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REVIEW ARTICLE

Aquaculture as a tool to support goby-fry fishery? Current knowledge on biology and ecology of the red-tailed goby *Sicyopterus lagocephalus*

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Abstract

Sicydiinae species are amphidromous gobies, adults spawn in freshwater, whereas free embryos undergo a pelagic open sea phase. Post-larvae or juveniles are caught for human consumption when entering in freshwater after their pelagic larvae life in seawater. Such goby-fry fisheries are existing since centuries and widespread in tropical areas over the world. There are uncertainties related to caught volumes and trends but, overall, go-fry fisheries are declining and their sustainability is questionable. Aquaculture is a potential tool in conservation and management of wild goby stocks. Among Sicydiinae species, the red-tailed goby *Sicyopterus lagocephalus* is the most spread and used as a model species in numerous works involving amphidromous fish. The aim of the study was to evaluate the potential in aquaculture of the red-tailed goby through the analysis of the literature available on this species. We found that this species has some assets to be a potential candidate for aquaculture such as a short production cycle and a high fecundity as well as potential high market values. Nevertheless, given the small size at hatching and the long pelagic larval life, larval rearing is likely to be a challenging rearing phase but appears to be feasible based on past experiences with other goby species. Throughout the paper, we provided recommendations for future research in red-tailed goby aquaculture.

KEYWORDS
amphidromous fish, aquaculture, captive breeding, conservation, Gobiidae: Sicydiinae

1 | INTRODUCTION

Goby-fry fisheries have existed for centuries, with the earliest mention dates from the 18th century (Atwood, 1791), although there are limited historical data (Keith et al., 2015). Such fisheries have been documented in different tropical areas worldwide, including South East Asia, French Polynesia, Hawaii, the Caribbean region, West Africa and Mascareignes Archipelago (see for review Bell, 1999; Thomas, 2017). Although most of the goby-fry fisheries have been considered local and artisanal (McDowall, 2007), yield can be high. Thus, Manacop (1953) estimated that 20,000 tons of gobies (mainly *Sicyopterus lagocephalus* and *S. lacrymosus*) have been caught in 1930 in Northern Luzon in the Philippines; such volumes are equivalent to several dozens of billion individuals harvested.

Goby-fry fisheries mainly target species belonging to the Sicydiinae sub-family (Manacop, 1953; Bell, 1999). More precisely, the most exploited genus is *Sicyopterus*, especially in the Philippines and Reunion Island (Bell, 1999; Delacroix, 1987; Manacop, 1953). These amphidromous species share a very distinctive life cycle. The Sicydiinae species have amphidromous life histories with spawning in freshwater. Their larvae drift downstream to the sea, where they have a marine larval life before migrating back into the rivers to grow and reproduce (Manacop, 1953; McDowall, 1988). Harvest occurs when large schools of post-larvae ascent into the mouths of rivers using nets, diverse gears and traps (Bell, 1999; Delacroix, 1987). Still today, the impact of fisheries on Sicydiinae populations remains largely unknown.

Post-larvae of Sicydiinae play an important socio-economic role by providing food for local populations. Therefore, goby post-larvae are prized products in some regions and can reach very high prices on local markets (e.g. > \$80 kg^{-1} in Reunion Island [Thomas, 2017]; i.e. 4% of the average local month salary per kg harvested). Nevertheless, there is only limited information regarding the volumes harvested. Several studies agree that many of the goby-fry fisheries have declined considerably (Bell, 1999; Castellanos-Galindo et al., 2011; Manacop, 1953) and recommend management and conservation measures such as banning fisheries during specific periods of the year. Nevertheless, high discrepancies in harvested volumes and trends have been highlighted. For example, in FishStatJ, the FAO's dataset on global aquaculture production, fishery data on Gobiidae reported for Reunion Island, one of the most studied goby-fry fisheries were 1–2 tons per year from 2002 to 2008 (FAO, 2021). Over the same period, Thomas (2017), based on surveys and literature review, estimated average harvested volumes from 30 to 45 tons annually. Such mismatch production statistics between different sources have been reported for other species (Garibaldi, 2012; Metian et al., 2014) which can distort decision-making for fish stocks management.

Fisheries are not the only human pressure on Sicydiinae species. They also faced other anthropogenic pressures that often impact aquatic species from tropical islands (Artzrouni et al., 2014). As amphidromous species, free movement between freshwater and the marine environment is crucial for completing their life cycle. River mouth closures caused by inadequate river flow management can lead to long-term fish extirpation (McDowall, 1995). A lack of recruitment at the river mouth may cause a decrease in the adult population in the catchment. The presence of dams along the rivers further limits both the upstream colonization of fish and the chances of larvae reaching the sea, but quantitative assessments of such anthropogenic impacts are still limited (see Jarvis & Clos, 2019 for review). Such studies used different methods based on the intensive fishway monitoring to evaluate population dynamics (Lagarde et al., 2015), the biometric and morphometric analysis to measure the effects of dams on the individual morphological selection (Lagarde et al., 2020a) or the direct assessment of the passage of obstacles by the biota (Kreutzenberger et al., 2021). As a general rule, studies conclude that goby-fry fisheries are not sustainable under current conditions mainly because of the lack of knowledge on the biology and ecology of these species (Delacroix, 1987; Keith et al., 2015; Valade et al., 2009). The same studies recommend a reflection regarding the management of wild goby stocks.

