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Review Article

Non-native freshwater fishes in India: existing evidence and knowledge gaps

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Abstract

India has experienced the introduction of numerous non-native fish species (NNF), some of which have caused ecological and economic impacts. This systematic review provides a currently lacking overview of NNF research in India, potential biases, available evidence, and knowledge gaps. Using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, we identified a total of 332 records, documenting the presence of 58 NNF distributed across 17 basins, and 19 translocated species in India. The Ganga was the most studied basin (113 studies), followed by the West Flowing Rivers Tadri to Kanyakumari basin (37 studies), however, with 30 NNF reported from each of these basins. We demonstrate how these results can be due to saturated sampling in the Ganga and identify which basins might be currently understudied. We also illustrate how extreme floods precipitated an increase in NNF into rivers and lakes from confinement in the West Flowing Rivers Tadri to Kanyakumari basin. The common carp, *Cyprinus carpio*, was the most frequently reported NNF (160 times), while Mozambique tilapia, *Oreochromis mossambicus*, was the most widely distributed NNF (13 basins). We found there is a growing number of publications in the field, but that up to 40% of studies have appeared in potentially predatory journals. A minority of studies (44%) investigated NNF impacts, most of which used data from the literature (58%) and reported only qualitative impacts (69%). Most documented impacts were ecological (79%), while some were socio-economic (11%) or both (10%). Only 18% of the studies addressed NNF management. The knowledge synthesized and the gaps identified in this study might serve as a basis for future studies and be useful for efficiently allocating limited resources for investigating NNF in India.

Key words: Asia, freshwater ecosystems, invader impacts, invasive alien fishes, management of invasive alien species, spatial distributions

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Introduction

While the research field of invasion biology has largely focused on terrestrial taxonomic groups (Pyšek et al. 2008; Jeschke and Heger 2018), freshwater fishes are one of the most extensively introduced and impactful groups (Leprieur et al. 2008; Cucherousset and Olden 2011; Marcolin et al. 2025). A total of 1451 non-native fish species (NNF) are known to have established globally in novel environments (Seebens et al. 2023), and many of these have become invasive, i.e., have caused deleterious impacts on native biodiversity, ecosystem services or human economy and well-being (following the definition of the International Union for Conservation of Nature; IUCN 2000). For instance, the invasive Nile perch, *Lates niloticus*, caused the extinction of 200 native endemic fish species in Lake Victoria, Africa, resulting in irreversible damage to the lake's ecosystem and affecting the livelihoods of fishermen (this example and others were reviewed by Bernery et al. 2022; Bacher et al. 2023). Further, an estimated 37 billion USD in economic losses have been caused globally by 27 invasive non-native fish species (Haubrock et al. 2022).

While most research on NNF has focused on wealthy regions like North America, Europe and Australia (Olden et al. 2008; Bernery et al. 2022; Marcolin et al. 2025), we here focus on India, which has also experienced many NNF introductions. It is a vast country with 4% of the earth's freshwater resources spread across 25 river basins (India-WRIS 2012) and hosting about 936 native freshwater fish species (AqGRISI 2024), many of which are endemic (Dahanukar et al. 2004; Singh and Sarma 2015). The first documented NNF in India was the brown trout, *Salmo trutta*, which was introduced in 1863 as a sport fish for angling (Singh and Lakra 2011). Subsequently, there were intentional and unintentional introductions of many NNF through various pathways, such as ornamental trade, aquaculture and biological control (introduction pathways to India were reviewed by Singh and Lakra 2011), whose estimated numbers today vary between 288 and 633 (Ghosh et al. 2003; Singh 2021a; Sandilyan 2022). Fourteen NNF have been classified as invasive in India, following the criteria suggested by the Convention on Biological Diversity 2002 (Sandilyan et al. 2019).

Various aspects of freshwater NNF have been extensively studied in India, encompassing their presence (Kurup et al. 2006; Das et al. 2013; Gurumayum 2021), population trends (Kumar 2000; Raghavan et al. 2008), biology (Raj et al. 2021b; Singh et al. 2021), impacts (e.g. decline in native fish catch in river Ganga; Singh et al. 2013), and strategies to manage them (e.g. declaring Himalayan rivers' headwater as invasion refugia for native fishes; Sharma et al. 2021). There has also been research on NNF as potential disease vectors (Tripathi et al. 2022) and on heavy metals in NNF including contamination, bioaccumulation and use of NNF in toxicological studies (Singh et al. 2012). Other studies examined the performance of NNF in aquaculture (e.g. common carp, *Cyprinus carpio*; Manna and Som 1982; Das et al. 2021) and for biological control (e.g. western mosquito fish, *Gambusia affinis*; Chakraborty et al. 2008; Ghosh et al. 2011). Moreover, several reviews have provided insights into various aspects of NNF (Sarkar et al. 2012; Singh 2021a; Sandilyan 2022). Despite the extensive research conducted in these areas, a comprehensive synthesis integrating these studies is currently lacking which can support evidence-based decision-making and help prioritize management actions (Cook et al. 2013).

This study aims to provide such a review on NNF in India, compiling studies on NNF across all freshwater basins in India. Specifically, we provide an overview of the available types of studies that directly or indirectly investigated NNF in India, their development over time and in which scientific journals (non-predatory vs. potentially predatory) they were published. Further, we identify the NNF for which most research studies were carried out in India and provide a map showing the distribution of NNF corrected for basin area and research effort in India. We also analyze determinants of the number of NNF and show how these numbers have changed through time for different basins and India as a whole. Additionally, we report on the proportion of studies addressing different types of NNF impacts and the level of collaboration between executing agencies, as well as the influence of funding on the assessment of potential impacts. Finally, we compare recommended management strategies and their comprehensiveness.

Methods

Data collection

We gathered records of NNF in India up to the end of 2022 following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) for ecology and evolutionary biology (O'Dea et al. 2021). We scanned literature from the Google Scholar and Web of Science databases using the English search string: "Invasive" OR "Exotic" OR "Alien" OR "Introduced" OR "Non-native" OR "Nonnative" OR "Non-indigenous" OR "Nonindigenous") AND "India" AND "Fish*". A total of 2305 studies were identified of which 332 studies were considered relevant for our study (see Suppl. material 1: table S1 for details). A study was considered relevant if it dealt with freshwater NNF (excluding studies on marine and estuarine NNF) in the geographical extent of India.

