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REVIEW

REVIEWS IN Aquaculture

An assessment of the aquaculture potential of indigenous freshwater food fish of Fiji, Papua New Guinea, Vanuatu, Solomon Islands, Samoa and Tonga as alternatives to farming of tilapia

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Abstract

An important driver behind introductions for aquaculture of alien fish species into Pacific Island Countries and Territories (PICTs) is a lack of knowledge about domestication suitability and specific culture requirements of indigenous taxa. Introductions may be appropriate in some circumstances, but in other circumstances, the associated risks may outweigh the benefits, so greater understanding of indigenous species' aquaculture potential is important. This review summarises literature for indigenous freshwater food fish species from Papua New Guinea, Fiji, Vanuatu, the Solomon Islands, Samoa and Tonga, and evaluates their aquaculture potential for food security and/or small-scale livelihoods. A species selection criteria incorporating economic, social, biological and environmental spheres was used to score 62 candidate species. Tilapia (*Oreochromis mossambicus* and *O. niloticus*) now established in PICTs were evaluated for comparison. Results show that 13 species belonging to the families Mugilidae (Mullets), Terapontidae (Grunters), Kuhliidae (Flagtails) and Scatophagidae (Scats) have the highest culture potential according to selection criteria. These feed at a relatively low trophic level (are herbivores/detritivores), have comparatively fast growth rates and overall possess characteristics most amenable for small-scale, inland aquaculture. The four top-ranked candidates are all mountain mullets *Cestraeus* spp., followed by Nile tilapia (*Oreochromis niloticus*). Lower ranked candidates include three other mullets (*Planiliza melinoptera*, *P. subviridis* and *Mugil cephalus*) and rock flagtail *Kuhlia rupestris*. Importantly, many species remain data deficient in aspects of their reproductive biology or culture performance. Species profiles and ranked priority species by country are provided with logistical, technological and environmental assessments of country capacities to culture each species.

KEYWORDS
aquaculture, domestication, freshwater fish, indigenous, Pacific islands

1 | INTRODUCTION

Aquaculture makes important contributions towards almost all of the United Nations Sustainable Development Goals SDGs for Agenda 2030.[1,2] Although it is still a small food production sector among the Pacific Island Countries and Territories (PICTs) within the membership of the Pacific Community (SPC), many PICTs prioritise aquaculture as important for achieving their sustainable development aspirations. In addition to various national-level strategies and plans for aquaculture, at a regional level, PICTs have made collective declarations such as to 're-emphasize the multiple and interdependent purposes that aquaculture can serve: food security, economic and restoration; and stress the key importance and expected contribution of small-scale non-commercial aquaculture to food security and livelihoods', and 'call for further guidance and effort on sustainable and environmentally friendly aquaculture, including culturing native species and species with low environmental impacts'.[3]

Freshwater aquaculture, despite a history of being under-researched when compared to finfish mariculture, has steadily increased its share of global farmed fish production over the last 20 years and now provides 75% of edible aquaculture products,[4] generated mostly by small-scale farmers. Freshwater aquaculture is capable of contributing yet more toward sustainable agri-food systems, via policies to promote inclusive, equitable and nutrition-sensitive approaches,[1] and via research efforts toward practical on-farm innovations in fish nourishment, health and genetics.[5] This sector can align well with the calls for action emanating from the 2021 UN Food Systems Summit, and the Shanghai Declaration of the Global Conference on Aquaculture Millennium +20, which advocate inter alia for increased integration of aquatic foods into food systems,[6] adoption of the Sustainable Healthy Diets SHDs concept,[7] and for nature-positive and climate-smart food systems that take into consideration the equity and sustainability of food production in addition to quantity and value.[8]

Among PICTs, freshwater aquaculture has long been viewed as worthwhile for integration with other rural livelihoods and food security options (see, e.g. Anonymous[9]), and it has widespread support notwithstanding various constraints,[10] of which one is unavailability in the PICTs of fish species suitable for freshwater aquaculture.[11,12] Freshwater aquaculture is projected to be one of the beneficiaries under climate change projections for the high island PICTs of the southwest Pacific due primarily to range extensions (e.g. breeding at higher altitudes) and habitat expansion due to increased river flows.[13] Against a backdrop of declining coastal fisheries production due to factors such as climate change, over-fishing and population growth,[14] aquaculture generally, and freshwater aquaculture, in particular, are viewed by PICTs as an important sustainable development option.[11]

PICT aspirations to promote freshwater aquaculture have tended to focus upon introduced species such as tilapia or Asian carps.[11,15] This is because of their long histories of domestication, simple life-histories and suitable agronomic traits which provide a basis for successful aquaculture industries in other regions. The indigenous freshwater fish fauna of the geologically young volcanic islands of the insular Pacific, on the other hand, is of relatively recent marine ancestry, depauperate in terms of the number of species, has high endemism, occur within restricted ranges, have small population sizes, is very data deficient, and is entirely diadromous, that is, have complex life histories that span both marine and freshwater environments.[16–20] 'True' freshwater species are absent, apart from recently introduced alien species such as tilapia, Asian carps, *Gambusia* or guppies (family Poeciliidae).

The implications of diadromy for freshwater aquaculture is a higher degree of difficulty in domestication and breeding, requiring saltwater hatcheries. The significant food fish within the indigenous fauna also have marine larval stages which either have never yet been successfully bred and reared in captivity or, if so, have proven to be as technically difficult and expensive to rear as high-value marine fish like the Serranidae (see, e.g. Hutchison et al.[21]). Because there are freshwater fish species in other regions already proven to be good candidates for aquaculture compared to undomesticated and data-deficient Pacific indigenous species, often strong arguments are made for the introduction and translocation of alien species in order to establish fish farms in PICTs.[22]

Introduction of aquatic species brings risks (such as introduced marine pests or pathogens) which decision-makers weigh up against projected benefits; as a result, four of the six top-ranked aquaculture species in the Pacific, representing 90% of value, are introduced species.[15] The trend in most PICTs is towards the strengthening of biosecurity legislation and policies in order to address animal health-related issues, food safety standards and species introductions (export and import standards), including for aquatic species.[15] One issue when considering the introduction of an alien species is to determine whether the introduction is really necessary, and what measures may be taken to prevent possible undesirable consequences.[22,23] To make such determinations there must be knowledge about the types of indigenous species present in the locality where the proposed introduction of an alien species is to take place, and to evaluate whether any of these indigenous species may be cultured in place of the alien species and might better match domestic or export market requirements.

For any PICT jurisdictions with low- or zero-tolerance approaches to risks from introduced alien species, aspirations to expand and diversify their freshwater aquaculture activities will require that attention be given to utilisation of their indigenous freshwater fish fauna. This will not be a rapid process, however. On average it takes 10–15 years of applied research to domesticate even a promising new aquatic species to the point where adoption of successful culture techniques by producer groups is possible.[11] Nevertheless, it is timely to review the indigenous freshwater fish fauna of key PICTs, to find out which species might have agronomic traits suitable for domestication and establishment of viable aquaculture projects. Any critical technical constraints or knowledge gaps should be identified, to provide a focus for targeted research that might lead to successful domestication of indigenous freshwater food fish in the island Pacific.

The overall aim of this review is to conduct a literature review of indigenous freshwater food fish species present in the high island countries of the southwest Pacific (Papua New Guinea, Fiji Islands,

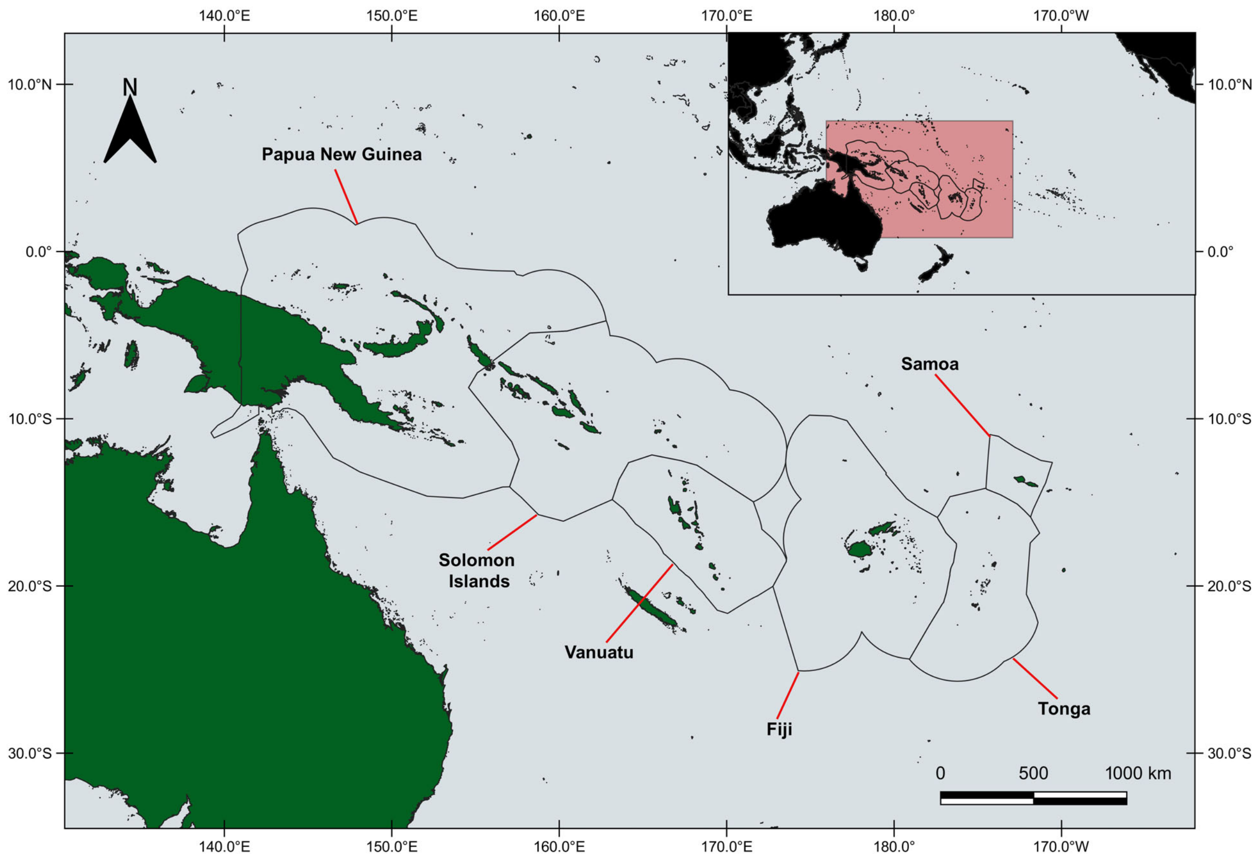

FIGURE 1 Map of the southwest Pacific identifying high island countries reviewed and their exclusive economic zone (EEZ) boundaries. Produced using QGIS v3.14.16-Pi. Reference EEZ boundaries were generated from publicly available data on the SPC Pacific data hub (https://pacificdata.org/). Inset map shows the Pacific basin and locations of countries reviewed.

