae and is a separate lineage of snakeheads. Based on the morphological disparity of *Aenigmachanna* from members of the Channidae, they erected a new family of snakehead fishes, Aenigmachannidae, as a sister group to Channidae, to accommodate these unique snakehead fishes.

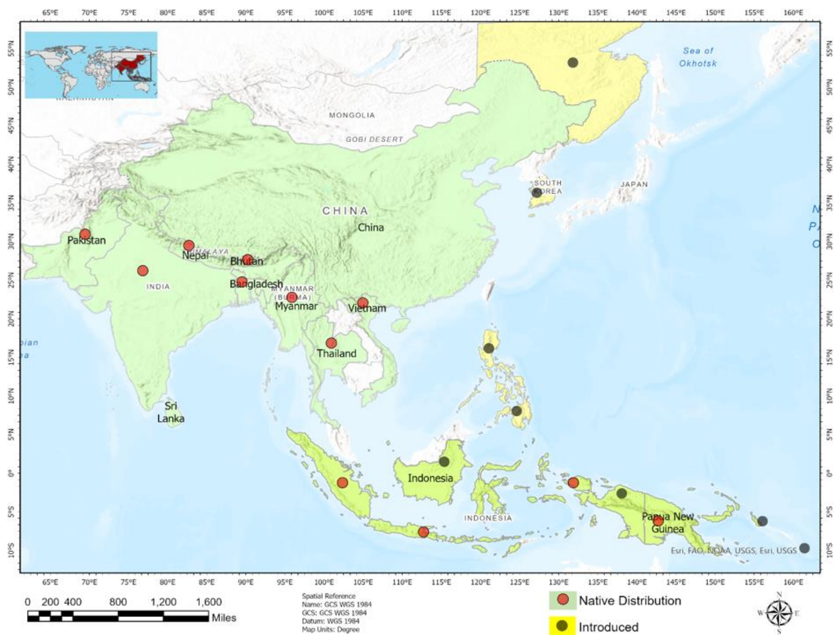

Figure 2. Country-wise native and introduced distribution of *Channa striata*

C. straita is commonly called the striped snakehead, Common snakehead, Chevron snakehead and Banded snakehead. *Ophioceplalus striata*, *O. wrahl*, *O. chena*, *O. planiceps*, *O. vagus*, *O. philippinus*, *O. melanopterus* are synonymous with *C. striata*. Snakeheads belong to the family Channidae [78] and genus *Channa*. However, species identified and reported during the early 1700 and 1800s belonged to the genus *Ophiocephalus*, which was later brought under the genus *Channa*. In the past 2 decades, almost 24 new species have been identified under the genus *Channa*. The taxonomic hierarchy of *C. striata* according to the Integrated Taxonomic Information System is given below,

Kingdom	Animalia
Phylum	Chordata
Subphylum	Vertebrata
Superclass	Actinopterygii
Class	Teleostei
Superorder	Acanthopterygii
Order	Perciformes
Suborder	Channoidei
Family	Channidae
Genus	*Channa*
Species	*Channa striata*

Trophic ecology

Diet composition

Snakeheads are generally carnivorous fish. Chakraborty [79] stated that *C. striata* is a carnivore, predatory and bottom-dwelling fish and fishes were the principal food items, followed by insects and crustaceans. *C. striata* preys on young fish, turtles, frogs and small ducklings in the pond [80]. Rao et al., [81] analysed the gut content of 3 *Channa* species, namely *C. punctatus*, *C. striata* and *C. orientalis,* and stated that food items of the three species include phytoplankton, zooplankton, annelids, crustaceans, fishes and molluscs. The various phytoplankters identified belonged to the genera *Closterium, Cosmarium, Spirulina, Microcystis, Hydrodicta, Characium, Navicula, Gamphonema,* *Ulothrix, Rhizosolenia, Spirogyra, Oscillatoria and Stephanodiscus. The zooplankton comprised of Actinospharium, Ceratium, Amoeba, Arcella, Actinophrys, Daphnia, Macrothrix, Diaphanosoma, Pseudodiaptomus, Paramecium, Volvox, Chilomonas, Vorticella, Spirostomum, Zooanthium, Trichocera, Didinium, Stentor, Keratella, Rotaria, Polyarthra, Stephanoceros, Lacrymeria and Hexarthra*. Worms were represented by earthworms and nais worms. Crustaceans comprised of the adults of *Macrobrachium lamerri* and *Caridina* spp., and larval forms like nauplius, zoea and mysis. Fish like *Puntius*, *Amblypharyngodon* and *Glossogobius* spp. were identified in the diet. Among all these, crustaceans and fishes formed the major food items.