For each of the 332 identified relevant studies, we compiled the following information: (1) author name(s); (2) year of publication; (3) name of journal or other type of publication; (4) type of article (peer-reviewed or potentially predatory articles in scientific journal, book/book chapter, seminar proceedings or magazine article); (5) the focal study area ("*checklist*": documented diversity of fish, "*biology*": biology of NNF, "*fish health*": disease/pathogens and their spread, "*aquaculture*": fish production and enhancement including nutrition, "*review*": review papers, "*impact*": impact of NNF in recipient ecosystem, "*management*": management of NNF, "*fishery*": fishery of NNF, "*toxicity*": bioaccumulation and effect of pesticides and heavy metals, "*reports*": reporting of presence or range extension of NNF, "*status*": population trend of NNF; "*biocontrol efficiency*": testing efficiency of NNF for disease control; and "*others*": ornamental trade/database/supply chain management/use of DNA in taxonomy and post-harvest/processing); (6) in which river basin the study was carried out (field studies) or the fishes were collected (laboratory studies); (7) the focal NNF and/or translocated species; (8) qualitative or quantitative impact; (9) type of impact (experimental, observational or inferred); (10) direction of impact; (11) any acknowledged funding; (12) author affiliations; and (13) any suggested management measures (see below and Suppl. materials 3, 4 for details).

We consulted several sources to determine if an article was published in a potentially predatory journal. Beall's list contains potentially predatory journals or publishers (https://beallslist.net/), whereas Clarivate's Journal Citation Report (https://jcr.clarivate.com/jcr/browse-journals) and National Academy of Agricultural Science (NAAS), India (https://naas.org.in/NJS/journals2022.pdf), publish lists of peer-reviewed journals every year. Therefore, we categorized a study as potentially predatory if the respective journal was listed in Beall's list and if it was not listed in the reports of Clarivate's Journal Citation Report or NAAS.

As river basins (also known as catchment areas or watersheds) form the natural biogeographical barriers for freshwater fishes (Leprieur et al. 2008), we noted in which river basins each study was carried out. To do so, we extracted boundaries of 25 river basins provided by HydroBASINS (Lehner and Grill 2013) based on the river basin boundaries established by the Government of India (India-WRIS 2012) (https://indiawris.gov.in/wris/#/atlas). Depending on the geographic location that was investigated in a study, it was assigned to the respective river basin. Laboratory studies were assigned to river basins if the information on the location of sample collection was available; if not, records were classified as laboratory studies without information on river basin. Records where the study areas were mentioned as political boundaries (states or country) or eco-regions (Indian Northeastern Region, Indian Himalaya, Western Ghats) were classified separately, and the same was true for studies covering multiple river basins.

We noted which non-native or translocated fish species were mentioned in each study. We defined non-native fish species (NNF) as those that have been introduced to India by human action, either intentionally or unintentionally (following Blackburn et al. 2011; Jeschke et al. 2022; synonyms to "non-native" are "alien", "exotic" or "non-indigenous"); and we defined translocated fish species as those that are native to India but have been introduced within India by human action, either intentionally or unintentionally, to one or more river basins outside of their native range. Since both Latin and common English species names change over time and synonyms exist, we standardized species names using Eschmeyer's Catalog of Fishes (Fricke et al. 2024).

Regarding NNF impacts, we discriminated qualitative from quantitative impact assessments. Studies that reported impacts non-numerically or descriptively (for example, non-native fishes gradually replacing native fish fauna in the middle stretch of the Cauvery river; Roshith et al. 2022) were labelled as qualitative impacts; whereas studies that reported impacts numerically (for example, estimates of annual fish landings of non-native common carp, *Cyprinus carpio* and native fish species in the River Ganga, and its comparison with historical fish landings; Ray et al. 2021) were considered as quantitative impacts. Impacts were described as ecological, socio-economic, or both, and the direction of impact as deleterious, beneficial, or both (following Jeschke et al. 2014). Finally, we classified the mode of impact assessment as either (i) observational, impacts were observed by the authors (for example, burrows dug by the Amazon sailfin catfish, *Pterygoplicthys pardalis*, in canal margins; (Raj et al. 2021b) or temporal variation in fish catch composition (Sarkar et al. 2012); (ii) experimental, impacts were assessed by conducting experiments as in comparing the efficacy of two non-native larvivorous fish (Ghosh et al. 2011); or (iii) inferred, impact deduced from the literature, based on the species known to have impacts elsewhere (Raj et al. 2020).

We also gathered information on suggested management measures. Robertson et al. (2020) proposed a framework for the management of biological invasions with ten key management terms that broadly cover all active management objectives including the support of active management (monitoring, risk assessment etc.). Using these terms, we categorized the management measures suggested in our studies (see Suppl. material 4 for details).

With the resulting dataset, we investigated trends in NNF research, proportion of potentially predatory articles, numbers of NNF, most studied NNF, most studied river basins, river basin with most NNF. We also map the spatial distribution of NNF across basins (corrected for basin area) and for the basins Ganga, Brahmaputra, EFR (East Flowing Rivers) Pennar to Kanyakumari, and WFR (West Flowing Rivers) Tadri to Kanyakumari, as well as collectively for India, we chronologically analyzed the relationship between the cumulative number of NNF species and the number of studies conducted there. Further, we examined patterns in impact assessments, proportion of studies in different focal areas, collaboration in research, and suggested management measures.

Statistical analyses

We analyzed differences in research effort among river basins. Some basins have not been studied at all. Therefore, we first used a binomial Generalised Linear Model (GLM) to test if the probability of at least one study being conducted in a basin is dependent on its size. We used the natural logarithm of area (in km^2) of each basin in the model:

[1] studyConducted ~ log(basinArea)

Then we used a linear model to see if, among the studied basins, larger basins were prioritized. To ensure normal distribution of residuals, both the number of studies and the basin area were log-transformed. The data were scanned for outliers and the following model was run with all basins as well as without the Ganga:

[2] log(nStudies) ~ log(basinArea)

A third model was used to detect any possible relationship between basin area, number of studies and the number of detected NNF in a basin. Here again, the reduced dataset was used covering only studied basins and area and number of studies were log-transformed. The full model consequently is:

[3] nNonNativeFishSpecies ~ log(nStudies) + log(area) +log(nStudies):log(area)

All models with all parameter combinations were compared using the dredge function of the MuMIn package (Bartoń 2023). All parameters that appeared in the best models with and accumulated model weight of > 0.95 were considered. The resulting most parsimonious model is given in the Results section.