Vanuatu, Solomon Islands, Samoa and Tonga, see Figure 1) and evaluate them for their aquaculture potential by applying a framework of species selection criteria. Emphasis was placed upon finding robust and easily cultured indigenous species for farming in inland freshwater areas, for the primary purpose of food security and small-scale livelihoods. Two tilapia species already established in parts of the insular Pacific, Mozambique tilapia *Oreochromis mossambicus* (Peters, 1852) and Nile tilapia *O. niloticus* (Linnaeus, 1758) were also included in the review, as a basis for comparison of agronomic traits.

The objective of this study is to conduct a literature review on indigenous freshwater food fish species present in the high island countries of the southwest Pacific (Papua New Guinea, Fiji Islands, Vanuatu, Solomon Islands, Samoa and Tonga, see Figure 1) and evaluate their aquaculture potential as alternatives to farming of tilapia, and identify any gaps in knowledge or key constraints.

2 | METHODS AND MATERIALS

A species selection criteria framework composed of characteristics considered to be important for small-scale, inland aquaculture was created with guidance from literature sources.[22,24–27] Economic, social, biological and environmental spheres were included as part of the criteria to produce a holistic evaluation tool with which various species could be critically evaluated. Fish species potentially suitable for freshwater aquaculture were identified from scratch, and were not limited to those already known to possess positive culture attributes. Databases searched included Scopus and Google Scholar, along with the taxonomic data aggregators the Global Biodiversity Information Facility, GBIF (www.gbif.org) and World Register of Marine Species, WoRMS (www.marinespecies.org) for species occurrence records. Keywords employed in searches included species, their occurrence locations and PICT names. The species selection criteria are presented in Table 1.

A list of candidate fish species was then produced by reviewing scientific literature pertaining to known food fish species occurring in the Fiji Islands, Vanuatu, Solomon Islands, Samoa and Tonga. A list of food fish species from Papua New Guinea was not analysed as part of this study because this country has already evaluated their indigenous freshwater fish fauna and developed a priority list of candidate species to be the focus of on-going research.[28,29] However, as some neighbouring PICTs (e.g. Solomon Islands and Vanuatu) share species with PNG, a summary of species showing culture potential is mentioned here, to provide a more complete and updated review of the southwest Pacific region to inform policy development for freshwater aquaculture.

TABLE 1 Species selection criteria compiled from Pillay[22]; Shetty, Bowers, Pagán, Pillay, Shang and Schmidt[24]; Silva, Oddsson and Gunnarsson[25]; Weston, Hardcastle and Davies[26] and Williams.[27]

	Score		
Criteria	**1**	**2**	**3**
Economic considerations			
Scale of operation required	Large	Medium	Small
Market size	Domestic	National	Regional
Consumer preference	Low	Intermediate	High
Organoleptic characteristics (e.g. colour, appearance, texture, taste etc.)	Poor	Intermediate	Good
Biological/ecological considerations			
Simplicity of lifecycle (ease of reproducibility in a hatchery)	Lifecycle not closed, little to no information known on reproductive biology. Low fecundity, difficult to breed, low larval/fry survival rates. Technically demanding.	Lifecycle closed, intermediate fecundity, moderately difficult to breed, moderate larval/fry survival rates. Seed production possible with intermediate levels of technical infrastructure.	Lifecycle closed, high fecundity, easy to breed, high larval/fry survival rates. Seed production possible with low levels of technical infrastructure.
Trophic level position	Carnivore	Omnivore	Herbivore/Detritivore
Growth rate	Slow	Intermediate	Fast
Processed feed acceptability and feeding requirements	Does not readily accept processed feeds. Has many special feeding requirements.	Accepts processed feeds. Has a few special feeding requirements.	Easily accepts processed feeds. No special feeding requirements.
Disease tolerance	Low	Intermediate	High
Environmental condition tolerance (to varying DO_2, pH, salinity levels, etc.)	Low	Intermediate	High
Behaviour/adaptability to culture conditions	Behaviour unsuitable for conventional, low cost culture systems. Adapts poorly to culture.	Behaviour suitable for culture conditions. Adapts moderately well to culture.	Behaviour well suited to culture conditions. Adapts well to culture.
Environmental considerations			
Habitat use[a]	Makes poor use of habitat provided in culture system.	Makes an intermediate level of use of habitat provided in culture system.	Makes good use of habitat provided in culture system.
Consequences of escapes (e.g. gene pool contamination, ecological upsets, etc.)	Many foreseen negative environmental consequences.	Some foreseen negative environmental consequences.	Few foreseen negative environmental consequences.
Environmental effects of culture practices required (e.g. use of chemicals and drugs)	Many foreseen negative environmental effects.	Some foreseen negative environmental effects.	Few foreseen negative environmental effects.
Gaps in knowledge			
	Very little or no knowledge available on biological, ecological, economic and environmental aspects to assist domestication efforts	Some knowledge available on biological, ecological, economic and environmental aspects to assist domestication efforts	Substantial knowledge available on biological, ecological, economic and environmental aspects to assist domestication efforts

[a]Habitat use refers primarily to a species making use of three-dimensional space available in the water column potentially permitting higher stocking densities, instead of demersal species which may utilise only areas near the bottom of a rearing environment.

Selection criteria for species to be included on the candidate species list were kept simple, and were based on the species already known to be food fish over their distributional ranges and attaining sufficient size for human consumption. This last criterion was necessary because species listed as having important fisheries but utilised only as bait fish were not included. The species selection criteria were then applied to individual candidate species in order to determine their suitability for aquaculture, by scoring them according to the criteria. Species lists of those species assessed as having high, intermediate and low potentials for inland aquaculture were then produced by ranking their species selection criteria scores. Individual species profiles of those species assessed as having a high potential for culture are included as results here.

3 | RESULTS

A complete list of the 62 candidate species extracted from literature, to which the species selection criteria were applied, is included in Table S1. A spreadsheet detailing species scores is provided in Table S2. This list is organised into species that have high, intermediate and low levels of potential for culture.

3.1 | Species with high potential for culture

According to the species selection criteria, a total of 11 species belonging to the families Mugilidae (Mullets), Kuhliidae (Flagtails), Terapontidae (Grunters and Tigerperches), and Scatophagidae (Scats) have the highest culture potential. These species are listed in Table 2. Two introduced species from the family Cichlidae (Tilapias) are provided in Table 3. A further list of 17 species (Table 4) belonging to the families Mugilidae (Mullets), Terapontidae (Grunters and Tigerperches), Cyprinidae (Carps), Percichthyidae (Temperate Perches), Lutjanidae (Snappers), Kuhliidae (Flagtails), Toxotidae (Archerfishes), Eleotridae (Sleepers), Serranidae (Groupers and Sea basses) and Chanidae (Milkfish) were also found to have high culture potentials; however, possessed drawbacks in suitability for aquaculture or were data deficient with respect to culture attributes.

TABLE 2 List of 11 indigenous species assessed to have high feasibility for culture

Rank	Species	Common name	Score
1	*Cestraeus goldiei*	Goldie river mullet	40
1	*Cestraeus oxyrhyncus*	Sharp-nosed river mullet	40
1	*Cestraeus plicatilis*	Lobed river mullet	40
1	*Crenimugil heterocheilos*	Half fringelip mullet	40
3	*Planiliza melinoptera*	Otomebora mullet	38
3	*Planiliza subviridis*	Greenback mullet	38
3	*Mugil cephalus*	Flathead grey mullet	38
3	*Kuhlia rupestris*	Rock flagtail	38
4	*Scatophagus argus*	Spotted scat	37
5	*Crenimugil crenilabis*	Fringelip mullet	36
5	*Terapon jarbua*	Jarbua terapon, doctorfish	36

TABLE 3 List of 2 introduced species assessed to have high feasibility for culture

Rank	Species	Common name	Score
2	*Oreochromis niloticus*	Nile tilapia	39
4	*Oreochromis mossambicus*	Mozambique tilapia	37

3.2 | Top 13 species profiles

Detailed profiles, species line drawings and distribution maps of the 13 highest-ranked species from Tables 2 and 3 have been compiled and included in the following section.

3.3 | Family Mugilidae

Seven species of mullet generated high scores, including the Goldie river mullet *Cestraeus goldiei*, Macleay, 1883 (Figure 2a), Sharp-nosed river mullet *Cestraeus oxyrhyncus*, Valenciennes, 1836 (Figure 2b), Lobed river mullet *Cestraeus plicatilis*, Valenciennes, 1836 (Figure 2c), Half fringelip mullet *Crenimugil heterocheilos*, Bleeker, 1855 (Figure 3a), Otomebora mullet *Planiliza melinoptera*, Valenciennes, 1836 (Figure 3b), Greenback mullet *Planiliza subviridis*, Valenciennes, 1836 (Figure 3c) and Flathead grey mullet *Mugil cephalus*, Linnaeus, 1758 (Figure 3d). These species may be broadly split into two categories, the mountain mullets (*C. goldiei*, *C. oxyrhyncus* and *C. plicatilis*) which occupy fresh and brackish water habitats, and the catadromous species of *Planiliza*, *Crenimugil* and *Mugil* which occupy marine, fresh and brackish water habitats. The three species of mountain mullet are commonly reported to reach a similar total length of 20 cm,[30,31] whereas the other species are typically captured at varying sizes; 23 cm for *Cr. heterocheilos*, 18 cm for *P. melinoptera*, 25 cm for *P. subviridis* and 35 cm for *M. cephalus*.

