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South American fish species suitable for aquaponics: a review

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Abstract

Tilapia and catfish are the most popular fish species in aquaponics. However, they are not well-accepted in all markets, and finding alternative species is important in order to increase the variety of food products and meet market demands. South America has several potential fish species for aquaponics systems. Encouraging the implementation of integrated aquaculture systems by providing information about the production of South American species can help to increase the supply of high-quality food and aquaculture diversification. Thus, data for five South American fish species with potential for aquaponics were compared with existing data for the main traditional warm water species in this system, tilapia and catfish. Moreover, the degree of suitability of the novel species for these systems in terms of zootechnical performance, tolerance to water quality and nutritional composition of fish flesh were discussed. The South American species considered were jundia or silver catfish (*Rhamdia quelen*), yellowtail lambari (*Astyanax lacustris*), pacu (*Piaractus mesopotamicus*), tambaqui (*Colossoma macropomum*) and snook (*Centropomus* spp.). Their description and the tabular comparison with the most traditional aquaponic-cultured species show they are suited for this production system. How suitable they are will depend on the system design, as well as the regional characteristics of the market where they will be produced.

Keywords Aquaponics · Integrated food production · Food security · Aquaculture diversification

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Sara M. Pinho and Luiz H. David contributed equally to this work.

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This article is part of the Topical Collection on *Aquaponics and Biofloc*

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Introduction

A food production system is considered sustainable when it efficiently uses natural resources to produce high-quality food for human consumption (Wunderlich and Martinez 2018; Wilfart et al. 2013). Aquaponics has been recognized as a sustainable food production system, as it reuses a large proportion of its internal waste streams. It is defined as an integrated multitrophic aquatic food production method, which contains at least one direct connection between an aquaculture and a plant production unit (Lennard and Goddek 2019). Aquaponics is already widely applied in many developed countries (Villarroel et al. 2016; Love et al. 2014).

Food supply in South American countries is mainly based on monocultures; aqua-agriculture-integrated food production systems are not yet widespread (Rodrigues et al. 2019; Liu et al. 2018). Monocultures are one of the causes of the overexploitation of both the soil and natural resources (Hampf et al. 2020; Joyce et al. 2019; de Castro et al. 2014) and, in the long run, are inefficient in supplying the local population with healthy food. In addition, the social problems faced by many South American countries contribute to their current levels of malnutrition (PAHO 2020) and increase the need for efficient food production systems. In 2017, the annual freshwater fish production per capita in South America was below the worldwide average, 3.2 kg vs. 8.2 kg respectively, and the average of vegetable and fruit supply was also low: 51.6 kg per capita in South America vs. 135.7 kg per capita worldwide (FAO 2020).

Providing information on the production of South American species in aquaponics systems can encourage the implementation of these systems, and therefore help to minimize the continent's problems related to high-quality food supply and the pressure on natural resources. Compared to cage and pond-based aquaculture systems, both recirculating aquaculture systems (RAS) and aquaponics need lower volumes of water and smaller areas of land to produce fish (Oladimeji et al. 2020; Lennard and Goddek 2019; Martins et al. 2010). In aquaponics, some of the negative effects of fish production, such as nutrient-rich effluent discharge, can be reduced through nutrient reuse by plants and energy/nutrient recovery after waste treatment by implementing additional technologies (Goddek et al. 2019a). Moreover, chemical and antibiotic-free fish and pesticide-free plants are produced, which makes this system useful in promoting food security (Kyaw and Ng 2017).

Regarding the most common aquaponics design (i.e. coupled or one-loop aquaponics system), the process water is fully recirculated between the RAS and the hydroponics unit (Yep and Zheng 2019; König et al. 2018). An alternative configuration is known as the decoupled aquaponics system (DAPS), where the respective subsystem components can be seen as stand-alone systems. This allows for optimal conditions to produce both fish and plants (Monsees et al. 2017). In addition, multi-loop aquaponics systems have also been introduced (Lennard and Goddek 2019) that can comprise additional loops containing digestion units (Delaide et al. 2019) and/or desalination units (Goddek and Keesman 2018). Such additional loops are added to the system to increase the nutrient and water reuse efficiency of the overall system. For example, nutrient mineralization and mobilization units in the form of bioreactors can be used to reduce the need for additional fertilizers in the hydroponics unit. Desalination technology can be used to extract nutrients from the RAS water in a highly concentrated form and provide it to the hydroponics unit (Goddek and Keesman 2018). Regardless of the chosen design, it is important to make a careful selection of the fish and plant species that will be grown, in order to both optimize nutrient utilisation and achieve maximum profitability.