We also investigated other potential biases in our studies. For this, we performed pairwise Chi-square tests with 100’000 bootstrap simulations to test if the funding source (public or private) has an influence on the predicted impact of the invader (deleterious or beneficial). Where not explicitly mentioned otherwise, all analyses were conducted using the R base package (R Core Team 2020).

Results

There has been an exponential growth in the number of publications on NNF in India over time. The first of the 332 identified studies is from 1957; however, there were no publications in the next decade (1961–70) and fewer than 10 publications per decade until 2000. In the following decades, the number of studies accelerated, with around 50 publications from 2001 to 2010 and almost 190 from 2011 to 2020. There were 73 publications in the first two years of the current decade (2021–2022). Projecting this number to all 10 years of the current decade means there will be an estimated 365 publications from 2021 to 2030 (Fig. 1). This projection is conservative, as it does not assume a further increase in the numbers of publications per year.

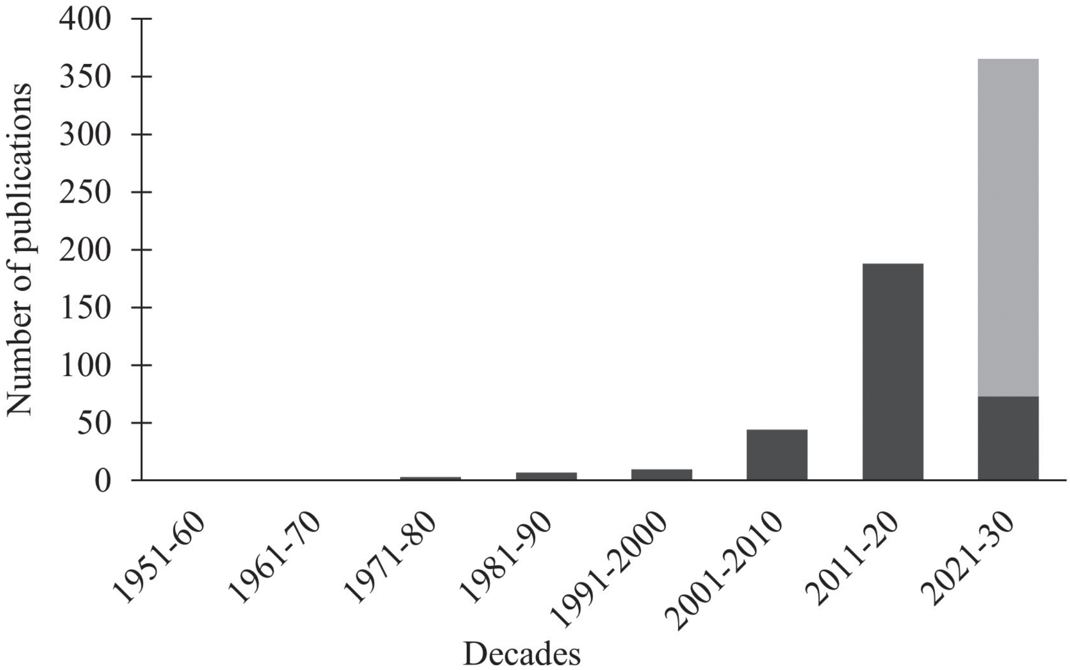

Figure 1. Decadal trend of publications in research about non-native fishes in India. The gray box for the current decade indicates the conservatively estimated number of publications from 2021 to 2030, assuming that the publication rate observed in this decade's first two years (73 publications in 2021 and 2022) will be constant until the end of the decade.

Most records are publications in scientific journals (309 records or 93%), but 41% of those were published in potentially predatory journals. For studies published by authors affiliated with universities, even the majority (54%) of publications in scientific journals were published in potentially predatory journals, whereas it was about a quarter (24%) for publications from non-university research institutes (see Suppl. material 2: fig. S1). For studies with both universities and non-university research institutes as affiliations, the proportion of publications in potentially predatory journals was in between (35%).

About 38% of the records examined NNF directly, investigating either their biology, impact, management, fishery, report, status or bio-control (see Suppl. material 2: fig. S2). A high number of studies (31% or 103 records) focused on documenting fish diversity (checklist) where NNF were opportunistic detections, while only 3% of the studies primarily reported NNF (11 records). Fish health (9%) and aquaculture (7%) are two other important topics of the studies in our dataset, which also includes several reviews (6%).

From our records, we detected 58 NNF distributed across 17 basins and 19 translocated fishes in India (Tables 1, 2). Of these, 55 NNF were reported from open waters (natural rivers and lakes as well as man-made reservoirs) in at least one basin. We were able to assign 250 studies (75%) to 17 river basins, whereas no studies were found for the remaining eight river basins (Table 3). The other 25% of the studies referred to political boundaries rather than river basins as study area (13%), were laboratory studies with no information on where the fish sampling location (10%) or focused on eco-regions or multiple river basins (3% combined). About half of the 250 studies were conducted in the Ganga basin (46% or 113 records), making it by far the most studied river basin in India followed distantly by the basin West Flowing Rivers Tadri to Kanyakumari (15% or 37 records). Significantly, despite this research bias there were 30 NNF reported for each of these

Table 1. List of non-native fish species (NNF) in India reported in the studies included in our dataset.