Natural distributions vary, with four species restricted to the Pacific basin and the remaining three (*P. melinoptera P. subviridis* and *M. cephalus*) ranging across both Pacific and Indian Oceans. Within PICTs, *C. goldiei* is known from Vanuatu, the Solomon Islands[32] and PNG (Port Moresby district), *C. oxyrhynchus* from Fiji and Vanuatu; and *C. plicatilis* from Celebes (Sulawesi, Indonesia), New Caledonia, Vanuatu and Fiji. Occurrence of *Cr. heterocheilos* is reported from Vanuatu only, while *P. melinoptera* is known from Fiji, Samoa, Tonga and the Solomon Islands and *P. subviridis* from Fiji, Vanuatu, the Solomon Islands and Samoa. The broadest PICT distribution is known for *M. cephalus*, which overlaps with countries recorded for *P. subviridis*, with the addition of Tonga.[30,31,33]

All species are demersal dwellers, oviparous and pelagic spawners producing non-adhesive eggs. The Goldie river mullet (*C. goldiei*) has been reported to ascend substantial distances up river systems, with individuals documented occurring up to 350 m above sea level. Similarly, *C. heterocheilos* while typically occurring in coastal waters, penetrates far upstream from river mouths and may be captured in turbid channels and over gravel bottoms. Three of the species assessed tend to occupy more marine habitats; *P. melinoptera* is reef-associated, however, it like *P. subviridis* schools in shallow coastal habitats and

TABLE 4 List of 17 indigenous species assessed to have high feasibility for culture, but are likely to possess drawbacks to suitability for inland aquaculture

Rank	Species	Common name	Score
6	*Planiliza macrolepis*	Largescale mullet	34
6	*Crenimugil seheli*	Bluespot mullet	34
6	*Kuhlia salelea*	Salele flagtail	34
6	*Hephaestus fuliginosus*	Sooty grunter, black bream	34
7	*Barbonymus gonionotus*	Silver barb	33
7	*Mesopristes kneri*	Orange-spotted therapon	33
7	*Macquaria novaemaculeata*	Australian bass	33
8	*Kuhlia marginata*	Dark-margined flagtail	32
8	*Kuhlia mugil*	Barred flagtail	32
8	*Lutjanus fuscescens*	Freshwater snapper	32
8	*Macquaria colonorum*	Estuary perch	32
8	*Mesopristes cancellatus*	Tapiroid grunter	32
8	*Toxotes jaculatrix*	Banded archerfish	32
9	*Giuris margaritacea*	Snakehead gudgeon	31
9	*Epinephelus polystigma*	White-dotted grouper	31
9	*Mesopristes argenteus*	Silver grunter	31
9	*Chanos chanos*	Milkfish	31

enters lagoons, estuaries and rivers to feed. Juvenile *P. subviridis* may be found in rice fields and mangroves. The flathead grey mullet (*M. cephalus*) inhabits inshore marine waters, estuaries, lagoons and rivers, with adults often schooling.[30,31]

Knowledge of the reproductive biology of the three mountain mullet species is scarce, except that they are targeted by gillnets during seasonal spawning aggregations at river mouths.[30,31,33] Spawning behaviour of *M. cephalus* is well known, and occurs at sea at various times of the year depending on location. Eggs can number between 5 and 7 million. First spawning occurs with individuals in their third or fourth year, and mature fish group in estuaries, form shoals, and move out to sea to spawn in surface waters. Spent fish return to brackish and fresh waters of estuaries, rivers, or lakes. Newly hatched fry feed on zooplankton, and migrate to estuaries to swim upstream. Juveniles are typically found in sheltered lagoons and bays. Immature 'hardgut' fish make preliminary migrations out to sea but do not spawn, and return without feeding.[30,31]

Feeding habits of the two *Planiliza* sp. and *M. cephalus* are documented, with adults consuming plant detritus, microalgae, minute bottom-living organisms and organic matter contained in sand and mud. Fry are reported to feed on zooplankton, diatoms, detrital material and inorganic sediment.[30,31] Capture methods are reported for the two *Planiliza* sp. and *M. cephalus*, with all three species fished from shallow coastal waters, estuaries, backwaters and lagoons using cast nets, stake nets, beach seines and gill nets; and marketed fresh. Salting and freezing is also employed for *P. subviridis* [which is also boiled (Thailand), canned and/or frozen (Australia)] and *M. cephalus*. The roe is also marketed salted for the former, and sold fresh or smoked for the latter. The latter species forms the basis of a major commercial fishery and represents half of the entire mullet landings in eastern Australia and Tonga.[30,31]

3.3.1 | Comments

There are significant knowledge gaps on the biology and ecology of the three mountain mullet species, *Cr. Heterocheilos* and *P. melinoptera*, and baseline research targeting grow-out, brood stock availability, and seed production aspects for aquaculture needs to be carried out. Froese and Pauly[31] remark that these species are likely to have a future use in aquaculture, and may respond to similar breeding techniques as those employed for *M. cephalus*. Perhaps the best researched mullet species are *P. subviridis*[33] and *M. cephalus*,[34,35] with techniques developed for successful seed production and grow-out. The greatest amount of research focus has been assigned to *M. cephalus*, which may be considered domesticated.[34] There is a long history of trial culture activities undertaken in Fiji and Tonga,[35] and in Samoa (Pickering, T. D. *pers.obs.*), intermittently from the early 1980s up until the present day. These are founded upon capture-based culture of wild fingerlings, which proves sufficient for experimental grow-out trials in cages or enclosures but insufficient for significant aquaculture at scale.

3.4 | Family Kuhliidae

Rock flagtail *Kuhlia rupestris*, Lacepède, 1802 (Figure 4a,b) has a maximum reported total length of 56 cm. This species is widespread across the Indo-Pacific region from the Red Sea to South Africa, and from the Ryukyu Islands in Japan to Queensland and eastward to the Society Islands. Its PICT presence is in Fiji, Vanuatu, the Solomon Islands and Samoa. The Rock Flagtail is a catadromous species, occupies marine, freshwater and brackishwater habitats. This is primarily a freshwater inhabitant, but it may penetrate adjacent marine habitats. Adults occur in estuaries and the middle reaches of rivers, usually in relatively fast-flowing, clear streams. It is usually found in rainforests, as well as in rocky pools below waterfalls. Adults are omnivorous, feeding on small fish, insects, crustaceans and fruits (figs) that drop into the water. A good food fish, caught primarily by small-scale beach seines, gill nets, throw nets and by anglers with hook-and-line. This species is oviparous with pelagic larval development. Specific breeding habits are unknown, but adults move downstream into estuaries or to the sea to spawn.[31,36]

3.4.1 | Comments

Australian researchers have now developed hatchery methods for breeding and rearing *K. rupestris* up to fingerling size for the purposes of river re-stocking for recreational fishing.[21] These hatchery methods could be transferred to PICTs. Significant knowledge gaps remain around culture conditions and nutrition, and economic viability, for grow-out to market size as food fish.

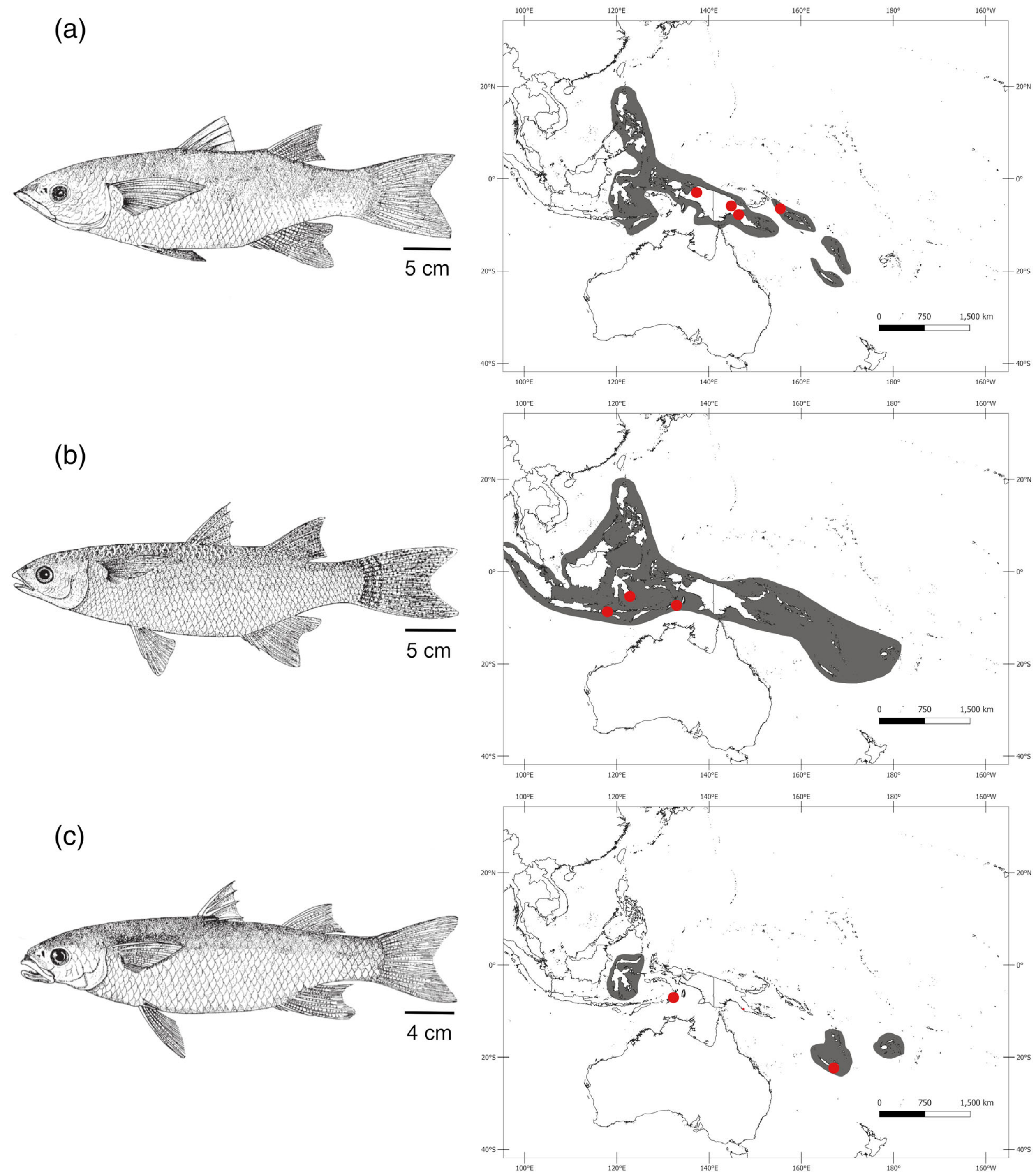

FIGURE 2 (a) Goldie river mullet *Cestraeus goldiei*.[30] *Source*: Harrison and Senou.[30] (b) Sharp-nosed river mullet *Cestraeus oxyrhyncus*.[30] *Source*: Harrison and Senou.[30] (c) Lobed river mullet *Cestraeus plicatilis*.[30] All species images and distribution extents (grey shaded areas) are reproduced from Harrison and Senou.[30] Species occurrence locations are represented as red dots using data obtained from the Global Biodiversity Information Facility (www.gbif.org, dataset[84] doi: https://doi.org/10.15468/dl.t2q3gv) and FishBase (www.fishbase.se) records. Scale bars are based on maximum fish standard lengths and maps were produced using QGIS v3.14.16-Pi