With respect to the fish species, tilapia (*Oreochromis niloticus*) and several catfish (order Siluriformes) are the most traditional warm water species for aquaponics (Yep and Zheng 2019; Mchunu et al. 2018; Love et al. 2015). However, these species are not well-accepted in all markets. This is because tilapia is usually masculinized with steroid hormone (Joshi et al. 2019; Golan and Levavi-Sivan 2014) and there is a high dependence on antibiotics to achieve high yields (Roriz et al. 2017). Also, catfish is known as a fish potentially containing heavy metals as it is conventionally reared using water from contaminated rivers such as the Mekong Delta (Vietnam) and Lake Rukwa (Tanzania) (Mapenzi et al. 2020; Madsen et al. 2015). In general, consumers of these species are concerned that undesirable substances have entered the food chain, especially due to the deposit of residues in the fish flesh (Zhong et al. 2016; Megbowon and Mojekwu 2014). Furthermore, tilapia and the most popular catfish (*Ictalurus punctatus*, *Pangasius pangasius*, *Clarias gariepinus*) are exotic in South American countries and, if accidentally released into the environment, could become predators of native species (Padial et al. 2017; Bittencourt et al. 2014).

As stated above, the search for alternative species for aquaponics production is important to meet market demands. This will increase the variety of available food products, allowing farmers to produce species that match local characteristics (Pinho et al. 2017; Goddek et al. 2015), and encourage aquaculture diversification (FAO 2016). The nutritional quality and flesh safety of the fish produced are also important factors when selecting suitable species. Fish is recognized as one of the best animal proteins, being highly digestible and an important source of essential fatty acids (Pal et al. 2018; De Smet 2012) and other nutrients for human health (Tilami and Sampels 2018).

South America is home to the largest biodiversity of fish in the world (Reis et al. 2016) and several species have been identified as potential candidates for aquaculture production. In some South American countries, native fish are already widely produced in pond or cage systems (Valladão et al. 2018). However, the feasibility of producing these species in aquaponics is still not well known. In this review, we compare five South American fish species with potential for aquaponics with the main traditional warm water species in this system, i.e. tilapia and catfish. We also discuss the degree of suitability of the novel species for different kinds of aquaponics systems in terms of zootechnical performance, tolerance to water quality and nutritional composition of fish flesh.

What makes a fish species suitable for aquaponics?

From a fish production perspective, aquaponics is bound to the same chemical, physical and biological conditions that occur in RAS (Espinal and Matulić 2019). This means that, just like in RAS, fish species must show some overall characteristics in order to be produced intensively in aquaponics systems, such as a tolerance to both high densities and high levels of total suspended solids and dissolved nutrients (Yep and Zheng 2019). Maintaining fish welfare is also necessary in these systems since it boosts their health and allows the fish to reach their maximum growth potential (Yildiz et al. 2017). In small-scale or hobby aquaponics systems, these are usually the only characteristics considered. However, for commercial productions, some additional specific points must be taken into account and they differ for coupled and decoupled systems.

In coupled systems, the aquaculture, hydroponics and biological filter units are interconnected; therefore, finding a trade-off between the proper water conditions for each subsystem is required (Palm et al. 2019). The choice of fish species in coupled aquaponics should depend on the crop grown. This is because plants are often the main source of income (Bosma et al. 2017) and, to keep the facility profitable, meeting plant requirements without harming fish growth or filter operation is desired. In these systems, the fish should be rustic and tolerate a wide range of physical-chemical water parameters. The fish should also tolerate high concentrations of macro and micronutrients which are often added to the water as a supplement for plant growth (Yildiz et al. 2017). In coupled aquaponics, the optimal conditions in each subsystem cannot be reached without either harming fish growth and survival or causing the plants to grow very slowly and show nutrient deficits. Achieving good economic system efficiency is a huge challenge when dealing with the trade-offs in terms of temperature, pH and nutrient concentration (measured in electrical conductivity) (Goddek et al. 2019b).