Non-native fish species	Non-native fish species
Osteoglossiformes: Arapaimidae	Siluriformes: Pangasiidae
Arapaima gigas	*Pangasianodon hypophthalmus*
Osteoglossiformes: Osteoglossidae	Characiformes: Serrasalmidae
Osteoglossum bicirrhosum	*Colossoma macropomum*
Lepisosteiformes: Lepisosteidae	*Piaractus brachypomus*
Atractosteus spatula	*Piaractus mesopotamicus*
Salmoniformes: Salmonidae	*Pygocentrus nattereri**
Oncorhynchus mykiss †	Beloniformes: Adrianichthyidae
Oncorhynchus nerka ‡‡	*Oryzias javanicus*
Salmo salar ‡‡	Cyprinodontiformes: Poeciliidae
Salmo trutta †	*Gambusia affinis** †
Salvelinus fontinalis ‡‡	*Gambusia holbrooki** †
Salvelinus namaycush ‡‡	*Poecilia mexicana*
Cypriniformes: Cyprinidae	*Poecilia reticulata*
Barbonymus altus	*Xiphophorus hellerii*
Barbonymus gonionotus	*Xiphophorus maculatus*
Carassius auratus	Cichliformes: Cichlidae
Carassius carassius	*Amphilophus trimaculatus*
Ctenopharyngodon idella	*Andinoacara rivulatus* §
*Cyprinus carpio** †	*Astronotus ocellatus*
Cyprinus rubrofuscus	*Coptodon zillii*
Puntius brevis	*Hemichromis bimaculatus*
Cypriniformes: Xenocyprididae	*Mayaheros urophthalmus*
Hypophthalmichthys molitrix	*Oreochromis aureus*
*Hypophthalmichthys nobilis**	*Oreochromis mossambicus** †
*Mylopharyngodon piceus**	*Oreochromis niloticus**
Cypriniformes: Tincidae	*Oreochromis urolepis* §
Tinca tinca	*Thorichthys meeki* §
Siluriformes: Clariidae	Anabantiformes: Channidae
*Clarias gariepinus**	*Channa lucius*
Siluriformes: Ictaluridae	Anabantiformes: Helostomatidae
Ictalurus punctatus	*Helostoma temminckii*
Siluriformes: Loricariidae	Anabantiformes: Osphronemidae
Hypostomus plecostomus	*Macropodus opercularis*
*Pterygoplichthys ambrosettii**	*Osphronemus goramy*
*Pterygoplichthys disjunctivus**	*Trichopodus microlepis*
*Pterygoplichthys multiradiatus**	*Trichopodus trichopterus*
*Pterygoplichthys pardalis**	*Trichopsis vittata*

* Invasive in India based on Sandilyan et al. (2019) who followed the definition of the Convention of Biological Diversity (2002).
† Among the '100 of the World's Worst Invasive Alien Species' (GISD 2024).
§ Reported from fish farms but no record from the wild in our dataset.
‡‡ Non-native population potentially extinct (Joshi and Lal 2017).

Table 2. List of translocated fish species in India reported in the studies included in our dataset.

Basin(s)	Reported translocated fish species
5, 7, 9, 12, 19, 24, 25	*Cirrhinus mrigala*, *Labeo catla*, *Labeo rohita*
1	*Anabas cobojius*, *Anabas testudineus*, *Channa punctata*, *Channa striata*, *Cirrhinus mrigala*, *Clarias magur*, *Danio rerio*, *Esomus danrica*, *Heteropneustes fossilis*, *Labeo catla*, *Labeo rohita*, *Notopterus notopterus*, *Puntius sophore*
7	*Badis badis*, *Lepidocephalichthys guntea*, *Osteobrama cotio*, *Pethia gelius*, *Pethia phutunio*
5, 9, 17, 24, 25	*Tor khudree*

Basins: (1) Andaman Nicobar Islands, (5) Cauvery, (7) EFR Pennar and Kanyakumari, (9) Godavari, (12) Krishna, (17) Narmada, (19) Pennar, (24) WFR Tadri to Kanyakumari, (25) WFR Tapi to Tadri.

Table 3. List of river basins in India with the number of non-native fish species (NNF) reported for each basin and the number of studies.

Number	Basin name	Area (km²)	# NNF	# Studies
1	Andaman Nicobar Islands	8249	12	4
2	Barak and Others	41723	0	0
3	Brahmani and Baitarani	51822	0	0
4	Brahmaputra	194413	12	17
5	Cauvery	81155	11	10
6	EFR Mahanadi and Pennar	86643	0	0
7	EFR Pennar and Kanyakumari	100139	19	11
8	Ganga	861452	30	113
9	Godavari	312812	10	7
10	Indus	321289	7	16
11	Inland Drainage in Rajasthan	139917	0	0
12	Krishna	258948	11	16
13	Lakshadweep Islands	32	0	0
14	Mahanadi	141589	7	5
15	Mahi	34842	1	4
16	Minor Rivers Draining into Myanmar and Bangladesh	36202	0	0
17	Narmada	98796	4	2
18	North Ladakh not draining into Indus	26018	0	0
19	Pennar	55213	6	1
20	Sabarmati	21674	2	1
21	Subernarekha	29196	0	0
22	Tapi	65145	1	1
23	WFR Kutch and Saurashtra	321851	2	1
24	WFR Tadri to Kanyakumari	55177	30	37
25	WFR Tapi to Tadri	55940	8	4

NNF: Non-native fish species, EFR: East flowing river, WFR: West flowing river.

two basins (Fig. 2A, B). The common carp, *Cyprinus carpio*, was the most frequently reported NNF (160 times) followed by the Mozambique tilapia, *Oreochromis mossambicus* (108 times) (see Suppl. material 2: fig. S3A). However, the latter was the most widely distributed NNF (13 basins) followed by *Cyprinus carpio* (12 basins) (see Suppl. material 2: fig. S3B). Additionally, there were 24 NNF that were reported from only one basin each (see Suppl. material 5 for details).

The log(n) of the basin area had no significant relationship with the probability of at least one study being conducted in a basin (binomial GLM with $p = 0.15$). Further, the number of studies for studied basins was correlated to the basin area when using log-log transformation (linear model with adj. $R^2 = 0.18$, $p = 0.049$), but this relationship was exclusively driven by the largest and most studied river basin – the Ganga – and disappears when it is removed (linear model with adj. $R^2 = 0.02$, $p = 0.27$). Results for the full model (model [3] in the Material and Methods section) show that the number of detected non-native fish species is mainly related to the number of studies conducted in the respective basin, not to its area or the interaction of studies and area (see Suppl. material 1: table S6). Results for the most parsimonious model – the number of fish species in relation to the log of the number of studies (adjusted $R^2 = 0.69$, $p < 0.001$) – are shown in Fig. 2C, D. This model is robust to removing the Ganga basin ($R^2 = 0.56$, $p < 0.001$).