3.5 | Family Cichlidae

Nile tilapia *Oreochromis niloticus*, Linnaeus, 1758 (Figure 4c) has a maximum length of approximately 60 cm[39] with a maximum weight of 6.01 kg.[40] The Nile tilapia originates from Egypt, Senegal, Ghana and Kenya and occurs in a wide range of freshwater habitats including rivers, lakes, streams and canals. It is able to tolerate brackish-water and is omnivorous, feeding mainly on phytoplankton or

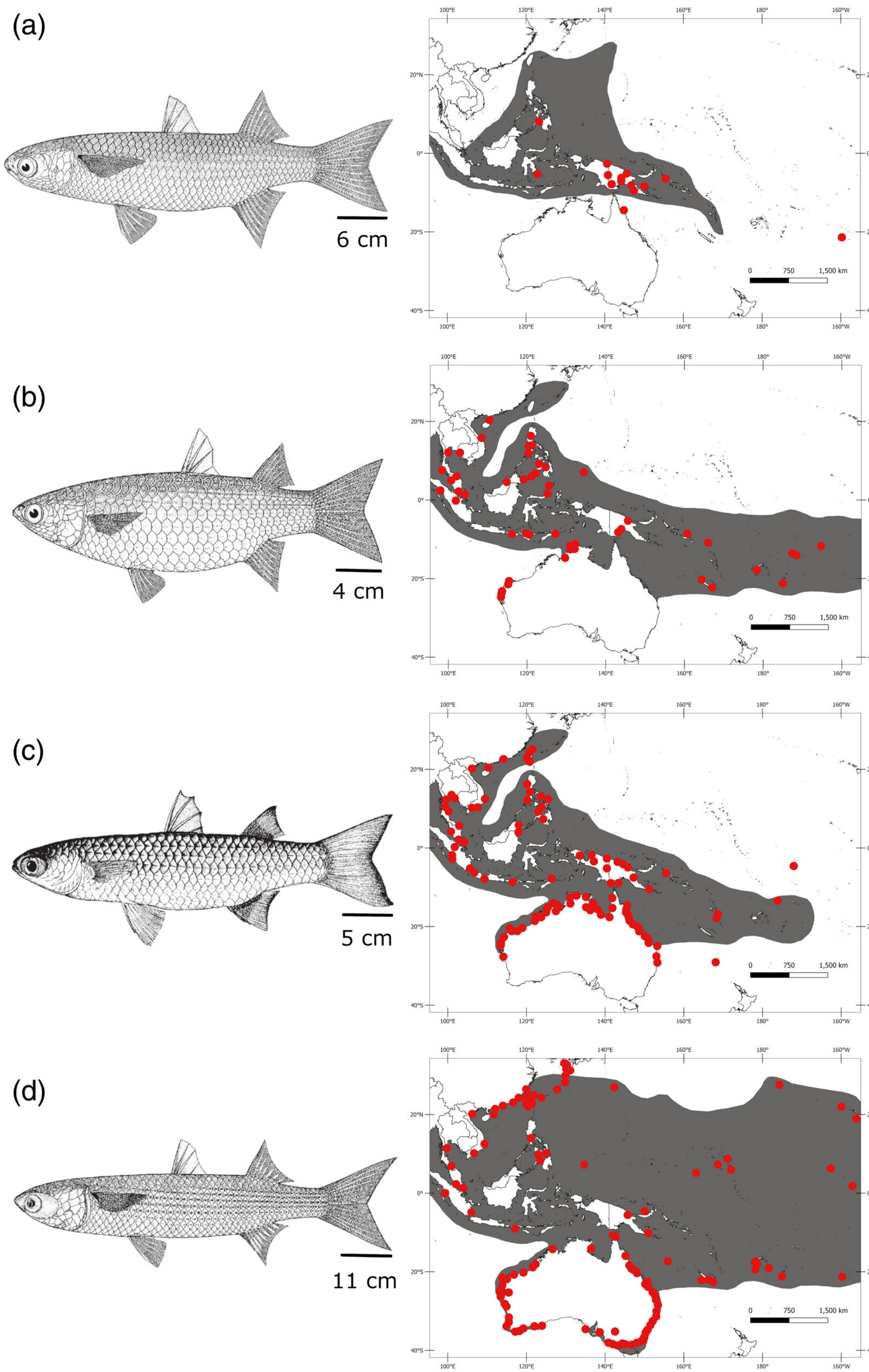

FIGURE 3 (a) Half fringelip Mullet *Crenimugil heterocheilos*.[30] (b) Otomebora mullet *Planiliza melinoptera*.[30] (c) Greenback mullet *Planiliza subviridis*.[30] (d) Flathead Grey Mullet *Mugil cephalus*.[30] All species images and distribution extents (grey shaded areas) are reproduced from Harrison and Senou, after Senou, 1988.[30] Species occurrence locations are represented as red dots using data obtained from the Global Biodiversity Information Facility (www.gbif.org, dataset[84] doi: https://doi.org/10.15468/dl.t2q3gv) and FishBase (www.fishbase.se) records. Scale bars are based on maximum fish standard lengths and maps were produced using QGIS v3.14.16-Pi.

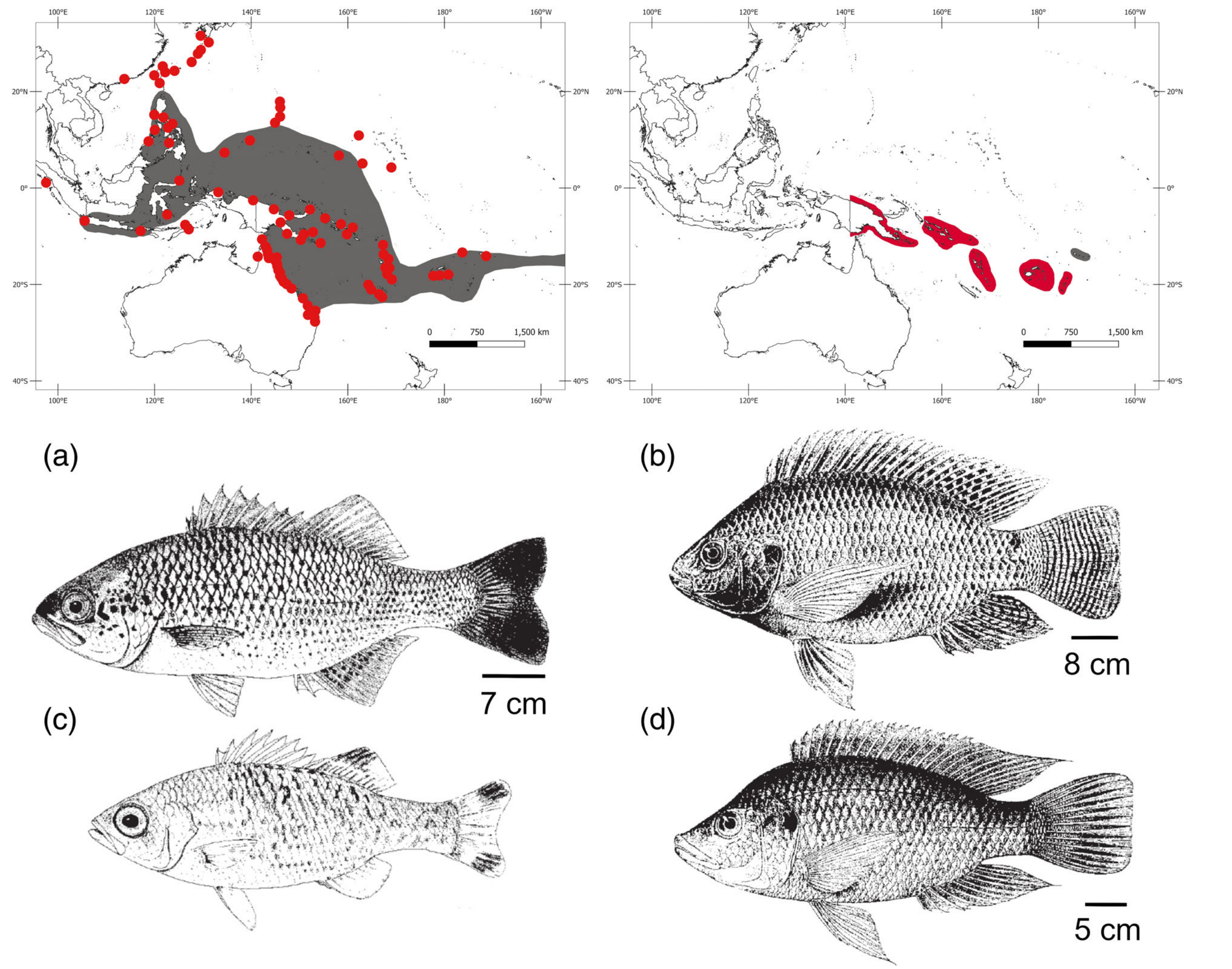

FIGURE 4 (a, b) Rock flagtail *Kuhlia rupestris* from Carpenter,[36] after Masuda et al., 1984. (a) depicts the adult and (b) the juvenile. (c) Nile tilapia *Oreochromis niloticus*[37] and (d) Mozambique tilapia *O. mossambicus*.[37] Species images and distribution extents (grey shaded areas) are reproduced from Carpenter[36] for *K.* rupestris and De Silva[38] for the two *Oreochromis* spp. Species occurrence locations are represented as red dots using data obtained from the Global Biodiversity Information Facility (www.gbif.org, dataset[84] doi: https://doi.org/10.15468/dl.t2q3gv) and FishBase (www.fishbase.se) records. As the two tilapias are introduced species, the extent of introductions into focus PICTs only for both species is shown in red, and for *O. mossambicus* only in grey. Scale bars are based on maximum fish standard lengths and maps were produced using QGIS v3.14.16-Pi.

benthic algae. It is a maternal mouthbrooder[41] and invasive capable of interspecific hybridisation with other *Oreochromis* sp.[38,42] This species is a globally important freshwater aquaculture commodity, particularly in Asia, Latin America and the Pacific region.[43] Its PICT presence is in Papua New Guinea, Fiji, Tonga, Vanuatu, the Solomon Islands and Samoa. It has several biological attributes which make it amenable to culture, including fast growth rates, wide tolerance of environmental conditions, ease of seed production and ready marketability.[44,45] The Genetically Improved Farmed Tilapia (GIFT) is a selectively bred strain of the Nile tilapia (*Oreochromis niloticus*), originally developed by the WorldFish Center (WFC) in the Philippines. GIFT tilapia were developed from four wild strains of *O. niloticus* sourced from the species' natural distribution along with four high-performing cultured strains from the Middle-East, Israel, Singapore, Taiwan and Thailand.[46,47]