Rao et al., [81] mentioned that *C. striata* preferred fish and fish juveniles. This fact was also vouched by Qayyum and Qasim [82]. However, Das and Moitra [83] reported that *C. striata* is a bottom feeder, which contradicts to the above results. Rao et al., [81] stated that fish constituted a larger portion of food item in *C. striata*. Fish like *Trichogaster pectoralis*, *T. trichopterus, Osteochillus hasseltii*, and *Oreochromis mossambicus* are known to be the prey fish for *C. striata* [84].

Prey consumption rates

The predator's handling size of prey is determined by the mouth gape [85-90] and differences in spatial scales in combination with the swimming abilities of predator and prey [91]. Das et al., [92] stated that in an experiment to investigate the predatory behavior of the fish, *C. striata* preyed on fishes in the order of small, medium, and large fishes. They also mentioned that the fish usually feed during the morning and evening hours and finishes its prey within 45-50 seconds.

Habitat specificity and diel activity pattern

C. striata is widespread throughout lowland regions [57] and is found in water bodies that are less than 1 m in depth and have abundant weeds. It can be seen in a wide range of temperatures and [57]. It is also noticed in ponds, canals, paddy fields, irrigation reservoirs, and swamps [93-94]. It is reported that during the rainy season, these fish migrate to flooded areas and once the flooded area is dried, it returns back to the permanent water body [74-75]. *C. striata* exhibits crepuscular activity [95]. Diel activity pattern is the pattern which describes how the activity of an animal is distributed daily, with which the behaviour of the organism can be understood [96]. Based on the diel activity pattern, adaptations an animal makes by trading off between resting, competition, foraging, avoiding predators, etc due to the environmental variations in a day can be determined [97-98]. In fishes, diel activity patterns determine their interactions with other species, governing which prey they are likely to consume and which predators they are vulnerable to [99]. In *C. striata*, the peak predation was observed in the morning (9-10h) and the evening (18-19h), while the low predation was observed during midday (13-14h) and mid-night (23-24h) [92].

Reproductive potential

Sex ratio is known to be species-specific and may vary annually within the same population [100]. In *C. striata*, a female: male sex ratio of 1.5:1 [101] and 2:1 [102] has been reported. Intersex (ovotestis) type of gonad has been recorded in this species with a standard length of 81-229 mm [102]. Similarly, 2 types of gonads in fish of standard length 110-241 mm have been noted: a pair of ovaries suspected to be undergoing apoptosis, and a pair of developing testes [102]. Hence, it was suggested that C. striata may be potentially hermaphroditic, and further study was recommended [102].

In *C. striata*, 4 stages of maturity, *viz*., immature, maturing, mature, and spent/recovering, were recorded [103] with mature ovaries from March, with abundance in June and July, and spent ovaries between the end of July and October. Males are identified using the genital papilla, while females are identified with soft and swollen bellies [104]. Applying gentle pressure on the belly of female fishes will ooze out eggs, but male couldn't ooze out milt upon pressure [104], and due to their crescent-shaped testis, stripping is a major problem [105].

The spawning season of snakehead differs between geographical areas. *C. striata* spawns throughout the year, and some may breed twice in a year [106], which was confirmed by Ali [107]. *C. striata* migrates to waterbodies characterized by numerous shrubs or grasses, which is essential for larval growth, leading to a high survival rate of offspring [108]. In Bangladesh, the spawning season of *C. striata* were from June to July [103]. Similar result was reported by Ferdausi et al., [109], who mentioned that *C. striata* spawns during April-July in Bangladesh. It is generally understood that the fish spawns during heavy rainfall, from June–October in India [110], April-July in Bangladesh [109], and July to November in Taiwan [101]. Contrary to this, the fish spawns when the water temperature increases in April in central Laos [111]. In Sri Lanka, the peak spawning season of *C. striata* is from May to September, with a secondary spawning season from October to December [112].