The river basins in India displayed a varying extent of (apparent) saturation in terms of NNF detections. The saturation curve almost flattened in the WFR Tadri to

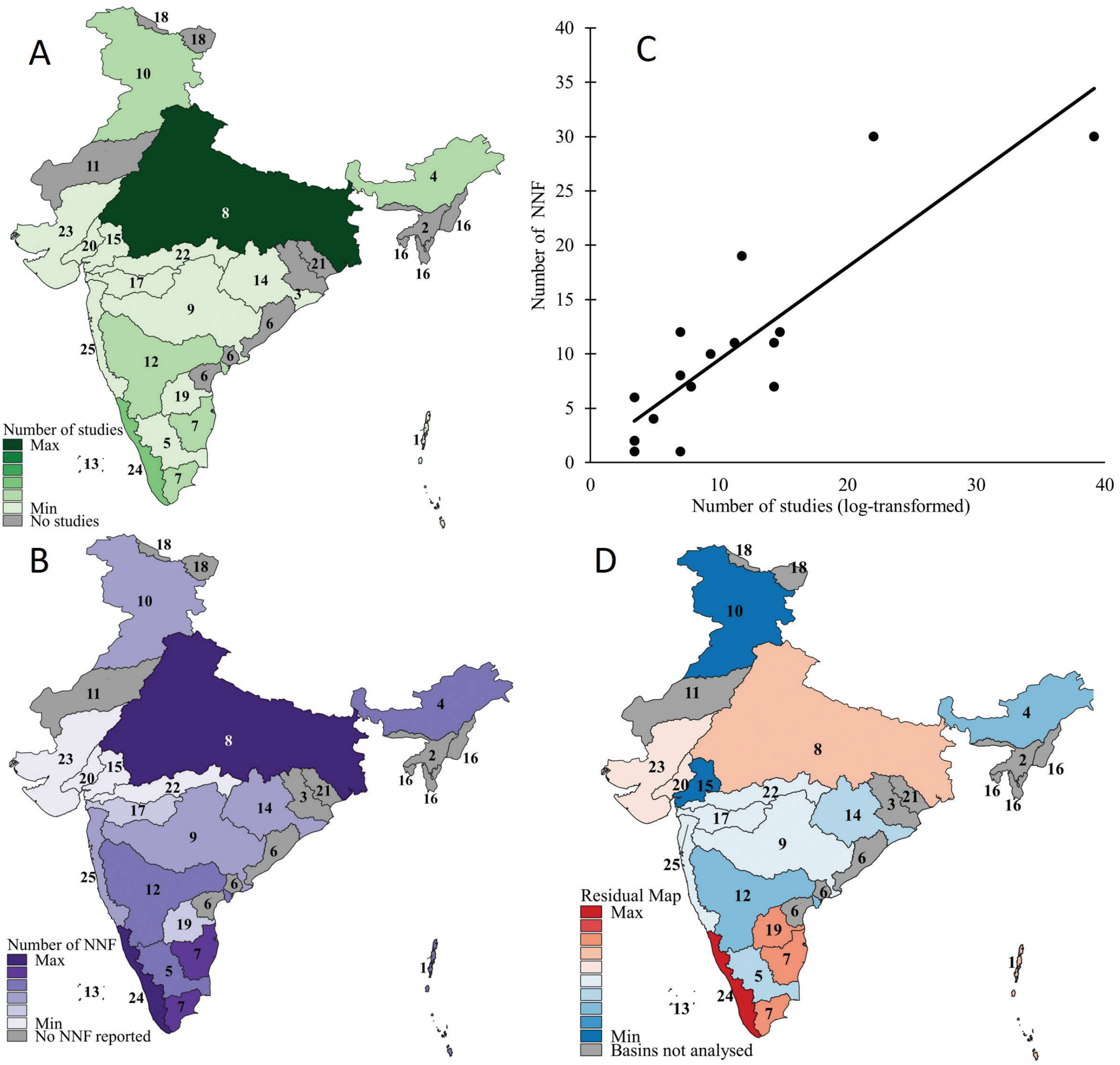

Figure 2. **A** number of studies on non-native fish species (NNF) for each river basin in India **B** number of reported NNF for each basin **C** relationship between the number of reported NNF and the number of studies for each basin (log-transformed) (adjusted R^2 = 0.69, $p < 0.001$) **D** map of residuals from plot C: red and blue colors indicate higher and lower numbers of reported NNF for each basin considering the number of studies, respectively. Grey color indicates basins with no studies (**A**), with no NNF reported (**B**) and that were not considered for analysis due to the absence of studies (**D**). Basins: (1) Andaman Nicobar Islands, (2) Barak and Others, (3) Brahmani and Baitarani, (4) Brahmaputra, (5) Cauvery, (6) East Flowing River (EFR) Mahanadi and Pennar, (7) EFR Pennar and Kanyakumari, (8) Ganga, (9) Godavari, (10) Indus, (11) Inland Drainage in Rajasthan, (12) Krishna, (13) Lakshadweep, (14) Mahanadi, (15) Mahi, (16) Minor Rivers Draining into Myanmar and Bangladesh, (17) Narmada, (18) North Ladakh not draining into Indus, (19) Pennar, (20) Sabarmati, (21) Subernarekha, (22) Tapi, (23) West Flowing River (WFR) Kutch and Saurashtra, (24) WFR Tadri to Kanyakumari, (25) WFR Tapi to Tadri.

Kanyakumari basin until 2021, but there was an abrupt rise in the number of detected NNF in 2022, which is also evident for India as a whole (Fig. 3A, E). With fewer additions to the NNF detections in the Brahmaputra basin in the last 50% of studies, it appears that most NNF in this basin have been detected (Fig. 3B). The detection of new NNF continues to increase almost linearly in the EFR Pennar to Kanyakumari basin (Fig. 3C). In the Ganga basin, the detection of NNF increased gradually and then almost plateaued with fewer detections for every additional study conducted (Fig. 3D).