The range of species that can be produced in DAPS or in decoupled multi-loop systems is, in general, larger than in coupled systems (Fig. 1). This is due to the possibility of meeting the specific required economic conditions of each loop in decoupled systems, mainly in relation to abiotic factors, such as water and environmental conditions, and to nutrient balances (Danner et al. 2019; Goddek and Körner 2019). Once the requirements of the aquaculture loop are met, fish become an important aquaponics product and the choice of species becomes directly dependent on their market acceptance, production costs and growth rate. In DAPS, fish species with favourable characteristics for intensive RAS production can be selected, as outlined above.

South American fish species

The South American continent is recognized for its great potential for aquaculture production. This is due to its water availability, favourable climate conditions, high variety of species (FAO 2018a; Valladão et al. 2018) and access to technical-scientific knowledge, equipment, supplies and manpower. Valladão et al. (2018) reviewed South American fish for continental aquaculture and described the main fish species, producing countries and systems or used techniques. The potential of such species for aquaponics systems was not evaluated. Based on their characteristics, we consider that the main alternative species that might be interesting for using in freshwater aquaponics systems are the silver catfish jundia (*Rhamdia quelen*), yellowtail lambari (*Astyanax lacustris* spp.), pacu (*Piaractus mesopotamicus*), tambaqui (*Colossoma macropomum*) and snooks (*Centropomus* spp.). The reason to review these species, among several others reared in South America, was due to their market value, nutritional quality for consumption and/or the large volume produced in conventional systems.

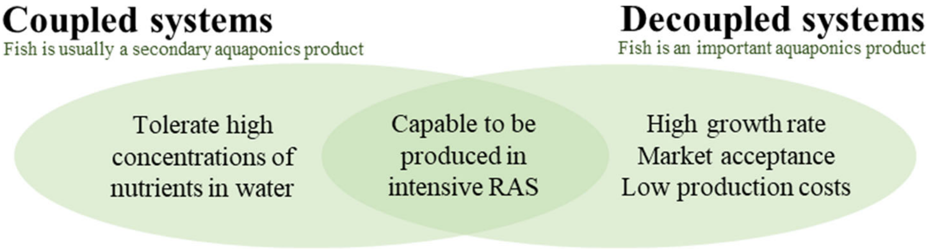

Fig. 1 The overall characteristics that fish species must have to be productive in coupled and decoupled aquaponics systems

A brief description of each one and a tabular overview are presented below. Photos of each species are presented in Fig. 2. The water quality, zootechnical and nutritional parameters are shown in Table 1. Data related to RAS and aquaponics systems were prioritized. In case no data was found, values from other production systems were reported and identified. With respect to the water quality, value ranges or maximum tolerable values of the main parameters suitable for each species were presented. The zootechnical and nutritional parameters were described according to the maximum values found for intensive cultures. For the stocking density, the values found for intensive cage systems were considered. The market characteristics for each species, such as harvest weight, mean values of nutritional composition for consumers and sale price, are summarized in Table 2.

In addition to the aforementioned species, a wide variety of fish should be considered in the future, especially hybrids of the "round fishes", for instance, tambacu (*C. macropomum* x *P. mesopotamicus*), paqui (*P. mesopotamicus* x *C. macropomum*), tambatinga (*C. macropomum* x *Piaractus brachypomus*), which were developed to be reared under different climatic conditions and to present better zootechnical results than the pure species (Hashimoto et al. 2012). However, insufficient productive results about them are available. In the case of the hybrids, their sustainability is uncertain due to lack of knowledge of their impact on the environment and effects on future generations of fish (Hashimoto et al. 2011).