The fecundity in *Channa* sp is reportedly low when compared to other commercially important fishes. An absolute fecundity ranging from 4,484 to 96,498 oocytes was reported from *C. striata* of Taiwan [101], whereas, from India, a maximum absolute fecundity of 11,811 was recorded [113]. Jhingran [114] noted fecundity of 3000-30000 oocytes/ ovary. The values reported for absolute fecundity from Sri Lanka were between those for Taiwan and India [112]. The fecundity of *C. striata* of Malaysia was from 4326 to 9017 oocytes [107].

Snakeheads exhibit parental care, and usually, the male guards the fertilized eggs [52, 104, 115]. Once the fertilized eggs are hatched, males ventilate the hatchlings with their pectoral fins by moving around them. Males are always aggressive and keep the young ones under vigil. It was also reported that snakeheads exhibit biparental care, where both males and females show parental protection towards young ones [116]. This was confirmed in *C. striata* [117]. Annett et al., [118] stated that the advantage of exhibiting biparental care is increased protection to the offspring against predators and the possibility of one parent taking care if the other dies. The details on secondary sexual characteristics, gonad structure, and maturity stages were already discussed by different researchers [119-120].

Aquaculture

Captive breeding

Snakeheads can be induced to breed using natural or synthetic hormones intramuscularly [104, 121]. Kiran et al., [104]induced snakehead using a synthetic product of SGnRHa at a single dose of 0.5 ml/ Kg body weight (BW). Haniffa et al., [121] reported that in *C. striata*, ovaprim gave better results in terms of large ova size and high fertilization and hatching rate compared to human chorionic gonadotropin, luteinizing hormone releasing hormone analogue and pituitary extract. Francis et al., [122] found that kisspeptin at 0.05 μg/g BW influenced higher levels of steroid hormones in both male and female *C. striata*. Similarly, Kumar et al., [123] reported higher relative fecundity, fertilization and hatching rates in the group implanted with HCG at 2000 IU/kg BW and carp pituitary homogenate at 30 CPH/kg BW of *C. striata*.

After hormone injection, generally, one female and two males are introduced into a breeding tank that has aquatic weeds and clay substrate [104, 115]. *Hydrilla verticillata* and *Eichhornia crassipes* can be used in the breeding tank [115]. They observed spawning activity after 6 h of hormone injection in *C. striata* and noticed courtship behavior until the complete release of eggs and milt, which took about 24-30 h. Males were actively involved in the courtship behaviour. It was reported that as a part of spawning behaviour, the mating pair usually jumps above the water column to a height of 30 to 90 cm [115]. Spawning occurred in 16-18 h at 26-28°C, and the eggs were spherical, non-adhesive, transparent, and straw yellow in colour and were free floating [124]. Snakeheads have external fertilization with floating eggs having an egg mass of about 6-14 cm diameter consisting of 2500-4000 eggs (diameter 1.2-1.5 mm) [115]. Singh [124] reported a fecundity of 10,000-15,000 eggs/kg female BW at a time in *C. straitus*.

Larval development

Marimuthu et al., [115] recorded a fertilization rate of 70-90% and mentioned that hatching takes place 24-30 h after fertilization in snakeheads. The embryonic and larval development in *C. striata* was documented by Marimuthu et al., [125], who mentioned that at 29±1°C, the incubation period of eggs was 23-24 h, resulting in 80-85% hatching. According to them, the newly hatched larva measured 3.4 ± 0.2 mm and completed yolk in three days. It takes 20 days for the larvae to metamorphose into juveniles [125]. Singh [124] reported 70-95% fertilization in *C. straitus*, which hatched out in 22-24 h.

The spawn of *C. straitus* is usually reared for a period of 7-10 days, and it can be fed with zooplanktons at ad libitum [124]. Fry can be provided with aquatic insects and chopped earthworms mixed with powdered fish meal and soya flour (3:1) at 5-10% BW twice a day in addition to live feed [124]. *C. striata* can be fed with cladocerans and Artemia nauplii as individual and mixed diets for enhanced performance [126]. It was reported that the incorporation of herbs Phyllanthus niruri, bacterium Bacillus subtilis, Almond Terminalia catappa, and aloe Aloe vera in the diet resulted in better growth performance and immunostimulation in *C. striata* fingerlings [126].