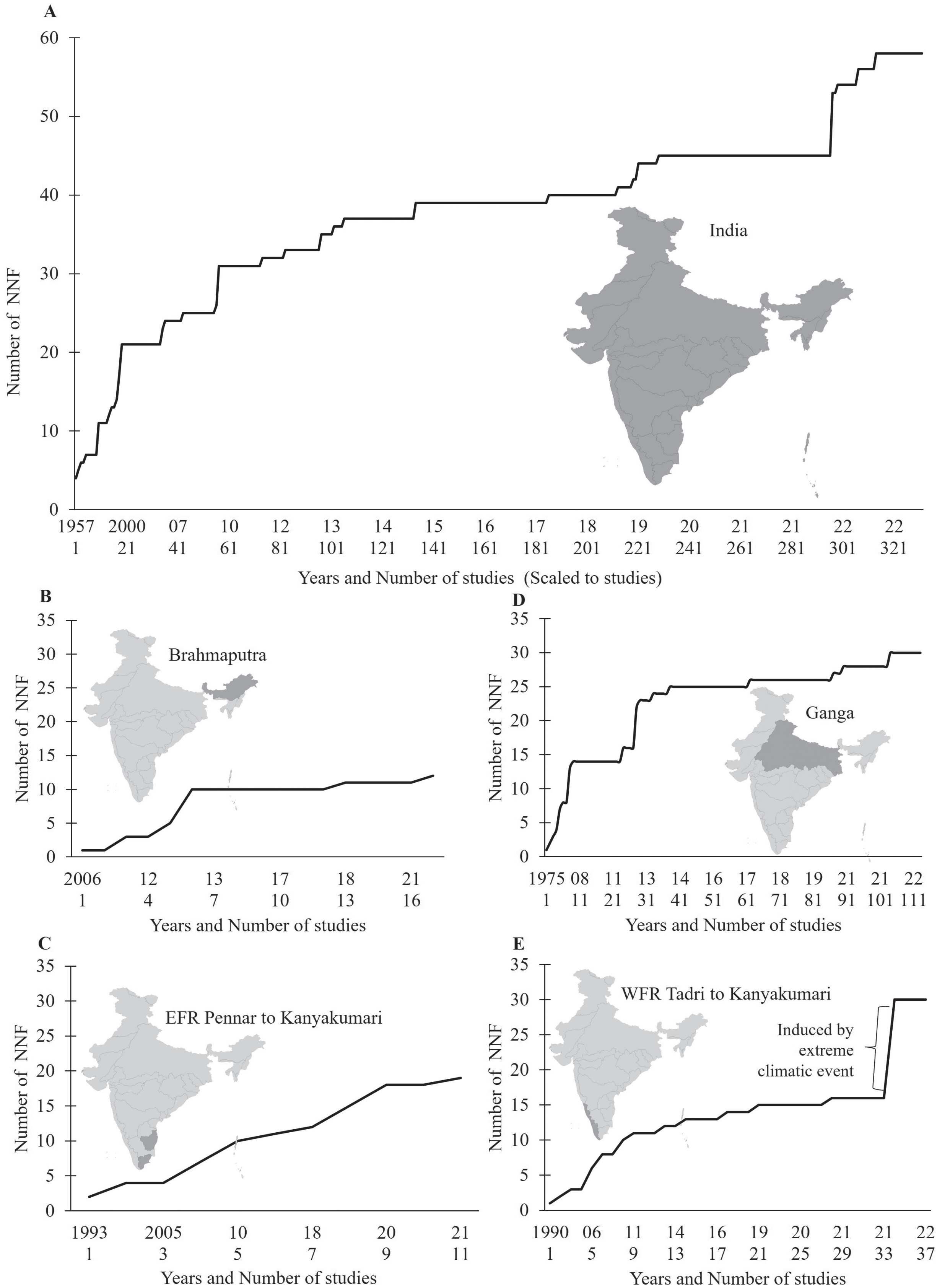

Figure 3. Relationship between the number of non-native fish species (NNF) detected over time with increasing number of studies for **A** India as a whole **B** the Brahmaputra basin **C** the EFR Pennar to Kanyakumari basin **D** the Ganga basin and **E** WFR Tadri to Kanyakumari basin. The abrupt increase in detection of NNF in **E** is attributed to severe floods in the basin that facilitated the escape of NNF from unregulated captive facilities.

Less than half of the records in our dataset (44% or 146 records) documented impacts of NNF (Fig. 4), and those that did mostly used secondary information: information deducted from the literature (58%), followed by observations (32%) and experiments (11%). Qualitative impact documentation was far more common than quantitative information (69% and 31%, respectively). Most documented impacts were ecological (79%), some were socio-economic (11%) or both (10%). There were far more negative impacts documented (69%) than positive ones (14%), and these outcomes were not related to funding agencies (X-squared = 5.11, p = 0.27). All p-values are Bonferroni-Holm corrected.

There were only few agencies funding the studies in our dataset, and there was a lack of networking between the executing institutions. The bulk of the studies (64%) did not report funding information. Of the 36% of studies that reported funding agencies, internal funding was most common: Government of India (GoI), state-level funding or a combination of these two amounted to 88%. International collaborations, partly with GoI, were funding 10% of the studies. The remaining studies were self-funded and amounted to only a few percent. Most of the studies were executed independently by academic institutions (47%) or non-academic research institutions (34%). There were few collaborative studies between domestic institutions (13%) and with international institutions (3%).