3.5.1 | Comments

Nile tilapia have been domesticated for over 60 years, with introductions made from at least 26 countries.[38] Culture attributes are well documented along production protocols,[43] making it one of the few freshwater fish species ideal for successful low-cost farming.[11] A concern with tilapia is the presence of tilapia lake virus, TiLV,[48] which is currently not present in any PICTs. It would be advisable to not permit tilapia introductions from Asia as TiLV has been detected in several countries including Thailand, Malaysia, India and the Philippines.[48]

Mozambique tilapia *Oreochromis mossambicus*, Peters, 1852 (Figure 4D) has a maximum length of approximately 39 cm however length at maturity can range from 6 to 28 cm.[49] The Mozambique tilapia has a natural range which includes the tropical and sub-tropical

African continent in both fresh and brackishwater, however, it has been widely introduced for aquaculture, and become established in the wild in several countries often outcompeting other species with adverse ecological effects.[38,50–52] Its PICT presence is in Papua New Guinea, Fiji, Tonga, Vanuatu, the Solomon Islands and Samoa. This species is omnivorous, feeding mainly on phytoplankton or benthic algae but will also consume insects and crustaceans. Large individuals reportedly prey on small fish.[51] It is highly euryhaline, tolerant of low dissolved oxygen conditions with the capability to utilise atmospheric oxygen.[53] It is a polygamous maternal mouthbrooder, occasionally cannibalising its own young. This species reaches sexual maturity at 15 cm, however, stunted individuals may breed a 6–7 cm.[41]

3.5.2 | Comments

Mozambique tilapia were among the first Cichlids to be domesticated for aquaculture, with the earliest introduction recorded in 1940 and subsequent translocations to 40 countries.[38] Culture attributes are well documented along production protocols,[43] however it is less suitable for aquaculture compared to its congener *O. niloticus* and has fallen short of expectations for a farmable freshwater food fish in Solomon Islands.[12] In the Pacific should consideration be given to culture of this species, source stock selection will be an important consideration, as the progenitors of all *O. mossambicus* in the South Pacific are reported to be five individuals obtained from a river estuary in West Java, Indonesia in 1954.[54] Subsequently, an analysis of genetic diversity in feral Fijian, Malaysian and Australian populations discovered low heterozygosity and evidence of previous genetic bottlenecks, suggesting little genetic variability to warrant stock improvement.[55]

3.6 | Family Scatophagidae

Spotted scat *Scatophagus argus*, Linnaeus, 1766 (Figure 5a) has a maximum reported standard length of about 30 cm, with a total length of about 35 cm. This species is distributed in the Indo-West Pacific distribution, from southern India and Sri Lanka to southern Japan and Tahiti. Its presence in the PICT is in Fiji, Samoa, Tonga, Solomon Islands and Vanuatu. The Spotted Scat is a reef-associated and amphidromous species occupying marine, freshwater and brackishwater habitats. Adults occur in estuaries, harbours, and the lower reaches of fresh-water streams, especially those with high mineral concentrations. They are usually found in harbours, natural embayments, brackish estuaries and the lower reaches of freshwater streams, frequently occurring among mangroves. Diet includes worms, crustaceans, insects and plant matter. They usually occur in aggregations and feed diurnally on a variety of benthic invertebrates, bottom detritus, algae, and garbage.[56] The dorsal, anal and pelvic spines are believed by Philippine fishers to be venomous and capable of inflicting wounds. It is considered to be of poor taste in some areas and esteemed in others. Juveniles are collected for the aquarium fish trade, and adults are sold in Hong Kong live fish markets. It is also used in Chinese medicine.[31,58] Barry and Fast[59] report captive breeding and early larval development of this species. Spawning occurs on coral reefs and juveniles migrate into fresh or brackishwater habitats. Juveniles go through a pelagic larval stage unique to a few genera of teleosts known as the 'tholichthys'. The Chaetodontidae (Butterflyfish) also possess this larval stage in their development.

3.6.1 | Comments

There are significant knowledge gaps on the reproductive biology of this species in the context of producing seed stock in a hatchery. Baseline research targeting grow-out and seed production aspects for aquaculture needs to be carried out. This species is farmed in Southeast China,[60] and is an important food fish in the Indo-Pacific region. Research has been carried out on morphometric traits[60] and salinity requirements for growing out juveniles.[61]

Fringelip mullet *Crenimugil crenilabis*, Forsskål, 1775 (Figure 5b) has a maximum reported standard length of 50 cm, however, individuals of 26 cm are more common. It occurs throughout the tropical Indo-Pacific from the Red Sea, Madagascar to the Tuamotu Islands. Its presence in the PICT includes Fiji, Samoa, Tonga, the Solomon Islands and Vanuatu.[30] Habitat areas are marine and include sandy and muddy areas of lagoons, reef flats and harbours. It is an important food fish in Polynesia, captured in gill nets and occurring as by-catch in seine nets, and used as live bait in the pole-and-line tuna industry.[30]

3.7 | Family Terapontidae

Jarbua terapon *Terapon jarbua*, Forsskål, 1775 (Figure 5c) has a maximum total length of about 35 cm, commonly between 20 and 27 cm. This species is widespread in the Indo-Pacific from East Africa, Red Sea, and Persian Gulf to Fiji and Samoa in the east, and New South Wales (Australia) in the south; northwards to Japan. Its presence in the PICT includes Fiji, Samoa, Tonga, the Solomon Islands and Vanuatu. The Jarbua terapon is a demersal and catadromous species occupying marine, freshwater and brackishwater habitats. Adults are found in loose aggregations over shallow sandy bottoms, in the vicinity of river mouths. They frequently enter estuaries and rivers. Juveniles in schools are common in sandy intertidal areas, often in tidal pools. The minimum depth record reported is 20 m. This species is omnivorous, feeding on fish, insects, algae and sand-dwelling invertebrates. They are able to produce sound with their swim bladder musculature. The Jarbua terapon is marketed fresh, dried or salted and caught using all types of inshore fishing gear including gill nets, traps, hand lines and bottom trawls. This species is oviparous with likely, pelagic larval development. It spawns in the sea only and juveniles migrate into fresh water. The eggs are guarded and fanned by the male parent until it hatches. Nothing further is known about the reproductive biology of this species.[31,57]

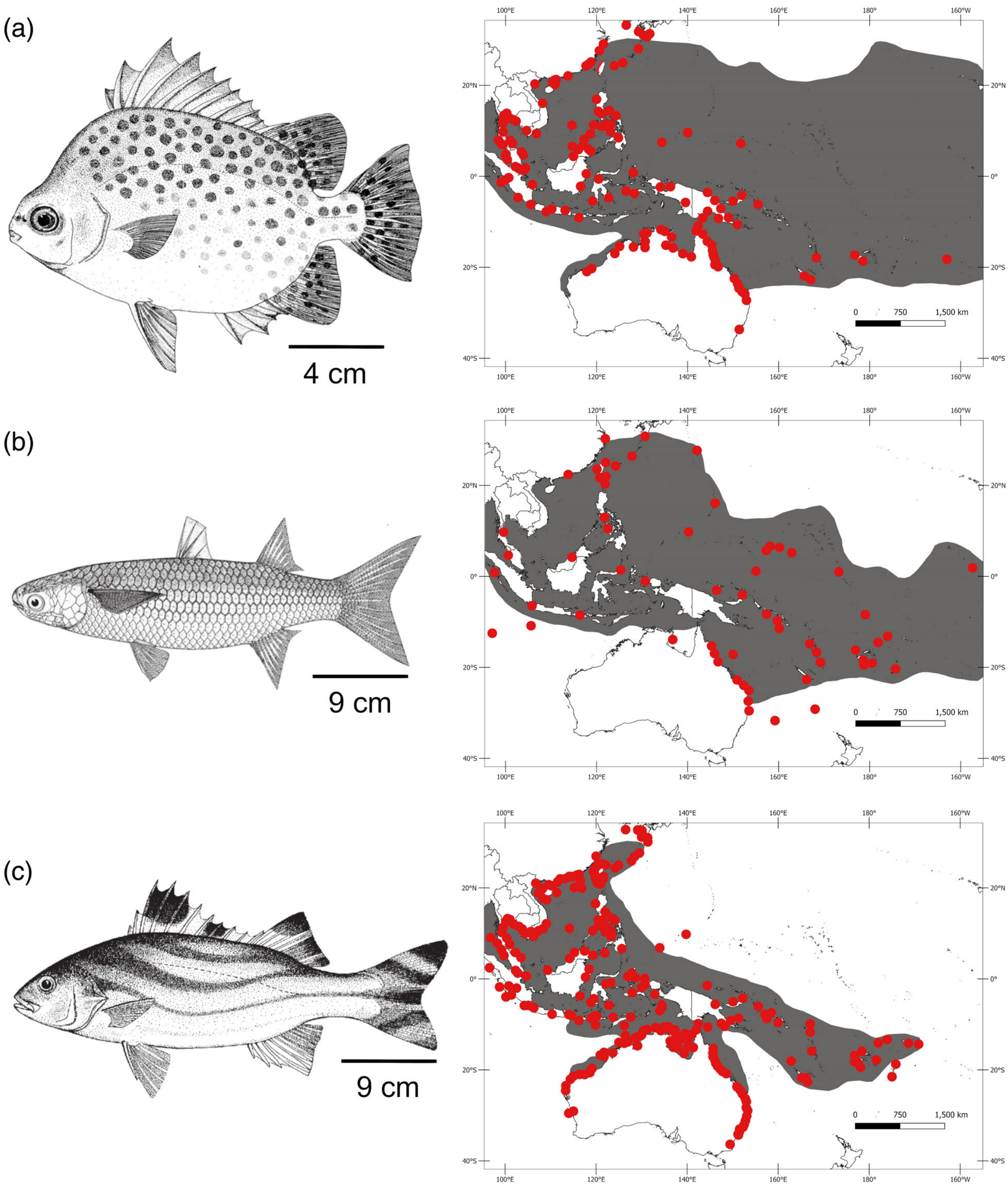

FIGURE 5 (a) Spotted scat *Scatophagus argus*,[56] (b) Fringelip mullet *Crenimugil crenilabis*[30] and (c) Jarbua terapon *Terapon jarbua*.[57] All species images and distribution extents (grey shaded areas) are reproduced from Anonymous[56] for *S. argus*, Harrison and Senou[30] for *Cr. Crenilabis* and Vari[57] for *T. jarbua*. Species occurrence locations are represented as red dots using data obtained from the Global Biodiversity Information Facility (www.gbif.org, dataset[84] doi: https://doi.org/10.15468/dl.t2q3gv) and FishBase (www.fishbase.se) records. Scale bars are based on maximum fish standard lengths and maps were produced using QGIS v3.14.16-Pi.