Wild seed collection and stocking

In the wild, after hatching out, in search of food, the seeds move in shoals along the marginal areas of the water body from where it can be collected [52]. The peak period for seed collection in Andhra Pradesh, India, was from May to August. The fingerlings of the snakehead can be collected from any water bodies where the species is naturally distributed [127].

Since snakeheads are hardy, air-breathing fishes, they are usually stocked at high densities of 20,000 to 30,000 fingerlings/ha [52]. Some farmers are stocking at 5000 to 8000 fingerlings/ha [128]. In the Indian state of Andhra Pradesh, snakehead seeds are stocked along with carp seed at 300-500 snakehead fingerlings/ha and are grown for 6-9 months [52]. Since snakehead is a hardy species [58, 129], it is usually cultured at densities of 40 – 80 fish/m^2 in grow-out ponds with yields ranging from 7-156 tonnes/ha 11].

Nutrition

In commercial farming of snakehead, it is mostly fed with feed made of fish paste and rice bran or wheat flour [130]. Similarly, in Thailand, snakeheads are also fed with feed consisting of trash fish along with wheat flour, rice bran, vitamin and minerals [131]. Artemia nauplii can be given as starter food and are able to accept formulated feed at ≥12 mm TL, while zooplankton and formulated feed can be given to fishes < 40 mm and larger fish, respectively [132]. When *C. striata* was fed with mosquito larvae, it gave best results in terms of growth and survival when compared to plankton and chironomus larvae [133].

Kumar and Haniffa [134] tested the effect of Tubifex, Chironomus larvae, beef liver, mosquito larvae and plankton in enhancing the growth of *C. striata* fry and reported that feeding fry with chironomus larvae showed better growth performance and survival. When *C. striata* was fed at 6% rate of fingerling biomass, it had optimum growth and survival with minimum cannibalism [135]. When early juveniles of C. striata were fed with cladoceran it gave better results in terms of growth and survival [136]. The details on weaning were already discussed by Kumar et al., [120].

Health management

It was reported that *C. striata* of all sizes are widely susceptible to the Epizootic Ulcerative Syndrome (EUS) [137] caused by Aphanomyces invadans leading to large scale mortality every year [52]. Roberts et al., [138] stated that snakeheads are particularly susceptible to EUS. Reports state that most of the fish affected by EUS are either bottom dwellers [139-140] or have air-breathing organs [138]. However, it is not always the case. Loss of appetite and lethargy are the common symptoms of fish affected with EUS. Pinhead-sized red spots can be noticed during the initial stage, which become small dermal ulcers during the intermediate stage whereas large hemorrhagic and necrotic open ulcers can be seen in the advanced stage [141-142]. Maintenance of proper water quality can minimize the breakout of EUS. Variable results have been reported when ash, turmeric, neem, dried banana leaves, immunostimulants etc. were used for treating EUS-infected fish [143-144]. So far, no protective vaccine has been reported against *A. invadans* [145]. Antibody responses were recorded when [146] immunized *C. striata* with different antigenic preparations from *A. invadans*.

Cannibalism

A detailed review on cannibalism mitigation in *C. striata* has been done by Raizada et al., [119]. Cannibalism is generally noted in carnivorous fish due to variations in size, high stocking density with less food supply [147]. However, the important factors contributing to cannibalism are size variation and limited food availability [148-149]. The main problem in snakehead culture is the low survival of fingerlings due to cannibalism and large size variation during grow-out culture [11, 130]. It was reported that snakeheads can swallow fish approximately half of their length [11, 58, 130]. Several researchers [80, 150] reported that a limited supply of food and differences in size during initial stages might induce cannibalism in snakehead and concluded that cannibalism was reduced from 86% to 36% when food supply was increased.