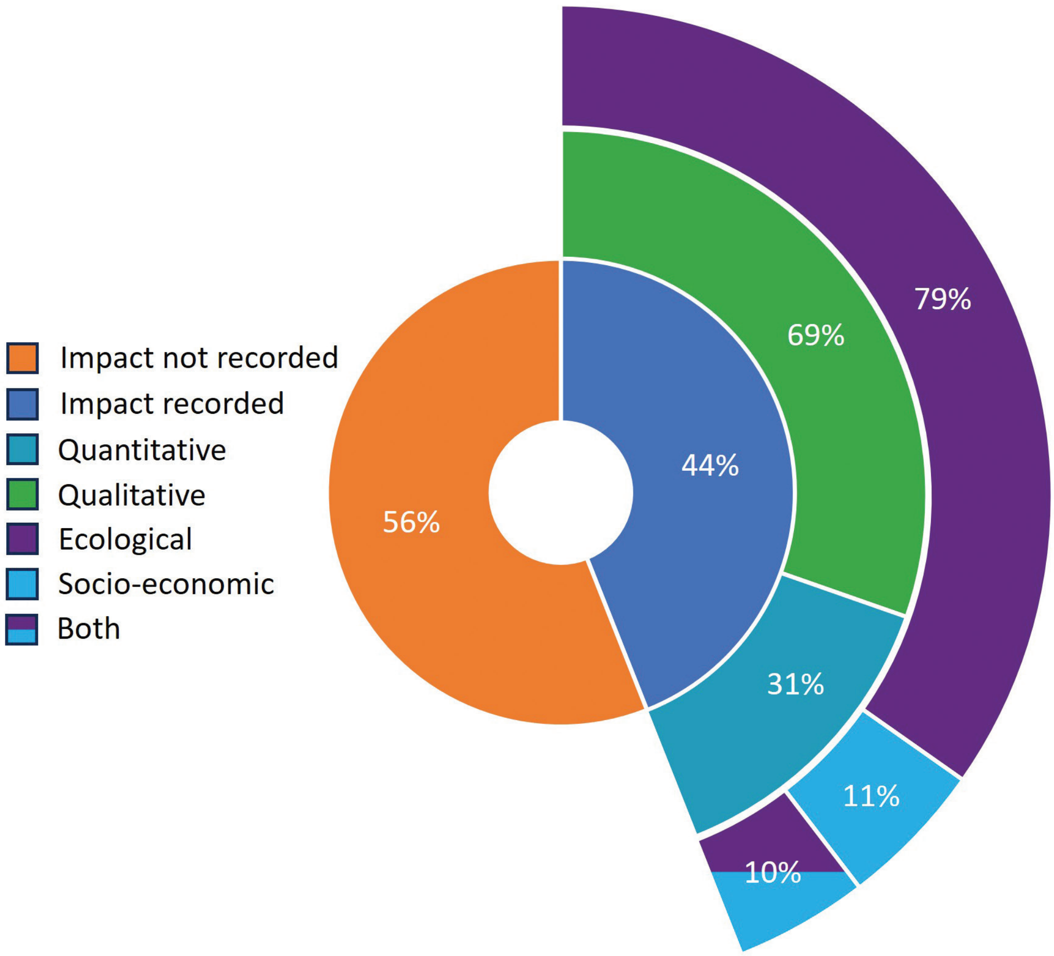

Figure 4. Impacts recorded by studies on NNF in India (n = 332 studies). The inner circle shows the proportion of publications that did or did not record the impacts of NNF. The middle circle shows the proportion of qualitative vs. quantitative impacts recorded by the studies. The outer circle shows the proportion of ecological, socio-economic or both types of impacts recorded by the studies.

Only 18% of the total records addressed the management of NNF. The majority of those suggest activities that support active management, such as ‘awareness’ or ‘monitoring and early detection’. The minority of suggestions were on active management such as ‘eradication’ (e.g. of the three-spot cichlid, *Amphilophus trimaculatus*; Kumar et al. 2021).

Discussion

The growing number of non-native fishes in India

The present study highlights the increasing numbers of NNF and the prevalence of translocated fish species in India. A degree of uncertainty was noticed in the number of NNF in India, as well as in their taxonomy and presence. Various estimates suggest that there are anywhere between 288 and 633 NNF in India of which 29–31 were introduced for aquaculture, 2-3 for mosquito control and 288–600 species or varieties for ornamental use (Ghosh et al. 2003; Singh and Lakra 2011; Singh 2021b; Sandilyan 2022). There is a lack of clarity on the total number of ornamental fish species because some estimates mention the count as ‘species’ and others as ‘varieties’ (Singh 2021b; Sandilyan 2022). Further, there is uncertainty over the presence of the red piranha, *Pygocentrus nattereri*, in India. The earliest mention of this NNF from our records was in 2000 (Kumar 2000). Subsequent genetic analysis of samples collected from different regions in India claimed that the species was actually the pacu, *Piaractus brachypomus*, a close relative looking similar to red piranha (Tiknaik et al. 2019). Further, it was reported that some NNF in cold waters of India have perished (Table 1) (Joshi and Lal 2017), casting doubt over the exact number of extant NNF in India.

Translocated fishes have the potential to become invasive, similar to NNF (Tarkan et al. 2017). In India, translocation of fish species, specifically Indian Major Carps (*Cirrhinus mrigala*, *Labeo catla*, *Labeo rohita*), was driven by national programs aimed at enhancing fish production from the reservoirs across the country through systematic stocking (Sarkar et al. 2018). Other species may have been translocated by hitch-hiking during the translocation of Indian Major Carps, while additional species may have been moved actively for ornamental purposes. In our dataset, some studies did not consider translocated species as non-native to the basin (Wagh et al. 2018; Ray et al. 2022). Conversely, other studies did so and concluded that translocated fishes are impacting native fish species (Sugunan 1995; Dahanukar et al. 2012; Katwate et al. 2012). Furthermore, research findings have demonstrated that translocation of Deccan mahseer, *Tor khudree*, has detrimentally affected the population of the endemic hump-backed mahseer, *Tor remadevii*, in the river Cauvery (Pinder et al. 2020). Therefore, we argue it is important to more widely study the impacts of translocated fishes.

Research biases and cumulative numbers of non-native fishes across river basins

Studies on NNF were not proportionally distributed across basins. Basin size had no significant influence on whether a basin was studied. Further, we did not find a single study for eight of the basins (greyed basins in Fig. 2D). This might be partly due to indexing issues and constraints of a systematic review because not all relevant records may be identified during the literature search owing to limitations in, for example, the search language (Livoreil et al. 2017). However, such limitations also apply to studies carried out in other basins for which we did find a number of records. We therefore suggest that these eight basins for which we found no relevant study are really – at least in relation to the other basins – severely under-researched. Underlying reasons potentially include lack of regional expertise, challenging terrains, accessibility issues or seasonal water bodies (Chatterjee 2008; India-WRIS 2012).

The number of detected NNF was not consistent across basins for a given number of studies (Fig. 2C). This inconsistency can be due to true differences in the number of NNF across basins, but partly also due to differences in apparent effort vs. actual effort. While the number of studies is 'apparent effort', the 'actual effort' also includes the focus of these studies. For example, compared to a study focused on assessing the biology or fisheries of selected fish species, a study focused on fish diversity is more likely to document a greater number of fish species, including NNF. Therefore, the optimal number of studies required to detect the maximum NNF (if not all) varies depending on actual effort per study. Further, targeted studies aimed at detecting NNF are more likely to identify them in time, which is crucial for implementing early detection and rapid response programmes (Morisette et al. 2020), which are currently lacking in India.

The cumulative number of detected NNF through time showed an apparent saturation for some basins. This was the case for the Ganga basin, suggesting that there may be only few additional NNF detected for any additional study conducted (Fig. 3D). Similarly, a study on the lower New River drainage in the USA found that the system is nearly saturated with NNF (Welsh et al. 2025). However, events can profoundly affect the number of NNF in a basin, thus apparent saturation trends can be misleading. For example, the First and Second World Wars resulted in an apparent saturation of NNF in the Seine River basin (France) in the first half of the 20th century, yet there has been a continuous rise in the number of NNF afterwards (Belliard et al. 2021). In our study, the WFR Tadri to Kanyakumari basin witnessed a sudden increase in the number of NNF which was due to an extreme climatic event causing two sequential floods in August 2018 and August 2019. This event altered the geomorphology and flow patterns of major rivers in the basin, facilitating escape of ten NNF into the wild from unregulated captive facilities (Fig. 3E) (Raj et al. 2021a). For the EFR Pennar to Kanyakumari basin, no saturation in the cumulative number of NNF was observed (Fig. 3C), thus there is high potential of detecting new NNF with additional studies.