Jundia or silver catfish (*Rhamdia quelen*)

The jundia (Fig. 2a) occurs naturally from southeast Mexico to Argentina. It is a suitable species for aquaculture in regions with a temperate or subtropical climate due to its optimal growth in summer and also its ability to withstand the temperatures of the South American winter (Abreu et al. 2016). In addition, jundia presents a high prolific rate, resistance to handling and high weight gain (Barcellos et al. 2009; Meyer and Fracalossi 2004). Reproductive management of this species is already dominated by the productive sector, with juvenile supply occurring from August to March (Barcellos et al. 2001). Its production has increased markedly because of the absence of intramuscular bones and high acceptance by consumers (Gomes et al. 2000). Under optimal conditions, it is possible to produce market size fish (800g) within 8 months (Barcellos et al. 2009). In the last decade, the total production of jundia has been decreasing (FIGIS-FAO 2020), mainly due to the increased production of exotic species, such as carp and tilapia (Baldisserotto 2008). From 2000 to 2010, the average annual volume produced was approximately 1000 tonnes, while in the following years, this average dramatically fell to 15 tonnes per year (FIGIS-FAO 2020).

No commercial production data of jundia in RAS or aquaponics is available. In experimental systems, the rearing of this species has been carried out for different purposes. Research with jundia in RAS includes evaluations of its reproduction (Goes et al. 2017; Tessaro et al. 2012; Coldebella et al. 2011), larviculture (Sulis-Costa et al. 2013; Uliana et al. 2001), productive management (Battisti et al. 2020; Owatari et al. 2018), nutrition (Yamashita et al. 2020; Ha et al. 2019; Battisti et al. 2017; Gominho-Rosa et al. 2015) and health (Cunha et al. 2018; Tancredo et al. 2015). These articles did not envision evaluating the growth performance of jundia in RAS compared to other production systems. However, their results showed that the species performs well in RAS environmental conditions.

To date, only two reports have been published about jundia reared in aquaponics. Rocha et al. (2017) evaluated the use of biofloc technology on the production of lettuce and jundia in a coupled aquaponics system. They demonstrated that it is possible to produce this fish in aquaponics and that the use of bioflocs did not influence the lettuce growth results. Araújo (2015) studied different feeding rates (7, 12 and 18 g per day) in the integration of jundia and cherry tomato (*Solanum lycopersicum*, var. Cerasiforme) produced in a coupled system. The author reported a difference between the optimum feeding rate for plants (12 g) and for fish (18 g) after 88 days of experiment. These results indicate the importance of continued investigation into jundia in aquaponics, particularly in decoupled systems, where the conditions can be adjusted to allow optimum performance for fish and plants.

Yellowtail lambari (*Astyanax lacustris*)

Yellowtail lambari (Fig. 2b), also known as yellowtail tetra or freshwater sardine, is a small (approximately 10 cm) and rustic fish from the Characidae family. The *Astyanax* genus is one of the most specious of the order Characiformes, encompassing more than 100 species distributed over the Neotropical region (Kavalco 2008). The species yellowtail lambari, present in the Upper Paraná Basin, was classified for many years as *Astyanax bimaculatus* (Linnaeus 1758). However, the systematic phylogeny of the *Astyanax* genus was reviewed, and it was found that *Astyanax bimaculatus* did not correspond to only one species, moving the yellowtail lambari to the denomination of *Astyanax altiparanae* (Garutti and Britski 2000; Garutti 1995). Later, the species *Astyanax altiparanae* was considered a synonym of *Astyanax lacustris* (Lütken 1875), which became the valid name of the species (Lucena and Soares 2016). All of these nomenclatures were considered in the literature review.