3.8 | Species with intermediate potential for culture

A total of 25 species were assessed as having an intermediate level of feasibility for inland aquaculture. These species belong to the families Eleotridae (Sleepers), Latidae (Lates Perches), Ambassidae (Asiatic Glassfishes), Cichlidae (Cichlids), Gobiidae (Gobies), Kuhliidae (Aholeaholes, Flagtails), Sillaginidae (Smelt-whitings), Centrarchidae (Sunfishes), Rhyacichthyidae (Loach Gobies) and Muraenidae (Moray eels). A list of these species is contained in Table 5.

TABLE 5 List of 25 indigenous species assessed to have an intermediate feasibility for culture

Rank	Species	Common name	Score
32	*Eleotris melanosoma*	Broadhead sleeper	29
32	*Lates calcarifer*	Barramundi, Asian sea bass	29
33	*Ambassis urotaenia*	Banded-tail glassy perchlet	28
33	*Ambassis interrupta*	Long-spined glass perchlet	28
33	*Sarotherodon occidentalis*		28
33	*Eleotris fusca*	Dusky sleeper	28
33	*Ophiocara porocephala*	Northern mud gudgeon	28
33	*Oxyeleotris sp.*	Indonesian guavinas	28
33	*Awaous guamensis*	Scribbled goby	28
33	*Kuhlia munda*	Silver flagtail	28
33	*Rhyacichthys aspro*	Loach goby	28
33	*Sillago sihama*	Silver sillago	28
34	*Micropterus dolomieu*	Smallmouth bass	27
34	*Micropterus salmoides*	Largemouth black bass	27
34	*Sicyopterus lagocephalus*	Red-tailed goby	27
34	*Stenogobius genivittatus*	Chinstripe goby	27
35	*Belobranchus belobranchus*	Throat-spine gudgeon	26
35	*Bunaka gyrinoides*	Greenback gauvina	26
35	*Butis butis*	Duckbill sleeper	26
35	*Eleotris acanthopoma*	Spinecheek gudgeon	26
35	*Awaous melanocephalus*	Largesnout goby	26
35	*Awaous ocellaris*		26
35	*Glossogobius celebius*	Celebes goby	26
36	*Strophidon sathete*	Slender giant moray	25
37	*Sillaginops macrolepis*	Large-scale sillago	24

3.9 | Species with low potential for culture

The seven species listed in Table 6 were assessed to have low potential for culture. These species belong to the families Anguillidae (Freshwater eels) and Ophichthidae (Worms and Snake eels).

4 | DISCUSSION

This review summarises literature on 60 indigenous and two introduced freshwater food fish species present in the Fiji Islands, Vanuatu, the Solomon Islands, Samoa and Tonga, and evaluates their potential for inland freshwater aquaculture for the first time.

TABLE 6 List of seven indigenous species assessed to have a low feasibility for culture

Rank	Species	Common name	Score
38	*Anguilla australis australis*	Short-finned eel	23
38	*Anguilla celebesensis*	Celebes longfin eel	23
38	*Anguilla marmorata*	Giant mottled eel	23
38	*Anguilla megastoma*	Polynesian long-finned eel	23
38	*Anguilla obscura*	Pacific short-finned eel	23
38	*Anguilla reinhardtii*	Speckled longfin eel	23
38	*Lamnostoma orientalis*	Oriental worm-eel	23

Particular attention was paid to identifying hardy species which may readily adapt to culture, to support inland community livelihoods and for food security. The great majority of taxa were data deficient, as they have either been poorly researched on aspects of their ecology, domestication has never been attempted, or both. For each country reviewed, rankings of leading candidate species have been provided along with an assessment of their domestication potential. A preliminary mention of this work is made in Pullin.[34]

4.1 | Profile analysis

Examining the species rankings following application of the selection criteria, the species that scored the highest feed at a low trophic level (herbivores/detritivores), have relatively fast growth rates and overall, possess characteristics which are most amenable for adaptation to small scale, inland aquaculture. The top seven rankings are dominated by species from the family Mugilidae (Mullets) for these reasons. The remaining three rankings are made up of three separate families belonging to the order Perciformes, which have very similar characteristics to those species listed in the top seven rankings.

An observation of note is that there are significant data deficiencies among the majority of the top 10 (and lower-ranked) species, primarily relating to aspects of the species' general biology or reproductive biology (with two exceptions—Rock flagtail *K. rupestris* and Grey mullet *M. cephalus*). These knowledge gaps need to be filled by baseline research activities if the true potential of these species for inland aquaculture is to be accurately assessed. Species which have higher requirements for seawater for part of their lifecycle have obtained lower rankings, as have those with carnivorous tendencies that will necessitate higher protein diets during grow-out. This is evident when the rankings of species such as eels are examined. Other species which are slow growing or which require high levels of technical infrastructure or capacity have obtained similar rankings, irrespective of whether or not their consumer-preference qualities are higher than those of species which have been determined to have high or intermediate feasibilities for culture.

Also noteworthy is that there are Pacific indigenous fish with rankings on a par with or marginally higher than Nile tilapia, even when considered on the basis of culture characteristics alone. If consumer preferences are also taken into account, this may further increase interest in aquaculture of some of the top-ranked indigenous species. Increased market pull over tilapia may be enough offset any comparative technical drawbacks. In some PICTs, fish consumers have less preference for eating tilapia.[12] Data deficiencies create risks for culture of indigenous species however, therefore knowledge gaps need to be filled before final assessment can be made.

The inclusion of milkfish (*Chanos chanos*) as an indigenous 'freshwater' species warrants explanation: it is a marine fish that supports small-scale artisanal fisheries, for example in the Solomon Islands and Vanuatu[62,63] but is a marine fish that can be acclimated to freshwater at fingerling stage for aquaculture grow-out in ponds. Hatchery techniques for milkfish have been established in Southeast Asia for several decades,[64] have been transferred to Kiribati[65] and are currently being established in Fiji. The logistics of obtaining and maintaining milkfish brood stock can be daunting, and hatchery production of fingerlings for grow-out needs to be done at scale in order to be economically viable. Past efforts in Tonga, Fiji, Vanuatu, Tuvalu and Solomon Islands to establish small-scale milkfish aquaculture based upon capture of wild fry or fingerlings have been frustrated by difficulty in obtaining sufficient numbers of fish.[63] Government hatchery production is established in Kiribati, and is in the process of being established at a government hatchery in Fiji.

4.2 | Country rankings

The top 10 species have been listed in the following section according to their presence in each PICT, and in priority order of feasibility for culture.

4.3 | Papua New Guinea

As mentioned earlier, a species feasibility analysis was not carried out for Papua New Guinea because this country has already evaluated their indigenous freshwater fish fauna and developed a priority list of candidate species to be the focus of on-going research.[28,29] A list of promising species for Papua New Guinea as included in Table 7 has been sourced from Masuda[28] and Smith.[29]

4.4 | Fiji

A list of the species prioritised for Fiji is presented in Table 8. The recommended top priorities for research efforts in this country are the two species of freshwater mullet *Cestraeus oxyrhyncus* and *C. plicatilis*. These two species are also the most likely to make a noteworthy impact on inland food security should culture efforts be successful.

Mullet culture is not new to Fiji, as previous research has been carried out with the flathead grey mullet *Mugil cephalus*,[35] and some technology transfer may be possible. Mullet culture research in the country began in 1973 at Raviravi, and examined culture methods to grow the flathead grey mullet, Rabbitfish (Siganidae) and tilapia (Cichlidae) in either monoculture or polyculture systems. Reports of results were positive, citing good growth rates for mullet in ponds and no problems with marketing the harvested product. Grow-out was based on wild fry collection, and this at times proved to be problematic.[35] No reasons are given as to why culture efforts were terminated. In the early 1980s, ICLARM had ambitions to set up a hatchery for *Cestraeus plicatilis* from the Cagayan River, Philippines, but could not obtain any broodstock following a long history of severe overfishing, driven by extremely high prices (Pullin, R, ICLARM, *pers. comm.*).

Fiji has the technical capacity and available aquaculture facilities to carry out research and development activities into the two recommended species, and may even be able to address one or more of the other six species present on the priority list for the country. The primary reasons behind the nomination of the two *Cestraeus* species are that they are both likely to have the least reliance on seawater during the grow-out phase of culture, and have lower dietary protein requirements. Despite these positive attributes, there is a distinct lack of knowledge about their reproductive biology. The other two species of mullet listed (*Planiliza melinoptera* and *P. subviridis*) appear to have a higher reliance on the marine environment for grow-out and may have a fully marine larval development phase, whereas it may be possible to complete larval development for the two *Cestraeus* species in brackishwater. Otherwise, there are positive similarities between the species listed under the two genera.

In the Philippines, *Cestraeus* spp. are highly sought after for their eating qualities, to the point where they have been heavily exploited and are now endangered.[66] It is likely in some PICTs including Fiji, that these mullets have also been overfished or impacted by habitat modification—gillnetting in the Waidina River, Viti Levu, Fiji, during 2017 collected a mere two specimens of *C. plicatilis*, and inland communities report that it is rare (Lekima Copeland, USP, *pers. comm.*). Similarly, Amick, Toko and Romain[67] report a first record for this species from New Britain, PNG from specimens collected in 2015, citing human disturbance and fishing pressures as contributors to population declines.

The rock flagtail *Kuhlia rupestris* appears to have a similar level of potential as the two species of *Cestraeus* mullets, and has the advantage that methods of breeding and rearing to fingerling size have now been developed.[21] However, it has the disadvantage that nutritional requirements for grow-out are not known and are likely to be high. The spotted scat and Jarbua terapon appear to possess attractive attributes for the grow-out phase of culture, but because they both have an established requirement for reproduction and larval development under marine conditions, they are nominated as the lowest priority species for the Fiji Islands.