Impacts and management of non-native fishes in India

In our dataset, NNF impacts were observed in 19% of the studies (62 out of 332 records), which is close to the global average of 22% (Roy et al. 2023b). Kulhanek et al. (2011) observed a lack of studies documenting quantitative impacts of non-native aquatic species, which is in line with our findings. Ecological impacts were reported more frequently, a trend also observed in Europe where invasive NNF exerted substantial environmental effects while their economic consequences remained less investigated (van der Veer and Nentwig 2015). This discrepancy in documentation can be attributed to inherent challenges in assessing economic impacts, which stem from a lack of multisectoral data; there are also challenges in translating impacts into monetary terms (Haubrock et al. 2022). Not surprisingly, there is generally also more information on ecological impacts of NNF at a global scale than for India. For example, species such as grass carp, *Ctenopharyngodon idella*, and common carp, *Cyprinus carpio*, have caused local extinctions of aquatic macrophytes in the USA and New Zealand (Hofstra and Clayton 2014; Bajer et al. 2016), and rainbow trout, *Oncorhynchus mykiss*, have eliminated native fish species from certain streams in South Africa (Shelton et al. 2015). The impacts of these NNFs in India has not been systematically assessed, thus evidence is lacking. Knowledge about the impacts of NNF in India is generally sparse, and we recommend that more research is carried out to quantify NNF impacts.

Management of invasive NNF strives to minimize their ecological and economic impacts (Britton et al. 2023). However, the percentage of studies recommending measures to manage NNF species in India was 18% lower than the global average of 23% (Roy et al. 2023a), indicating a lack of focus on management strategies in the existing NNF research in India. In addition, the recommendations in existing studies were largely unspecific: most of the active management interventions suggested in our records lacked information on spatial and temporal scale related to the suggested intervention. For instance, Kumar et al. (2021) recommended the eradication of three spot cichlid (*Amphilophus trimaculatus*) in the Cauvery River without proposing a geographic scope for the eradication program. Our results highlight the need for a comprehensive approach addressing both supporting and active management actions for effective NNF management in India (Robertson et al. 2020).

Potentially predatory publications

Our study shows that the literature about NNF in India is burdened with potentially predatory articles and lack of collaboration. Shen and Björk (2015) found that Indian authors contributed significantly (35%) to predatory journals, while authors from the USA contributed only 6%, a trend that aligns with our findings. In contrast, India being ranked 9th for its high-quality scientific publications in the Nature Index 2024 (Plackett 2024) and showing a declining trend in predatory publishing (Shen and Björk 2015) suggests that while this issue has been a concern, measures are being implemented to enhance research integrity (Patwardhan 2019). Additionally, collaborations can play a significant role in addressing complex problems (Hall et al. 2018) and have the potential to improve the quality of science by reducing the number of predatory articles (Campbell and Simberloff 2022), for which we show some support as well (see Suppl. material 2: fig. S1).

Limitations and future directions

Our study had three important limitations. First and as already mentioned above, we only searched for English literature, thus we may have missed information available in other Indian languages. India is a multilingual country, and, as such, information may be available in a variety of regional languages. However, given that higher science education is predominantly delivered in English, the vast majority of scientific publications are also in English. Second, the current form of some basin boundaries does not match the criterion of a true biogeographic boundary for freshwater fish distribution. The reason is that these basins were originally delineated for water management purposes (India-WRIS 2012). For instance, 45 rivers in the basin 'West Flowing River Tapi to Tadri' (basin 24 in Fig. 2A) are flowing independently into the Arabian sea and could therefore alternatively be delineated as 45 independent basins (Srivalli et al. 2019). Similarly, Andaman Nicobar islands (basin 1) is an archipelago of 572 islands, islets and rocky outcrops (Das 2011). Further, the basin 'East Flowing Rivers Pennar to Kanyakumari' is a two-piece land sandwiching the Cauvery basin (basin 5 sandwiched between basin 7, Fig. 2A), highlighting that this basin cannot be considered as one for fish distributional studies. Third and finally, we used data from potentially predatory articles in our study, despite questions about their quality (Boukacem-Zeghmouri 2023). We did so because the data extracted from these articles was basic in nature and can thus hopefully be trusted. Excluding such data would have significantly reduced the dataset (see Suppl. material 2: fig. S1).

Despite these limitations, this study offers the largest to date overview of existing published evidence and knowledge gaps about NNF in India. Following the global trend (Enders et al. 2019), the discipline of freshwater fish invasion science in India is growing exponentially, thus there is hope that the knowledge gaps shown here will be narrowed in the future. Given that the federal Indian government is the largest funding agency, resources may be rationally allocated for projects focusing on targeted detection and impact assessments of NNF, particularly in the understudied basins. Collaborations, both domestic and international, are important to facilitate and improve research in invasion science, which is inherently transboundary in nature. Delineating drainage basins for managing freshwater fishes is essential and, because every basin is unique, a national plan to manage NNF should be a collective of management plans devised for individual basins.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Author contributions

Conceptualization: LK, JMJ, FR. Data curation: LK. Formal analysis: FR, LK. Funding acquisition: LK. Investigation: LK. Resources: JMJ. Supervision: JMJ. Visualization: LK. Writing – original draft: LK. Writing – review and editing: JMJ, FR.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

PRISMA and models

Authors: Lohith Kumar, Florian Ruland, Jonathan M. Jeschke

Data type: docx

Link: https://doi.org/10.3897/neobiota.102.146421.suppl1

Supplementary material 2

Supplementary images

Authors: Lohith Kumar, Florian Ruland, Jonathan M. Jeschke

Data type: zip

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Supplementary material 3

Records used and information extracted

Authors: Lohith Kumar, Florian Ruland, Jonathan M. Jeschke

Data type: xlsx

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Supplementary material 4

Management measures suggested in records

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Supplementary material 5

Spatial distribution of NNF

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