Aquaculture techniques offer valuable tools for the production of fish for human consumption and can potentially help to manage wild fish stocks (Froehlich et al., 2017; Patterson, 2019). Thus, the development of goby aquaculture may be a valuable way to limit pressure on wild stocks:

1. Through releasing captive-bred individuals to improve wild recruitment (i.e. stock enhancement);
2. By providing the local production of captive-bred individuals for human consumption to counteract the declines of local goby-fry fisheries, as Robert (1977) suggested.

Properly implemented and well-managed aquaculture techniques can benefit fish species (Le Vay et al., 2007; Mustafa, 2003). Interestingly, to our knowledge, there is no report of amphidromous goby aquaculture neither as a conversation tool nor for human consumption.

The present work focused on the red-tailed goby *S. lagocephalus*. This widespread species is one of the main harvested species with fisheries in both Indian and Pacific oceans (Bell, 1999; Manacop, 1953) and the most studied Sicydiinae as a model species for amphidromous fish for studying life-history traits, biology and physiology (Lord et al., 2019). The main objective of this review was to evaluate the potential in aquaculture of the red-tailed goby based on the current knowledge on its biology and ecology and provide guidance for further research in goby aquaculture. The establishment of goby aquaculture requires a clear definition of the objectives (i.e. species conversation and/or human consumption) and may involve a market analysis, which is still premature and out of the scope of this review. However, we discussed some critical socio-economic points.

2 | MATERIALS AND METHODS

The search for bibliographic data was conducted in four steps. The first was collecting peer-reviewed literature from 1950 to May 2021, using Web of Science (WOS) and Google Scholar. Although WOS covers >12,000 scholarly journals and provides a fair representation of international mainstream scientific research (Moed, 2005), Google Scholar helps in the retrieval of most difficult information to find, even in non-English language journals (Falagas et al., 2008). Searches (on abstract, keywords and titles) were performed individually using the scientific name (accepted binomial taxonomic name and synonyms) as well as vernacular name in different Latin languages listed from Froese and Pauly (2021).

In the second step, the data were supplemented by searching for relevant information in the grey literature. The documentation of goby-fry fisheries began early (at least 18^{th} century) and often reported in non-peer-reviewed works. In the same way, information on biology and ecology has been mostly gathered from reports and Ph.D. thesis and not necessarily in peer-reviewed articles.

The third step was performed after analysing the relevance of the documents collected in the previous steps. Once the literature was sorted, the reference list of each of the papers was screened for