Yellowtail lambari is a species with a fast life cycle usually produced in semi-intensive rearing ponds (Silva et al. 2011), reaching the commercial size (10-15 g, Sussel 2015) within 3 months (Valladão et al. 2018; Garutti 2003). However, lambari is also suitable for production in intensive systems (Porto-Foresti et al. 2010; Garutti 2003). Yellowtail lambari females develop earlier than males; therefore, their production would be more interesting. However, sex separation or manipulation is not commercially applied, and mixed-sex populations have been reared by producers (Fonseca et al. 2017). Regarding its market factors, yellowtail lambari is usually sold per unit and appreciated as snacks or used as live bait, mainly in the Brazilian Southeast region (Valladão et al. 2018). The high demand for lambari in the Brazilian Southeast region probably boosted the local rearing of this species, representing in 2016 more than half of the 595.6 tonnes produced in this country (IBGE 2018). The production chain of lambari was described by Silva et al. (2011), showing that most of the lambari commercialized as snacks still originate from fisheries. The species is widely consumed, highly valued and is considered an alternative fish species for small family farmers, since on small pieces of land they can obtain a high income (Silva et al. 2011; Fonseca et al. 2017).

Yellowtail lambari is a promising species for aquaponics. Sussel (2015) reported that its culture has been carried out in ponds, cages, RAS and aquaponics systems. The author points out that natural food must be available to lambari during the first month, and after this period, it should be transferred to closed and intensive production systems. However, to date, only a few

Fig. 2 The five South American fish species with potential for use in aquaponics systems. **a** Jundia (*Rhamdia quelen*) juvenile, 23 cm total length (TL) (photo credit: Eduardo Antônio Sanches). **b** Adult yellowtail lambari (*Astyanax lacustreis*), 8 cm TL (photo credit: Emerson Durigon). **c** Pacu (*Piaractus mesopotamicus*) juvenile, 28 cm TL (photo credit: Eduardo Abimorad). **d** Adult tambaqui (*Colossoma macropomum*), 70 cm TL (photo credit: Jenner Menezes). **e** Common snook (*Centropomus undecimalis*) juvenile, 14 cm TL (photo credit: Flávio F. Ribeiro) ▶

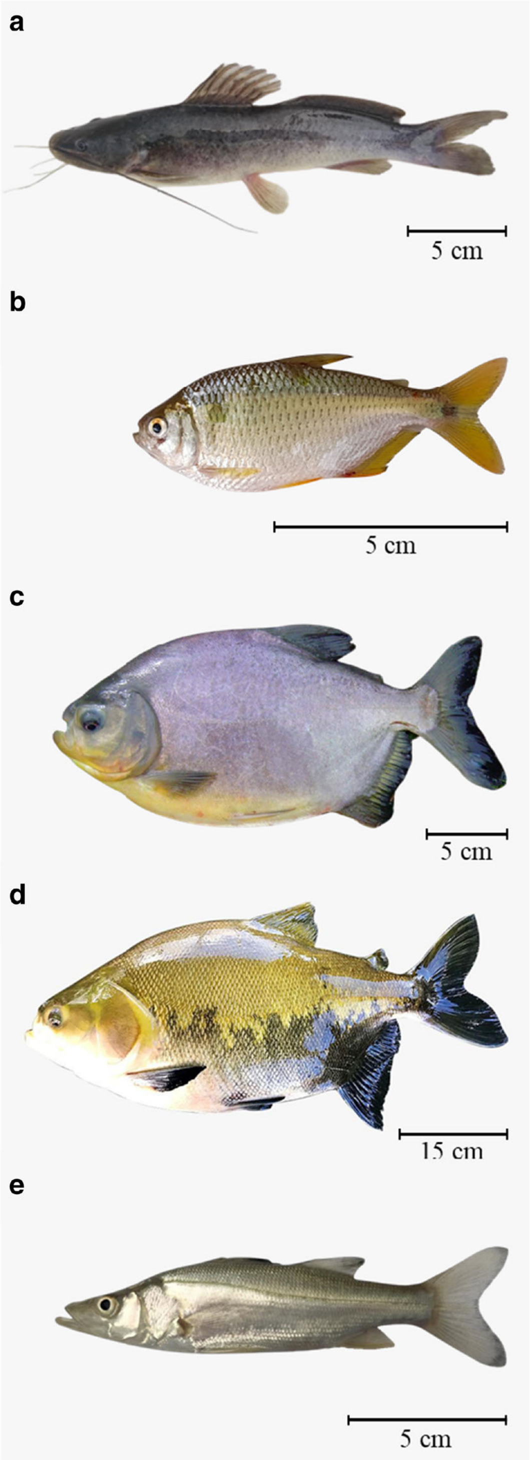
a
5 cm
b
5 cm
c
5 cm
d
15 cm
e
5 cm

Table 1 Overview of the water quality and productive parameters of the alternative South American fish species that could be considered for use in aquaponics systems compared to traditionally reared species