Medicinal value

The flesh of *C. striata* contains high levels of arachidonic acid, which affect blood clotting and wound healing [151]. The role of extract from *C. striata* in wound healing, tissue synthesis, and inhibiting free radical production is to be noted [152]. The biochemical properties of 100 ml of *C. striata* extract contain 3.36± 0.29 g of protein, 2.17± 0.14 g of albumin, 0.77± 0.66 g of total fat, 0.07 ± 0.02 g of total glucose, 3.34 ± 0.8 mg of Zinc, 2.34 ± 0.98 mg of copper, and 0.20 ± 0.09 mg of Iron [152]. The amino acid and fatty acid profiles of *C. striata* are presented in Figures 3 and 4.

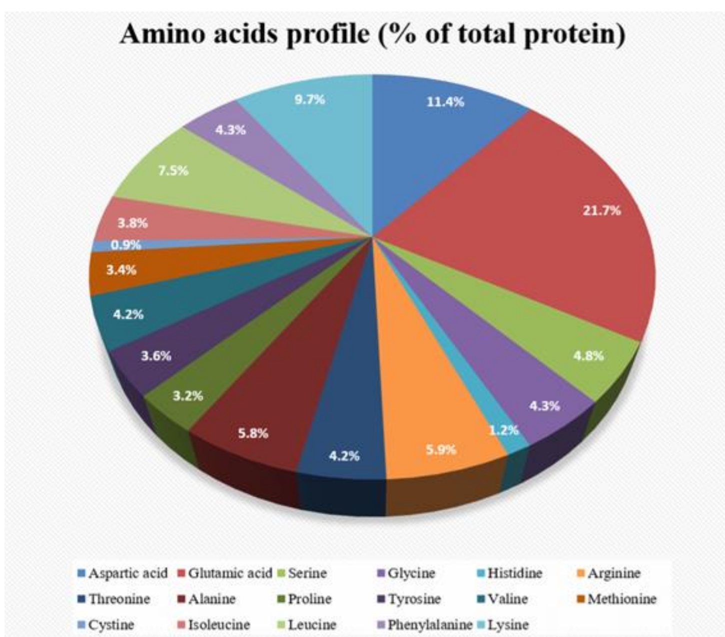

Figure 3. The amino acid profile (% of total protein) of *Channa striata* [55]

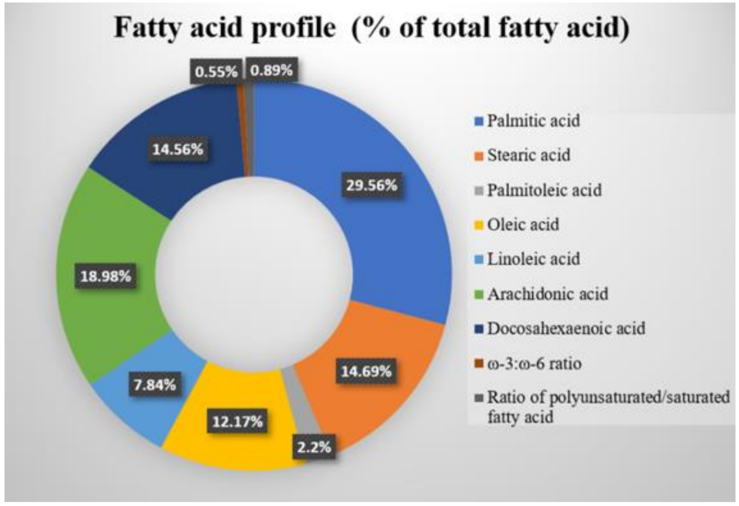

Figure 4. The fatty acid profile (% of total fatty acid) and ratio of ω-3:ω-6 and polyunsaturated/saturated fatty acid of *Channa striata* [55]

It was also reported that an extract from C. striata increased albumin levels in hypoalbuminemia and accelerated wound healing [152-155]. Suprayitno [156] stated that administration of extracts from *C. striata* daily for 5 consecutive days increased albumin level from 1.8 g/100ml to > 3.5 g/100 ml. *C. striata* extract shows antifungal activities against Aleurisma keratinophilum, Neurospora crassa, and Cordyceps militaris [157]. It has antimicrobial properties against *Aeromonas hydrophila*, *P. aeruginosa*, *Vibrio anguillarum* and *V. fischeri* [158]. It also has anti-bacterial activity against *P. aeruginosa*, *Klebsiella pneumoniae* and *Bacillus subtilis* [159].