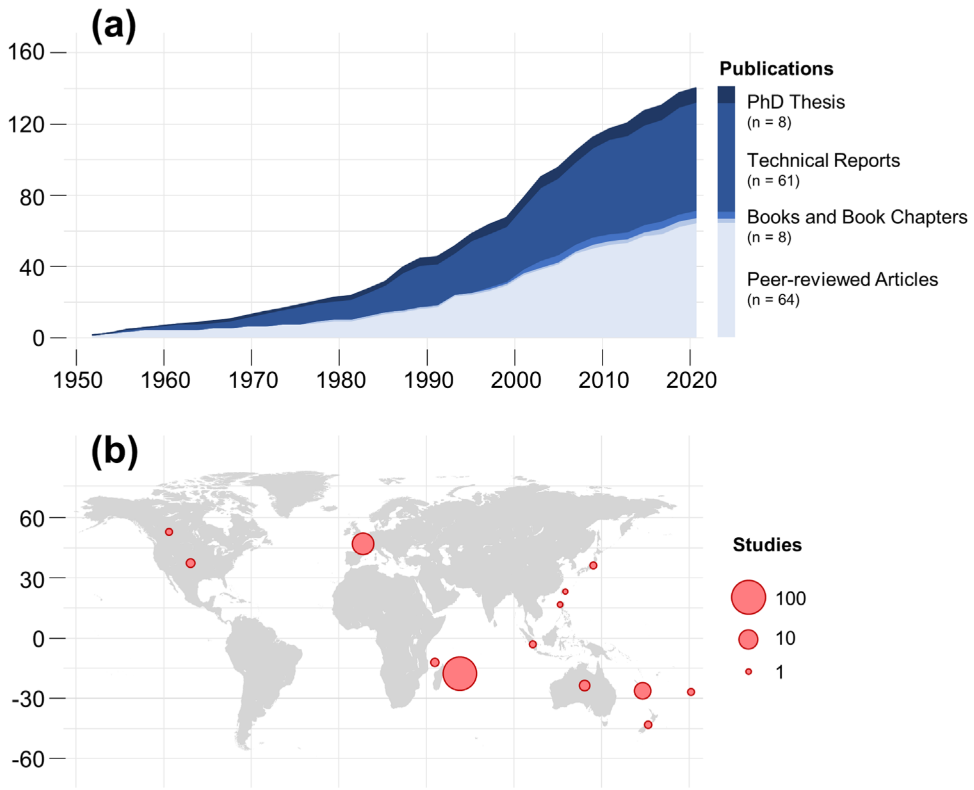

FIGURE 1 Bibliometric analysis of the papers published on the red-tailed goby *Sicyopterus lagocephalus* from 1950 to May 2021. (a) Publications over time ranking as peer-reviewed articles, book and book chapters, and Ph.D. thesis. The cumulative number of publications is indicated on the right. (b) The total number of studies performed by geographical area (i.e. the location of the experiment/sampling or, if any, the affiliation of the first author)

additional scientific titles and journals until no further relevant reference could be found ('snowballing' references; Sayers, 2007).

From the search results, non-relevant records (i.e. studies that did not explicitly address topics on the targeted species) were removed. Selected references ($n = 141$; Figure 1) were included in a database containing the following information: (1) the type of publication, (2) first author name, (3) year of publication, (4) journal (when appropriate), (5) country or region (based on the location of the experiment or sampling or, if any, the affiliation of the first author) and (6) the complete reference of the publication (see Supporting Information for the list of the selected references).

In the fourth and last step, the search for bibliographic data was extended to other Sicydiinae species when information about specific aspects (e.g. reproduction biology, larval development) was missing for the red-tailed goby.

3 | GEOGRAPHICAL RANGE AND TAXONOMY

Among amphidromous species, the gobies of the Sicydiinae subfamily are a species-rich group of >100 species (Taillebois et al., 2014). In the Sicydiinae, the genus *Sicyopterus* is the most diversified with 24 species (Lord et al., 2019) distributed in the Indo-Pacific area from west to east from Comoros Islands in the Indian Ocean to French Polynesia in the Pacific Ocean covering more than 18,000 km (Keith et al., 1999). However, only one species, the red-tailed goby *S. lagocephalus* (Pallas, 1770), is distributed throughout this entire range (Keith et al., 1999; Watson et al., 2000), within latitudes from −30 to 31 (Keith et al., 2011, 2012). The other *Sicyopterus* species generally have a more restricted distribution area, and they are endemic to a small group of islands (Keith et al., 2005). *Sicyopterus lagocephalus* was initially described as *Gobius lagocephalus* by Peter Simon Pallas (1770) based on a single specimen examined in the St. Petersburg Museum. The specimen has been described first as a *Gobius* by Joseph Koelreuter (1764) (Sparks and Nelson, 2004). However, the taxonomic status was questioned by Sparks and Nelson (2004), and Smith and Sparks (2007) proposed to suppress the name *G. lagocephalus* commonly used. Because of its wide geographical distribution range, some ichthyologists have sometimes considered several different species before analysing morphological and meristic variations by Watson et al. (2000). Thus, *S. lagocephalus* was supposed to be restricted to islands in the western Indian Ocean. In contrast, many similar species were considered to exist in the Pacific Ocean (e.g. *S. taeniurus*) in French Polynesia (Keith et al., 2005). Keith et al. (2005) confirmed, by phytogenetic analysis, the ubiquity of *S. lagocephalus* in the Indo-Pacific area and identified two different clades, one clustering most of French Polynesian haplotypes and the other clustering most of Mascarene (including Comoros) haplotypes.