Parameter	Units	Traditional species		South American species*				
		Tilapia	Catfish	Jundia	Lambari	Pacu	Tambaqui	Snooks
Temperature	°C	27-30 [1][a]	22-28 [1][a]	20-26 [1][a]	25-28 [3][a]	28-32 [1][a]	26-32 [1][a]	25-31 [1][a]
DO	mg/L	4-6 [1][b]	2-6.5 [1][a]	5.6-7 [1][a]	4-8 [1][c]	5.9-8 [1][b]	4-8 [1][b]	4-8 [1][b]
pH	-	7-9 [1][c]	5.6-7.6 [1][a]	5.4-7 [1][b]	6.5-8 [3][a]	6.9-7.8 [1][b]	4-7.3 [3][c][d]	6.9-7 [1][b]
Max. nitrate	mg/L	200 [1][d]	114 [1][b]	86 [1][c]	0.25 [1][c]	1.46 [1][b]	NR	1.5 [1][a]
Max. ammonia	mg/L	0.1 [1][a]	6.7 [1][a]	3 [1][d]	1 [3][a]	1.32 [1][b]	1.2 [1][e]	0.03 [1][a]
Stocking density	kg/m³	70 [1][e]	300 [1][c]	17 [1][d]	14 [1][c]	75 [2][c]	40 [2][f]	60 [2][c]
FCR	-	1.3-1.7 [1][f][g]	1.0-1.3 [1][c][d]	1.6-1.9 [1][a][d]	1.1-1.5 [1][c]	1.2-1.6 [1][b][d]	1.1-1.7 [1][e][g]	1.2-1.8 [1][d][e]
Feed habit	-	Omnivore [h]	Omnivore [a]	Omnivore [a]	Omnivore [a]	Omnivore [d]	Omnivore [e]	Carnivore [a]
CP content	%	35 [1][h]	40 [1][a]	39 [1][e][f]	32 [1][d]	32 [1][d]	30 [1][e]	45 [1][e]
References		[a] El-Sayed (2006) [b] Timmons and Ebeling (2013) [c] Ross (2000) [d] Dalsgaard et al. (2013) [e] Rakocy et al. (2004) [f] Rakocy et al. (2006) [g] Knaus and Palm (2017) [h] Goddek et al. (2016)	[a] Akinwole and Faturoti (2007) [b] Strauch et al. (2018) [c] Baganz et al. (2020) [d] Rocha et al. (2017)	[a] Piedras et al. (2004) [b] Maffezzolli and Nuñer (2006) [c] Poli et al. (2015) [d] Araújo (2015) [e] Ha et al. (2019) [f] Battisti et al. (2020)	[a] Porto-Foresti et al. (2010) [b] Fonseca et al. (2017) [c] Jatobá and Silva (2015) [d] de Moraes et al. (2018)	[a] dos Santos et al. (2017) [b] Pinho et al. (2017) [c] Bittencourt et al. (2010) [d] Machado-Neto et al. (2016)	[a] Silva and Fujimoto (2015) [b] da Costa et al. (2019) [c] Rodrigues (2014) [d] da Silva et al. (2007) [e] Oishi et al. (2010) [f] FAO (2019) [g] Paulino et al. (2018)	[a] Correia et al. (2018) [b] Pinho et al. (2016) [c] Alvarez-Lajonchère and Tsuzuki (2008) [d] David et al. (2019b) [e] Sanches et al. (2011)

DO dissolved oxygen, *FCR* feed conversion rate, *NR* not reported, *CP* crude protein