TABLE 7 Priority species for Papua New Guinea

Species	Authority	Common name	Family
Oxyeleotris lineolatus	Steindachner, 1867	Sleepy cod	Eleotridae
Neosilurus ater	Steindachner, 1867	Eel-tailed catfish/Black catfish	Plotosidae
Neosilurus hyrtlii	Perugia, 1894	Common eel-tail catfish	Plotosidae
Hephaestus fuliginosus	Macleay, 1883	Sooty grunter	Terapontidae
Lates calcarifer[a]	Bloch, 1790	Barramundi	Latidae
Lutjanus goldiei[a]	Macleay, 1882	Papuan black bass	Lutjanidae

[a]These species are not included in Masuda,[28] however, Masuda (*pers. comm.*, 2012) confirms that these species have obvious potential for culture and are being addressed by different research efforts.

TABLE 8 Priority species for Fiji

Rank	Species	Common name	Score
1	*Cestraeus oxyrhyncus*	Sharp-nosed river mullet	40
1	*Cestraeus plicatilis*	Lobed river mullet	40
2	*Planiliza melinoptera*	Otomebora mullet	38
2	*Planiliza subviridis*	Greenback mullet	38
2	*Mugil cephalus*	Flathead grey mullet	38
2	*Kuhlia rupestris*	Rock flagtail	38
3	*Scatophagus argus*	Spotted scat	37
4	*Terapon jarbua*	Jarbua terapon	36

TABLE 9 Priority species for Vanuatu

Rank	Species	Common name	Score
1	*Cestraeus goldiei*	Goldie river mullet	40
1	*Cestraeus oxyrhyncus*	Sharp-nosed river mullet	40
1	*Cestraeus plicatilis*	Lobed river mullet	40
2	*Crenimugil heterocheilos*	Half fringelip mullet	40
2	*Planiliza subviridis*	Greenback mullet	38
2	*Mugil cephalus*	Flathead grey mullet	38
2	*Kuhlia rupestris*	Rock flagtail	38
3	*Scatophagus argus*	Spotted scat	37
4	*Terapon jarbua*	Jarbua terapon	36

4.5 | Vanuatu

A list of the species prioritised for Vanuatu is presented in Table 9. The recommended top priorities for research efforts in this country are the three species of freshwater mullet *Cestraeus goldiei*, *C. oxyrhyncus* and *C. plicatilis*. These three species are the most likely to make a noteworthy impact on inland food security should culture efforts be successful. Reasons behind the nomination of these species for further research are identical to those listed for the Fiji Islands.

Second-level priorities for Vanuatu have been identified as the Mullets *Cr. heterocheilos*, *P. subviridis* and *M. cephalus*. These species all require seawater for the completion of their lifecycles, and should only be examined if in-country technical capacity is available. The reproductive biology of *Cr. heterocheilos* and *P. subviridis* is data-deficient, whereas the culture of *M. cephalus* is well established in other countries,[30] and a programme of technology transfer rather than a research programme would be requisite.

The lowest priorities nominated for Vanuatu are the rock flagtail *Kuhlia rupestris*, spotted scat *Scatophagus argus* and the Jarbua terapon *Terapon jarbua*. These species all have a documented reliance on seawater for completion of their lifecycle and/or are data deficient with respect to their reproductive biology (with the exception of *K. rupestris*); and hence, would be less favourable options for research focus compared to the higher ranked species.

Vanuatu may have the technical capacity and available suitable land area to carry out research and development activities into the remaining species present on the priority list for the country (e.g. at Luganville in Santo), however, the priority focus should remain with the three *Cestraeus* species mentioned earlier. An advantage for research into these species is the fact that giant freshwater prawn (*Macrobrachium rosenbergii*) and tilapia culture are already established in the country, and adaptation of existing culture facilities to suit these new finfish species may be possible[68] subject to budgetary and staffing constraints.

4.6 | Solomon Islands

A list of the species prioritised for the Solomon Islands is presented in Table 10. The recommended top priorities for research efforts in this country are the two species of Mullet *Planiliza melinoptera* and *P. subviridis* which are the most likely to make a noteworthy impact on inland food security should culture efforts be successful. Reasons behind the nomination of these two species are identical to those listed for the two species of *Cestraeus* for the Fiji Islands, and include trophic level position and grow-out feasibility.

The second-tier priority species nominated for this country is the flathead grey mullet *Mugil cephalus*. This species requires seawater for the completion of its lifecycle, and should only be given attention if in-country technical capacity is available. An advantage of this species

TABLE 10 Priority species for the Solomon Islands

Rank	Species	Common name	Score
1	*Planiliza melinoptera*	Otomebora mullet	38
1	*Planiliza subviridis*	Greenback mullet	38
1	*Mugil cephalus*	Flathead grey mullet	38
1	*Kuhlia rupestris*	Rock flagtail	38
2	*Scatophagus argus*	Spotted scat	37
3	*Terapon jarbua*	Jarbua terapon	36

TABLE 11 Priority species for Samoa

Rank	Species	Common name	Score
1	*Planiliza melinoptera*	Otomebora mullet	38
1	*Planiliza subviridis*	Greenback mullet	38
1	*Mugil cephalus*	Flathead grey mullet	38
1	*Kuhlia rupestris*	Rock flagtail	38
2	*Scatophagus argus*	Spotted scat	37
2	*Terapon jarbua*	Jarbua terapon	36

is that it is already well established in culture in other countries, with the lifecycle having been closed and seed production technology well documented.[30,63]

The lowest priorities nominated for the Solomon Islands are the rock flagtail *Kuhlia rupestris*, spotted scat *Scatophagus argus* and the Jarbua terapon *Terapon jarbua*. These species all have a documented reliance on seawater for completion of their lifecycle and/or are data deficient with respect to their reproductive biology.[63] At the time of writing, a freshwater fish brood stock centre for GIFT tilapia is under construction and nearing completion at Aruligo in Guadalcanal, which can provide facilities to potentially carry out research and development activities into any of the new species listed above. A further advantage is the presence of the Worldfish Centre in the Solomon Islands, because technical assistance and expertise may be sourced through this institution. Both the Ministry of Fisheries and Marine Resources (MFMR) and Worldfish have marine hatchery capabilities, at Honiara and Gizo, respectively, which could be used for breeding and rearing of mullet or flagtail. A concerted effort has already been made to trial capture-based milkfish *Chanos chanos* aquaculture in Solomon Islands, but this was discontinued mainly due to high cost of production.[63]

4.7 | Samoa

A list of the species prioritised for Samoa is presented in Table 11. The recommended top priorities for research efforts in this country are the two species of mullet *Planiliza melinoptera* and *P. subviridis*. Reasons behind the nomination of these two species are identical to those listed for the two species of *Cestraeus* for the Fiji Islands, and include trophic level position and grow-out feasibility. Mullet is especially prized for eating in Samoa.

The second-tier priority species nominated for this country is the flathead grey mullet *Mugil cephalus*, for the reasons mentioned earlier for the Solomon Islands. Milkfish culture has been attempted in the country previously; however, the project was abandoned in 1983 due to reasons of economic feasibility.[69] Given that similarities exist between the requirements for milkfish and mullet culture, existing national mariculture infrastructure and capacity may be utilised. The lowest priorities nominated for this country are the rock flagtail *Kuhlia rupestris*, spotted scat *Scatophagus argus* and the Jarbua terapon *Terapon jarbua*, for the reasons outlined earlier in the previous section under the list for the Solomon Islands. Samoa appears to possess the technical capacity, although the freshwater aquaculture facilities at Apia have staffing and space constraints and are currently dedicated to tilapia broodstock maintenance, while the mariculture hatchery at Toloa lacks sufficient supply of freshwater.

4.8 | Tonga

A list of the species prioritised for Tonga is presented in Table 12. This country has the shortest list of priority species compared to the other focus countries. The recommended top priority for research effort is the mullet *Planiliza melinoptera*. Wild collection of *P. melinoptera* fry in the country has been attempted previously, and considered a success. The fingerlings produced after growing wild-caught fry have also been trialled in pen culture, along with feed experiments.[70]

Mullet culture has been attempted previously in Tonga, with research effort centred primarily around the flathead grey mullet *Mugil cephalus*[35,70,71]; and this is the second priority species listed. Experimental mullet culture to support small-scale fish farming in the country began in 1975, and continued under two successive Five-Year Development Plans (1975–1980 and 1980–1985). These experimental culture efforts were terminated in 1979 with inconclusive results. There were reports of experimental mullet culture being a major aquaculture activity as a source of food and tuna baitfish[35]; however other reports suggest lesser degrees of success.

One example of this was five ponds constructed on the island of Mu'a in 1980 for the culture of tilapia. It was observed that mullet, milkfish and mollies also colonised the ponds, however, the problem of tilapia outcompeting the mullet and milkfish soon arose. A further disadvantage was found to be the low price of refrigerated versus freshly caught mullet, which led to the conclusion that little profit would remain after expenses on culture effort.[35]

A 5-year JICA project, entitled Aquaculture Research and Development, was initiated in October 1991 at the Ministry of Fisheries. Fish species targeted initially included mullet, rabbitfish and milkfish, with priority placed on mullet. At the request of the Tongan Government, research on the culture of mullet has been established as the first priority of fin-fish culture under this

TABLE 12 Priority species for Tonga

Rank	Species	Common name	Score
1	*Planiliza melinoptera*	Otomebora mullet	38
1	*Mugil cephalus*	Flathead grey mullet	38
2	*Scatophagus argus*	Spotted scat	37
3	*Terapon jarbua*	Jarbua terapon	36

programme. A mullet hatchery was considered but costs and expertise availability were considered prohibitive.[70] FAO support was provided for a further mullet capture-based culture project starting from 2011 onwards, however, it has not led to this activity becoming established in Tonga.

Tonga has little technical capacity and facilities for freshwater aquaculture and grow-out sites are limited by a lack of surface water resources on land. There is an excellent marine hatchery facility at Sopu on Tongatapu in which mullet could be spawned and reared. The lowest priorities nominated for this country are the rock flagtail *Kuhlia rupestris*, spotted scat *Scatophagus argus* and the Jarbua terapon *Terapon jarbua*, for the reasons outlined earlier in the previous section under the list for the Solomon Islands.

4.9 | Research priorities

The results clearly show there are significant data deficiencies among the majority of the top 10 species, primarily relating to aspects of general biology or reproductive biology. These knowledge gaps are further clarified below for each species, and the primary knowledge gap for most species lies with their reproductive habits and details of egg size, larval size and feeding habits of the larvae. This is a critical area in assessment of their suitability for culture, because species which produce small-sized larvae require suitably small-sized live feed items during the first few days of following hatch, such as S-type rotifers or copepod nauplii. Small-sized live feed items are technically demanding and costly to produce and maintain in mass culture, with timing of feed availability absolutely critical. It will be important to know which of these species of fish either do not have these feeding requirements for early-stage larvae, or can be provided by methods that are feasible within PICT technical capacity.