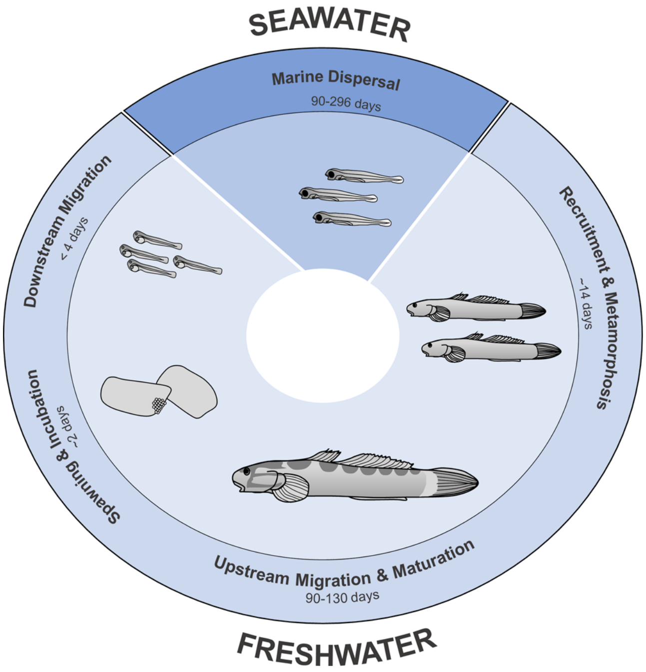

FIGURE 2 Amphidromous life-cycle of the red tailed-goby *Sicyopterus lagocephalus*. The oceanic pelagic phase is in dark blue, whereas the freshwater steps are highlighted in light blue

4 | BRIEF DESCRIPTION

The red-tailed goby is among the largest *Sicyopterus* species, achieving a maximum total length of 13 cm (Keith et al., 1999, 2015). In adults and juveniles, the body is somewhat elongated and sub-cylindrical. The snout is rounded, and the mouth is slightly inferior (Keith et al., 2015), typical of a 'grazing' feeding behaviour. In adults, sexual dimorphism is well pronounced. Males have prolonged second, third and fourth spines of the first dorsal fin. The membrane almost extends to the tip of these long spines. Males have a more slender and longer body than females (Teichert, 2012). Furthermore, males have a triangular urogenital papilla with a distal rounded tip, whereas females have bulbous urogenital papilla with fimbriate projection around the distal opening (Keith et al., 2015). Females are brown during the breeding season, and males are blue-green with a rounded caudal fin turning bright red (Keith et al., 1999; Teichert, 2012).

5 | BIOLOGICAL AND ECOLOGICAL BACKGROUND

5.1 | Life cycle characteristics

The red-tailed goby is an amphidromous species meaning that adults spawn in freshwater, whereas free embryos undergo a pelagic open sea phase (Lagarde et al., 2015; Teichert et al., 2012, 2014b; Thomas et al., 2018). The description of the life-cycle is presented in Figure 2. Females laid eggs in freshwater rivers (Manacop, 1953; Delacroix, 1987; Delacroix and Champeau, 1992; Keith et al., 1999). The newly hatched embryos passively drift down to the sea within a few days after hatching (Lagarde et al., 2017; Valade et al., 2009). The duration of the drift downstream coincides with the vitelline resorption and the opening of the mouth (Delacroix and Champeau, 1992). The larvae then begin their marine planktonic life, allowing them to disperse potentially over long distances (McDowall, 2010). At recruitment, post-larvae swim in schools of million individuals in coastal areas towards the rivers' mouths, limiting predation risks (Keith, 2003; Teichert et al., 2014a). In freshwater, for a few days, the post-larvae can keep a pelagic swimming and a herd behaviour with small schools of 10–100 individuals (Hoareau, 2005; Keith et al., 2015). Metamorphosis into juveniles occurs in freshwater (Keith et al., 2012; Taillebois et al., 2011), and fish become sexually mature after 90–130 days in rivers (Lagarde et al., 2020b). The red-tailed goby life expectancy in freshwater remained unknown but was estimated at 2 years (Artzrouni et al., 2014) by comparison with another similar species, *S. stimpsoni* (Blob et al., 2010). Among the life-cycle traits of red-tailed goby, Artzrouni et al. (2014) highlighted the need to prioritize the data acquisition on the life expectancy in rivers and the mortality at river mouths and during the drift of larvae to sea to describe wild population dynamics better.

5.2 | Habitat

From hatching to recruitment, red-tailed goby lives in a marine environment (Table 1). To date, knowledge of the ecology and biology of this species during their marine phase remains very limited. Because investigations in coastal and open ocean habitats are methodologically complex, critical aspects such as their habitat preferences are scarce. Nevertheless, the increasing use of analytical techniques, including microstructural and Sr:Ca or Ba:Ca ratio analysis in otoliths on recruiting post-larvae caught at river mouths (Lord et al., 2010, 2011) and stable isotope analysis (^{13}C, ^{15}N and especially ^{34}S; Dubé and Benoy, 2005; Sorensen and Hobson, 2005), can improve knowledge on their marine phase. Environmental DNA may also be a promising tool for identifying preferential habitats and facilitate fine-scale geographic and temporal mapping of fish populations at relatively low cost (e.g. Berry et al., 2019; Buxton et al., 2018; Collet et al., 2018; Stoeckle et al., 2017).

The knowledge about habitats of the red-tailed goby during its freshwater life period is derived mainly from those associated with studies performed in Reunion Island, where amphidromous gobies have been extensively studied for decades (Figure 1). Overall, red-tailed goby post-larvae colonize the streams independently of their river of birth, as shown by Berrebi et al. (2005), meaning that there is no 'homing' (McDowall, 2010) and suggesting the plasticity of this species in its environmental requirements.