[*] Jundia (*Rhamdia quelen*), also known as silver catfish; lambari (*Astyanax lacustris*), also known as yellowtail lambari, yellowtail tetra or freshwater sardine; pacu (*Piaractus mesopotamicus*); tambaqui (*Colossoma macropomum*); snook (*Centropomus* sp.), also known as robalo

[1] Data for closed systems (RAS, aquaponics or bioflocs systems)

[2] Data for cage farming

[3] Data for pond farming

Table 2 Overview of market characteristics of the alternative South American fish species that could be considered for use in aquaponics systems compared to traditionally reared species

Parameter	Unit	Traditional species		South American species*				
		Tilapia	Catfish	Jundia	Lambari	Pacu	Tambaqui	Snooks
Harvest weight	kg	0.6 ^{a}	0.7 ^{a}	0.8 ^{a}	0.02 ^{a}	1.5 ^{a}	2.5 - 3 ^{a}	0.5 ^{a}
Total protein**	%	20.1 ^{b}	15.5 ^{b}	18.9 ^{b}	16.3 ^{b}	18.2 ^{b}	19.0 ^{b}	22.0 ^{b}
Total fat**	%	1.7 ^{b}	7.6 ^{b}	4.2 ^{b}	5.7 ^{c}	8.4 ^{b}	2.7 ^{b}	2.2 ^{b}
n-3/n-6**		0.40 ^{c}	0.49 ^{c}	0.10 ^{c}	0.45 ^{c}	0.28 ^{c}	0.12 ^{c}	2.8 ^{b}
Price	€/kg	1.29 ^{d}	1.51 ^{d}	2.36 ^{d}	2.58 ^{d}	1.61 ^{d}	1.14 ^{d}	8.17 ^{d}
References		^{a} Goddek et al. (2016) ^{b} SND (2020a) ^{c} Kulawik et al. (2013) ^{d} CEAGESP (2020)	^{a} Akinwole and Faturoti (2007) ^{b} SND (2020b) ^{c} Ng et al. (2003) ^{d} TRIDGE (2020)	^{a} Barcellos et al. (2009) ^{b} Battisti et al. (2020) ^{c} Lazzari et al. (2011) ^{d} CEAGESP (2020)	^{a} Porto-Foresti et al. (2010) ^{b} Furuya et al. (2013) ^{c} Gonçalves et al. (2014) ^{d} CEAGESP (2020)	^{a} Campos et al. (2015) ^{b} Zuanazzi et al. (2013) ^{c} Ramos-Filho et al. (2008) ^{d} CEAGESP (2020)	^{a} Campos et al. (2015) ^{b} FatSecret (2020) ^{c} Filho et al. (2013) ^{d} CEAGESP (2020)	^{a} David et al. (2019b) ^{b} Hauville et al. (2015) ^{c} CEAGESP (2020)

1 € = R$ 4.65 (Jan 2020)

[*] Jundia (*Rhamdia quelen*), also known as silver catfish; lambari (*Astyanax lacustris*), also known as yellowtail lambari, yellowtail tetra or freshwater sardine; pacu (*Piaractus mesopotamicus*); tambaqui (*Colossoma macropomum*); snook (*Centropomus* sp.), also known as robalo

[**] All data for total protein, total fat and n-3 PUFA to n-6 PUFA (polyunsaturated fatty acids) ratio were obtained from the fillet composition, except for yellowtail lambari which is consumed as a whole and therefore its body composition was reported

studies with yellowtail lambari in RAS have been performed (de Moraes et al. 2018; Lira et al. 2018; Jatobá and Silva 2015) and no scientific information about its production in aquaponics has been published. In Brazil, the production of yellowtail lambari in aquaponics systems was initially developed by The Sao Paulo Agency of Agribusiness Technology and was applied in small coupled systems. However, the technology is in its early stages of implementation and the transferring of the production model to commercial scale is still to be achieved (AEAARP 2015).