Karmakar et al., [160] stated that the skin extract from *C. striata* called shol fish skin extract (SFSE) had cardiotoxic factor II which increases the cardiac marker enzymes such as creatine phosphokinase-MB and creatine phosphokinase values [161]. It was also reported that *C. striata* can be used as medicine for hypertensive patients due to its high angiotensin converting enzyme inhibitory activity [162]. Similarly, the SFSE could initiate apnoea and irreversible blockade of nerve-muscle preparation and influence the serotonergic receptor system [163], as an anti-depressant [164-165]. The neurons affected by traumatic injury were positively influenced and induced to regenerate with the help of this extract [166]. Reports state that *C. striata* can help in reducing the swelling of soft tissue and synovial inflammation and improve the density of PGP 9.5-immunoreactive nerve fibers in the synovial membrane of the osteoarthritis joints in rats, and hence it is used for arthritis treatments [167].

Laxmappa and Babu [52] mentioned that in the state of Andhra Pradesh in India, every year during June, snakehead fingerlings are given as medicine for asthma during Mrigasira Karthi for which people from all over the country gather at Hyderabad.

Commercial exploitation

Djumanto et al., [53] mentioned that the fishing process of *C. striata* is carried out throughout the year in Indonesia with an estimated catch of about 360 tons/year. The common gears used for capture are fishing rods, traps, spears, bamboo slat fences, circular and lift nets. They also stated that the population in a particular place is affected by growth rate, fishing pressure, natural deaths and the number of recruits. Torres et al., [61] reported a decline in catch from 10,469.58 metric tons in 2010 to 9,512.3 metric tons in 2017, which accounts for a 7% reduction. Puspaningdiah et al., [168] said that due to intensive fishing methods, poor quality of aquatic biota and use of improper gears, the native stock of *C. striata* decreases in Indonesian waters, leading to reduced capacity for reproduction. This large-scale exploitation challenges the recruitment process, especially when the parent stock is less in number [169].

Future research perspectives

Snakeheads are potential species for aquaculture due to their hardy nature. Our review identified a few scientific studies on its feeding ecology, reproductive biology, and medicinal value. However, an uninterrupted and continuous supply of fingerlings is required for successful aquaculture practices, which is the major hindrance since hatchery procedures have not yet been developed. Hence, during early stages, first feeding, rearing conditions, weaning diets, and weaning time must be optimized and monitored under both indoor and outdoor rearing systems to produce robust larvae.

In snakeheads, details on the nutritional requirements during early life stages and broodstock development are limited. Some region-specific commercial compound diets are being produced for snakeheads, whichares not species specific and their impact on production is still unknown. Therefore, compound diets with easily available ingredients must be developed to improve rearing practices. Nutritional experiments should be designed to enhance larval health by producing functional feeds using omic tools that perform well under different rearing conditions and feeding rates. Similarly, the feed produced must be complete and well balanced to reduce cannibalism and maximise the larval performance and quality.

Apart from these the following points must be addressed: (1) development and growth performances of larvae and fry produced by various synthetic hormones; (2) optimum prey-predator size ratio to reduce cannibalism; (3) optimum stocking densities at different developmental stages; (4) larval and fingerling rearing techniques; (5) broodstock nutrition to induce early maturation; (6) complete gonad developmental cycle at different seasons towards designing captive maturation programmes; (7) possible effects of climate change in this species.

The ability of the fish to survive under varying environmental conditions depends on the variability among populations as well as individuals within a population [170]. Snakeheads are under excessive exploitation by capturing fisheries and loss of aquatic ecosystems, combined with poor fishery management resulting in the depletion of the fishery stocks, which can lead to total gene pool loss [171]. Conservation of genetic diversity has emerged as one of the central issues in conservation biology [172], considering its value for the sustainability of populations. However, studies in this line for various populations of snakehead distributed worldwide are lacking. Therefore, it is essential to document the genotypic characterization of different populations of snakeheads in order to develop a holistic conservation strategy.

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