Teichert et al. (2014a) found that both adults and juveniles have weak habitat preferences based on the characterization of microhabitat variables (depth, velocity and predominant substrate) and the presence of conspecifics and sympatric species. Overall, in the investigated red-tailed goby habitats, depths ranged from 3 to 450 cm, and water

TABLE 1 Main characteristics related to the biology and ecology of eggs and larvae *Sicyopterus lagocephalus* for future research in aquaculture

Parameters	*Sicyopterus lagocephalus*	References
Egg diameter (mm)	0.5	Delacroix, 1987; Delacroix and Champeau, 1992
Incubation time (h)	50–60	Delacroix and Champeau, 1992
Size of newly hatched larvae (mm)	1.4–1.7	Ellien et al., 2020; Valade et al., 2009
Optimal temperature (°C)	20–23	Ellien et al., 2011; Valade et al., 2009
Transfer to seawater (days)	<4	Delacroix, 1987; Delacroix and Champeau, 1992; Teichert, 2012; Valade et al., 2009
Yolk sac resorption (days)	2–3 (After transfer in seawater)	Delacroix, 1987; Ellien et al., 2016; Valade et al., 2009
Mouth opening (days)	2–3 (After transfer in seawater)	Delacroix, 1987; Ellien et al., 2016; Valade et al., 2009
Diet	Mostly zooplankton (copepods)	Keith et al., 2008
Larval phase duration (pelagic phase in days)	90–296	Artzrouni et al., 2014; Delacroix, 1987; Hoareau et al., 2007; Lord et al., 2010; Teichert, 2012; Teichert et al., 2012; Thomas et al., 2018
Total length at recruitment (mm)	26.5–37	Delacroix, 1987; Hoareau et al., 2007; Keith et al., 2015; Lord et al., 2010; Hoareau, 2005; Teichert, 2012
Metamorphosis (time after recruitment in days)	~14	Keith et al., 2008

velocities ranged from 0 to 205 cm s^{-1}. Although microhabitat variables studied weakly explained the presence of the fish, they avoid fine sediments presumably because of the lower periphyton productivity, absence of favourable reproduction sites and/or hiding places from predators (Keith, 2003). Thus, the dominant substrate size modality was large boulders (26%), followed by large cobbles (23%) and small boulders (19%). In the same study, the authors found that spatial distribution is significantly influenced by the downstream–upstream gradient, with the presence of juveniles decreased from downstream to upstream (Teichert et al., 2014a).

6 | AQUACULTURE PERSPECTIVES

6.1 | Reflections on socio-economical aspects

Goby aquaculture may require a socio-economic analysis out of the scope of the present review. Determining the potential market, social acceptance (Ruiz-Chico et al., 2020) and production costs are significant points in the development of goby aquaculture. However, given the scarce data on the red-tailed goby's reproductive biology and husbandry techniques, research and development are required beforehand. Based on the data collected and analysed during this study, the research and development phase should at least include:

- determining the size, distribution and genetic variability of existing stocks (see Montalvo et al., 1997);
- determination of the type and form of aquaculture adapted to the needs of the local context (e.g. production/collection of post-larvae, juveniles, adults; hatchery, ponds, cages; low or high technology/intensification (Bell et al., 2009; Gilles et al., 2013; Tidwell, 2012) and inadequacy with the retention of genetic variability (if released into the wild), respect of biosafety and biosecurity policies (Hughes et al., 2008; Scarfe et al., 2006);
- a deep understanding of the biology/ecophysiology of red-tailed goby for reproduction;
- determination of potential bottleneck in production (e.g. larval feeding, mortalities);
- cost and production time optimization (e.g. aquaculture operations, investments, cycles).

In the case of conservation and/or repopulation/restocking programs, aquaculture techniques/protocols must be adapted to socio-ecological needs (e.g. strategies for retention and/or control of genetic resources; assessment, management and control of environmental biosecurity).

6.2 | Broodstock maintenance and sexual maturation

Non-invasive sexing, such as examination by direct observation or photography of the urogenital region, has been used successfully in red-tailed goby (100% reliable; Balon and Bruton, 1994).

In captivity, broodfish can be kept into small aquariums (~40 L) in a recirculating system dedicated to reproduction for environmental condition control and to limit the risk of diseases, as shown for other goby species (Lindstrom, 1988). Although Delacroix (1987) observed a sex ratio slightly biased in favour of males (1 male for 0.85 females), a sex ratio of 1 male to 1–2 females is likely the best compromise to avoid male competition for spawning sites. In addition, because the female seems to play a determining role in the pairing of red-tailed goby (Teichert, 2012), the presence of two females may maximize the chances of fertilization.