4.10 | Goldie river mullet *Cestraeus goldiei* and Sharp-nosed river mullet *Cestraeus oxyrhyncus*

No data is readily available on detailed egg characteristics, hatch or first-feeding requirements of larvae. Comments cited in literature include that reproduction is 'oviparous, eggs are pelagic and non-adhesive'.[30,31] Captive breeding of wild-caught broodstock will be necessary for this species in order for this baseline data to be collected. There is little information available about how, where and when to obtain brood stock fish from the wild.

4.11 | Lobed river mullet *Cestraeus plicatilis*

No data is readily available on detailed egg characteristics, hatch or first-feeding requirements of larvae. Comments cited in literature include that reproduction is 'oviparous, eggs are pelagic and non-adhesive'.[30,31] Captive breeding of wild-sourced broodstock will be necessary for this species in order for this baseline data to be collected. There is little information available about how, where and when to obtain brood stock fish from the wild. There appears to be some confusion about the environment in which this species reproduces. Gehrke, Sheaves, Terry, Boseto, Ellison, Figa and Wani[72] state that the species is believed to be 'potamodromous (breeds entirely in freshwater); based on the behaviour of the closely related species *Nematalosa erebi* in Australia'.

4.12 | Half fringelip mullet *Crenimugil heterocheilos* and Otomebora mullet *Planiliza melinoptera*

No data is readily available on detailed egg characteristics, hatch or first-feeding requirements of larvae. Comments cited in literature include that reproduction is 'oviparous, eggs are pelagic and non-adhesive'.[30,31] Captive breeding of wild-caught broodstock will be necessary for this species in order for this baseline data to be collected.

4.13 | Greenback mullet *Planiliza subviridis*

Natural spawning in captivity and larviculture of this species has been investigated, and the lifecycle successfully closed under artificial conditions. This species has been established in culture in South-East Asia for some time, and larviculture is routinely practised in concrete tanks in Thailand.[33] A report by Ruangpanit, Yashiro and Vatanakul[73] reports on a successful spawning event that occurred at night in seawater at a salinity of 30‰ when 20 males and 5 females were stocked in a 25-tonne spawning tank. Two million eggs were spawned and collected by fine mesh nets into 500 L incubation tanks the morning after spawning. The eggs hatched in 17–21 h at 26–29°C after spawning with a hatch rate of 71.5%.

Feeding with rotifers commenced on the second day after hatching until 15 days post-hatch. Brine shrimp nauplii were provided on Days 12–30 post-hatch and artificial feed was provided on Days 21–30 post-hatch. About 735,000 fry were produced after 30 days of culture with a survival rate of 51.4%. Larvae fed with *Artemia* together with artificial feed resulted in significantly higher survival rates ($p < 0.05$) than those fed only *Artemia*. Larvae between 12 and 30 days old were able to be nursed in a wide range of salinity (15–30‰) and the juveniles are also able to be reared at low salinities until acclimation to freshwater.

4.14 | Flathead grey mullet *Mugil cephalus*

Natural spawning in captivity and larviculture of this species has been investigated, and the lifecycle successfully closed under artificial conditions. This species is well established in culture predominantly in Southeast Asia.[30,31] Details regarding spawning, larval rearing and larviculture are very similar to those described for *Planiliza subviridis*. Meseda and Samira[74] detail an investigation which conducted induced spawning using HCG and LHRH-a. Spawning occurred after 17–24 h following induction, at a ratio of 3:1 males to females. Fecundity varied between 1 and 2.7 million eggs per spawn. They report that the embryo is noticeable 13 ± 1 h post-fertilisation, egg diameter was 870 ± 30 μm and oil globule diameter was 350 μm. After about 26 ± 4 h post-fertilisation, hatching commenced at a temperature of 25 ± 1°C and salinity of 34‰. The per cent fertilisation varied between 75% and 80% and hatching rate was about 90%. Newly hatched were 1.97 ± 0.23 mm in total length, and began feeding 3–5 days after hatching.

4.15 | Rock flagtail *Kuhlia rupestris*

Reproduction is 'oviparous with pelagic larval development'.[31,36] In response to demand within Australia for restocking of Flagtail into rivers to support recreational fisheries, breeding and rearing techniques up to fingerling size have been developed and are now available for transfer to PICTs. Rather than breed *Kuhlia* larvae and then add intensively reared live feeds to them in indoor systems, as would normally be done according to standard mariculture hatchery techniques, the approach taken by Hutchison, Lee, Nixon, Borchert, Chilcott, Shorten and Norris[21] is to first breed live feeds in extensive outdoor systems and then add *Kuhlia* larvae from controlled spawnings timed to utilise the outdoor feed at its optimum density. This approach will increase the feasibility for breeding and rearing of *Kuhlia* in PICTs. Gaps remain, such as culture conditions and nutrition for grow-out, culture performance in grow-out and economic viability of rearing to plate size.[75–83]

4.16 | Spotted scat *Scatophagus argus*

A large amount of data is not readily available on detailed egg characteristics, hatch or first-feeding requirements of larvae.[31,58] Barry and Fast[59] report on the captive breeding and early (but apparently incomplete) larval development of this species, mentioning that 'spawning occurs on coral reefs and juveniles migrate into fresh or brackishwater habitats'. Sexual maturation is stated to occur in females 7–9 months old weighing approximately 150 g, with fecundity being proportional to individual size. Data on monthly abundance of mature females and fry which were observed to peak markedly in August, suggest that monsoonal rains which commence in June may trigger spawning in this species. Induced maturation and spawning experiments fixed egg size at 0.68–0.75 mm in diameter.

The adults are reported to be primarily herbivorous, with a noted preference for filamentous algae. Wild fry and juveniles captured were found to have a preference for zooplankton, *Artemia* nauplii and mosquito larvae. Juveniles develop through a pelagic larval stage unique to a few genera of teleosts known as the 'tholichthys'. Chaetodontidae (Butterflyfish) also possess this larval stage in their development. Captive breeding of wild-caught broodstock along with further larval rearing efforts will be necessary for this species in order for baseline larviculture data to be collected.

4.17 | Jarbua terapon *Terapon jarbua*

No data is readily available on detailed egg characteristics, hatch or first-feeding requirements of larvae. Comments cited in literature include that reproduction is 'oviparous with likely pelagic larval development, and adults spawn in the sea only and juveniles migrate into fresh water. Eggs are guarded and fanned by the male parent until hatch'.[31,57] Captive breeding of wild-caught broodstock will be necessary for this species in order for this baseline data to be collected.

In summary, the priority species which require research to build on the state of knowledge of their reproductive biology are identified in Table 13. The current state of knowledge on the biology of these species has been taken into account, as has the likely level of technical 'difficulty' which may be encountered when captive breeding efforts are undertaken. Additionally, in the context of warming temperatures due to climate change, proximity to thermal thresholds (on a per-species basis) may be mitigated by moving to higher altitudes. This represents an important knowledge gap that future research can address.

In summary, three front-running indigenous species do emerge from this analysis, however:

- Grey mullet *Mugil cephalus*, because they feed at a relatively low trophic level, have comparatively fast growth rates and overall possess characteristics which are amenable for small-scale inland aquaculture, and because hatchery breeding methods already exist which could be transferred for adoption by some PICTs, however, there are knowledge gaps about the scale of production needed to justify hatchery investment (capture-based culture has not succeeded in this region).
- Mountain mullet *Cestraeus* spp., because they feed at a relatively low trophic level, have comparatively fast growth rates and overall possess characteristics which are amenable for small-scale inland aquaculture, and despite data deficiencies about reproductive

TABLE 13 Priority species for research

Priority rank	Species	Common name	Score
1	*Cestraeus goldiei*	Goldie river mullet	40
1	*Cestraeus oxyrhyncus*	Sharp-nosed river mullet	40
1	*Cestraeus plicatilis*	Lobed river mullet	40
1	*Crenimugil heterocheilos*	Half fringelip mullet	40
2	*Planiliza melinoptera*	Otomebora mullet	38
2	*Kuhlia rupestris*	Rock flagtail	38
3	*Scatophagus argus*	Spotted scat	37
3	*Terapon jarbua*	Jarbua terapon	36

biology because this may well resemble that of flathead grey mullet *Mugil cephalus*.

- Jungle perch *Kuhlia rupestris*, because of recent advances in methods to breed and rear them to fingerling size, and despite the likelihood of high water-quality and nutrition requirements in grow-out, and knowledge gaps about culture performance and economics.

5 | CONCLUSION

This analysis of indigenous freshwater fish in Fiji, Papua New Guinea, Vanuatu, the Solomon Islands, Samoa and Tonga shows that a total of 13 species belonging to the families Mugilidae (Mullets), Kuhliidae (Flagtails), Cichlidae (Tilapias), Terapontidae (Grunters and Tiger-perches), and Scatophagidae (Scats) have the highest culture potential according to the selection framework generated. Most (but not all) of these species feed at a relatively low trophic level (herbivores/detritivores), have comparatively fast growth rates and overall possess characteristics which are most amenable for adaptation to small scale, inland aquaculture.

An important finding is that these top 10 species scored very close to Nile tilapia (Tables 2 and 3) as candidates for aquaculture. Some scored slightly worse, and the *Cestraeus* spp. slightly better, when considered purely on the basis of their biological characteristics for culture. If consumer preferences about indigenous fish and tilapia are also taken into account (noting that these preferences vary within and among PICTs), then some strong candidates for domestication may emerge. There are considerable data deficiencies among the majority of the top 10 indigenous species, however, as well as lower-ranked species, primarily relating to aspects of the species' general biology or reproductive biology, and their performance in grow-out. Filling the knowledge gaps identified in this analysis will be necessary before each of these species can be fully and definitively assessed as candidates for aquaculture.

AUTHOR CONTRIBUTIONS

Monal Mohitesh Lal: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing – original draft; writing – review and editing. **Kelly Thomas Brown:** Data curation; formal analysis; resources; software; validation; writing – original draft; writing – review and editing. **Prerna Chand:** Data curation; formal analysis; methodology; resources; software; validation; visualization; writing – review and editing. **Timothy David Pickering:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing – original draft; writing – review and editing.

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DATA AVAILABILITY STATEMENT

We confirm that this review article is an original piece of work and has not been published, accepted for publication, nor is it under consideration for publication in another journal. All data (or literature, as applicable here) generated or analysed during this study has been cited in the article, or included as supplementary information.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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