TABLE 2 Main characteristics related to the biology and ecology of juveniles and adults *Sicyopterus lagocephalus* for future research in aquaculture

Parameters	*Sicyopterus lagocephalus*	References
Diet	Periphyton	Bielsa et al., 2003; Keith et al., 2008
Maximal total length (mm)	130	Keith et al., 1999; Keith et al., 2015
Sexual dimorphism	Yes	Delacroix, 1987; Keith et al., 1999; Teichert, 2012; Teichert et al., 2014b
Total length at sexual maturity (female, mm)	41–55	Delacroix, 1987; Teichert, 2012; Teichert et al., 2014b
Relative fecundity (oocytes per gram)	7000–15,000	Delacroix, 1987; Delacroix and Champeau, 1992; Teichert, 2012; Teichert et al., 2014b
Temperature for ovarian growth induction (°C)	19.2	Teichert, 2012; Teichert et al., 2014b
Sex ratio (male:female)	1:0.85	Delacroix, 1987
Preferential spawning substrates	Pebbles	Teichert, 2012; Teichert et al., 2013a, 2013b
Parental care	Yes	Teichert, 2012
Spawning interval (days)	24–60	Teichert, 2012; Teichert et al., 2014b
Reproduction period	Throughout the year	Teichert, 2012; Teichert et al., 2013b

The maturation of red-tailed goby females occurs at a minimum temperature of 19.2°C (Teichert et al., 2014b). The females are not mature at sizes below 41 mm (Teichert et al., 2014b). In the field, Lagarde et al. (2020b) found the age at first maturity is approximately 9 months for *S. lagocephalus*, i.e. 90–130 days after they returned to freshwater, but varied depending on the duration of pelagic larval life and the season of recruitment. Temperature seems to be a determining factor in maturation (e.g. Teichert, 2012), whereas other studies suggested decrease in photoperiod also plays a role in inhibiting reproduction (Valade, 2001). As for other fish species, females mobilize lipid reserves for gonadal development allowing accumulation of yolk in the oocytes (Bielsa et al., 2003; Teichert, 2012); therefore, the diet of broodfish must be enriched in lipids to facilitate oocyte maturation.

From the few studies performed on the nutrition of red-tailed goby adults, the current formulated feeds developed from omnivorous fish (such as carp or tilapias), usually with low protein content (≤30%) and formulated mainly from plant ingredients, may be appropriate for goby aquaculture. Additional feeding with a frozen diet such as *Artemia* sp. may be an asset (Lindstrom, 1988). Research in goby aquaculture should focus primarily on nutrition, a parameter that significantly influences the gametogenesis of fish, particularly females (Cabrita et al., 2008).

6.3 | Fecundity and egg production

The natural spawning sites are characterized by shallow depths (<60 cm), low conductivity (often <80 μS cm^{-1}; Keith et al., 2008), average temperatures ranging from 19 to 23°C, high oxygenation (>7 mg L^{-1} of O_2) and high flow regimes (>30 cm s^{-1}) (Bielsa et al., 2003; Teichert et al., 2013b; Valade et al., 2009). In the natural environment, the preferred laying supports are pebbles. In captivity, PVC shelters can be provided as nesting support (Lindstrom, 1988). Females lay an entire clutch in a unique event (from 14,000 to 232,000 eggs), and then another batch of oocytes is recruited (Teichert, 2012; Teichert et al., 2013a). They can spawn several times throughout the year with an inter-spawning interval of 1–2 months, but the spawning frequency can vary according to environmental cues and over the spawning period (Teichert et al., 2014b). The high fecundity of red-tailed goby (i.e. 7000-15,000 oocytes per gram; Table 2) is an asset for aquaculture production.

Among the abiotic factors influencing spawning, the most critical water parameter that stimulates spawning is the temperature (Teichert et al., 2013a). Other factors may play a significant role in triggering spawning events, including the availability of nest supports and the decreasing conductivity of the water due to rainfall (Teichert, 2012). More recent studies focused on larval drift (Lagarde et al., 2017, 2018) also hypothesized that the increase of discharge during austral summer is the primary driver enhancing spawning activity. These potential cues need to be tested in controlled conditions.

Some studies report injecting human chorionic gonadotropin (hCG) in mature red-tailed goby females (Delacroix, 1987; Delacroix and Champeau, 1992) to obtain eggs from captive broodfish. Nevertheless, the success of induction by hormone injection is limited (>30% of spawning success after injection), and mortality of injected fish is high (20% in less than 48 h post-injection; Delacroix, 1987; Delacroix and Champeau, 1992). Based on current knowledge, it is reasonable to expect spontaneous spawning in captivity if appropriate conditions are provided (see above).

6.4 | Incubation and larval rearing

In the wild, the incubation of the eggs, laid in adhesive clusters, is very short (i.e. 50–60 h; Table 1). This rearing step should be performed in well-oxygenated and well-circulated water. The male shows parental care behaviour (Teichert, 2012; Teichert et al., 2013a). Thus, in captivity, the incubation of eggs can be performed in the broodfish tanks and likely does not require dedicated structures.

Like other Sicydiinae species, larval rearing can be initiated with the transfer of the PVC shelter with attached eggs that are ready to hatch in larval rearing tanks (e.g. Bell and Brown, 1995). Alternatively, newly hatched larvae can be collected and then transferred (e.g. Archambeault et al., 2015). The latter option has a higher risk of mortality. Valade et al. (2009), monitoring the effect of temperature on unfed larvae survival time, reported the highest survival rate from 20 to 23°C, with mortality increasing at higher temperatures. Ellien et al. (2011) showed no effect of stocking density (between 30 and 150 larvae per litre) on the development and the mortality of newly hatched larvae.

In the wild, goby larvae migrate passively down to the sea very quickly. Thus, several studies have demonstrated the need to transfer larvae to seawater before the age of 4 days; otherwise, development cannot continue, and the larvae die (Ellien et al., 2011; Valade et al., 2009). The transfer does not necessarily need to be progressive with a gradual increase in salinity (Valade et al., 2009) and can be carried out as early as 24 h after hatching (Bell and Brown, 1995; Delacroix, 1987). In a recent study, Teichert et al. (2021) highlighted that the survival of red-tailed goby larvae in freshwater exceeded 150 h at 21°C, whereas it dropped below 50 h at 31°C. In seawater, the larval development of unfed larvae was affected by temperature with gradual decrease in survival with increasing temperatures. The mouth and anus opened after 30–50 h in seawater depending on the water temperature (Delacroix, 1987; Ellien et al., 2020; Teichert et al., 2021; Valade et al., 2009) suggesting that larvae need to find suitable prey in seawater within a short time. Field studies highlighted that larvae and post-larvae of Sicydiinae are secondary consumers and omnivorous during their pelagic phase and mainly feed on zooplankton and plant/macroalgae detritus (Baptista et al., 2020; Keith et al., 2008). Nevertheless, the exact nature of the first feeding of wild larvae is largely unknown, and given the small size of the larvae (total length: 1.4–1.7 mm; Ellien et al., 2020; Keith et al., 2015; Valade et al., 2009), this is the most critical point for the larval rearing of the goby species. Although this parameter has not been accurately measured, based on the analysis of published photographs (Delacroix, 1987; Valade et al., 2009) through ImageJ software (Abràmoff et al., 2004), the aperture of the mouth can be estimated at 80–85 μm in red-tailed goby larvae at the presumed first-feeding stage (Figure 3). According to Allen et al. (2006), the critical prey size depends on width rather than length. Therefore, some small rotifers such as *Proales similis* (~40 μm of width; Hagiwara et al., 2014) and copepod nauplii such as *Parvocalanus* sp. (~50 μm of width; Kline and Laidley, 2015) are likely to be suitable prey for young life stages. Kondo et al. (2013) succeeded in the larval rearing of three *Rhinogobius* species into 30-L transparent polycarbonate tanks by feeding larvae with the super-small rotifers (*Brachionus rotundiformis*) immediately after hatching. Phytoplankton (*Nannochloropsis oculata*) was added three or four times per day in the tank to enhance the nutritional values of the rotifers. Then, brine shrimp (*Artemia* sp.) were added as additional live prey after 7 days at 19–21°C. Lindstrom (1988) tested different first feeds for *Lentipes concolor* and performed gut content analysis. The study showed that larvae ingested all of them (i.e. phytoplankton, oyster trochophores, small rotifers, copepod nauplii and undetermined wild plankton).

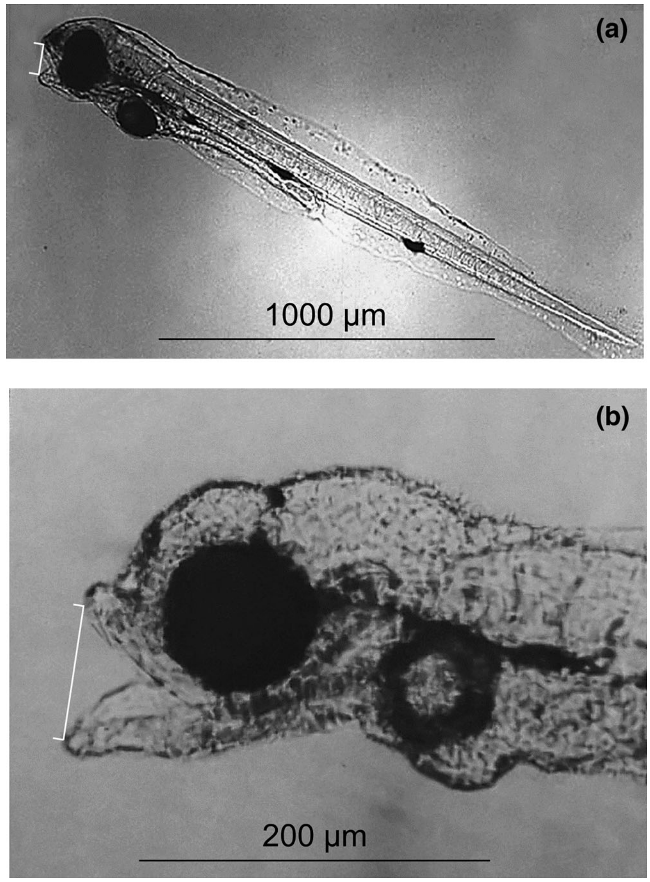

FIGURE 3 Measurement of mouth opening (white lines) in red-tailed goby *Sicyopterus lagocephalus* larvae 5 days after hatching from published photographs: (a) Valade et al. (2009) and (b) Delacroix (1987)

Altogether, these previous findings suggested that the red-tailed goby larvae diet should be first based on copepod nauplii and/or small-size rotifers, and then include brine shrimp nauplii, which is easier to cultivate, previously enriched with phytoplankton or commercial products. The quality of the first diet is, as in many species, a key parameter to explore through aquaculture research on goby species. Nevertheless, the studies on the larval development of Sicydiinae species carried out larval rearing for a few days or a few weeks only. So, the growth and survival performances during this rearing phase remain largely unknown and require further investigation.

The amphidromous nature of the red-tailed goby is a technical constraint. Although larvae can be transferred from freshwater to seawater relatively easily (Delacroix, 1987; Delacroix and Champeau, 1992; Valade et al., 2009), the transfer requires rearing structures that can operate with seawater (larval phase) and with freshwater (broodfish). Nevertheless, aquaculture of amphidromic species exists on a commercial scale. One of the closest examples is the aquaculture of ayu *Plecoglossus altivelis* in Japan. Ayu is an amphidromous fish in Japan, commercially important for freshwater fisheries. A decline in the abundance of wild ayu populations in rivers due to habitat destruction and blockage of migratory routes has promoted stock enhancement strategy from hatchery populations (Iguchi et al., 2003).

6.5 | From post-larvae to adults

The gregarious behaviour of the juveniles red-tailed goby until their sexual maturity (Teichert, 2012) suggests a possible maintenance in a common tank. During the first days after recruitment, post-larvae do not feed (Keith et al., 2012); afterward, the juveniles must switch from a planktonic feeding mode to a benthic feeding mode (Keith et al., 2008). Their diet is based on periphyton (protein: 12%–21% of dry weight and fat: 2%–3% of dry weight; Bielsa et al., 2003).

Therefore, commercial pellets used mainly for demersal omnivorous species such as cyprinids are likely appropriate for gobies. Nevertheless, the suitability of commercial pellets needs to be confirmed experimentally. In the wild, metamorphosis occurs approximately 2 weeks after recruitment in freshwater (Keith et al., 2008). In aquaculture, this step can be challenging; nevertheless, Keith et al. (2008) maintained individuals for approximately 1 month (until they reached adult size) in mesocosms without indicating any episodes of mortality related to metamorphosis.

7 | CONCLUDING REMARKS

The present study provides a critical overview of the scientific literature on the red-tailed goby *S. lagocephalus*. It is an attempt to foster further investigations in the aquaculture of these species. We do not advocate aquaculture as an obvious alternative to goby-fry fisheries because more research is needed to study the technical feasibility and sustainability of goby aquaculture. Nevertheless, this review lays the foundations for this research area, which has not been performed to date.

Below is a summary of key findings and recommendations for future research:

- Aquaculture is an area of research that should provide an alternative to fisheries and a new tool for the enhancement of goby post-larvae recruitment.
- Goby aquaculture can only be considered after a socio-economic analysis.
- The current knowledge on the biology and ecology of red-tailed goby suggests the potential of this species and, at this stage, holds promise for aquaculture.
- The efficiency of the transition from freshwater to seawater in captivity needs to be confirmed.
- Although it is reasonable to expect the spawning in captivity from broodfish, larval rearing may be more challenging.
- The nutrition of the early larval stages should be among the priorities of research for goby aquaculture.

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The authors declare no conflict of interest.

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This article does not contain any studies with animals performed by any of the authors.

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Simon Pouil designed the study, performed the analyses and wrote the manuscript, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing-original draft. Bérenger Colsoul contributed to the interpretation of the data. Both authors have reviewed and approved the manuscript, Data curation, Funding acquisition, Investigation, Validation, Writing-review & editing.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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