Pacu (*Piaractus mesopotamicus*)

Pacu (Fig. 2c) is one of the most commercially valuable fish in Brazilian fish farming and there is also a huge interest in its production in other South American countries along the Paraná River Basin, such as Paraguay, Uruguay and Argentina (David et al. 2019a; Valladão et al. 2018; Portella et al. 2014; Portella and Dabrowski 2008; Hashimoto et al. 2011). Pacu is valued as a table fish due to its high quality and tasty white meat and as game fish in view of its behaviour in continental sport fishing (David et al. 2019a; Furuya et al. 2008). Its production has been promoted by its being a rustic, omnivorous species with easy acceptance of formulated feed and intensive systems (David et al. 2019a; Nunes et al. 2013; Portella et al. 2012). This allows production of fish of approximately 1.3 kg in the first 12 months (Urbinati and Gonçalves 2005). In aquaculture systems, the reproduction of *P. mesopotamicus* is only possible by hormonal induction, and the supply of juveniles in the South American continent occurs between October and March (Portella et al. 2014; Urbinati and Gonçalves 2005).

Pacu has been mainly reared in Argentina and Brazil, and its production occurs widely via semi-intensive techniques in ponds (Valladão et al. 2018). In 2016, approximately 1950 tonnes of pacu was produced in Argentina, representing 52% of the total aquaculture production in this country (FAO 2018b), and 11,570 tonnes in Brazil (IBGE 2018). This species is easily adaptable to intensive production in cages (Hilbig et al. 2012; Bittencourt et al. 2010); however, in ponds, low production density varying from 0.5 to 2 kg m^{-2} is usually reported (Valladão et al. 2018). The technical viability of pacu culture in closed systems was described only for larviculture (Jomori et al. 2003) and juvenile production (David et al. 2019a; Machado-Neto et al. 2016) phases, while no information on commercial or experimental production in RAS for the growth-out phase is available. In aquaponics systems, pacu is commonly reported as a species that is already being produced (Yep and Zheng 2019; Martins 2017; Rakocy 2012). Love et al. (2015) interviewed more than 1000 aquaponists of different scales around the world and found that pacu was among the farmed fish produced. Pinho et al. (2017) evaluated pacu and tilapia growth performance and the use of effluent from each species to produce two varieties of garnish (scallion and parsley) in coupled aquaponics systems. They showed that plant growth was not affected by fish species cultured and that pacu is a viable alternative species for aquaponics production. Fed with a diet containing 32% of CP and reared in an average temperature of 27 °C, it grew at a specific rate of 2.35% day^{-1} and showed a feed conversion rate of 1.6 (Pinho et al. 2017).

Tambaqui (*Colossoma macropomum*)

Tambaqui (Fig. 2d) is a well-known Amazonian fish, mainly reared and consumed in countries such as Brazil, Colombia, Peru and Venezuela, although some production of tambaqui is also found in several Asian countries (FAO 2019). In 2016, approximately 142,100 tonnes of tambaqui was produced in these South American countries (FAO 2018a). Currently, it is the number one native species reared in several countries of the South American continent (FAO 2018a). The popularity of tambaqui in the aquaculture sector is due to its fast growth rate, the acceptance of commercial feed, relative resistance to diseases and tolerance of low water quality (Lima et al. 2019; Oishi et al. 2010). This species is highly prolific; its reproduction is achieved by hormonal induction during the breeding season (Rodrigues 2014), resulting in high availability of tambaqui juveniles (Gomes et al. 2010). Achieving the harvest weight of 3.5 kg is possible within 2 years under general fish farm conditions, although the market size of aquacultured tambaqui in Brazil is around 500 g (Pantoja-Lima 2020) to 2.5-3 kg (Almeida et al. 2016; Campos et al. 2015). Tambaqui flesh is a traditional protein source for the local Amazon population, where its meat is in great demand (da Costa et al. 2019), and also appreciated in other regions in the continent. However, like other Characid species, tambaqui has intramuscular bones, which makes its filleting for sale in foreign markets difficult (Perazza et al. 2017). An alternative that has been explored to increase its acceptability is the processing in different cuts, mainly the sale of its ribs (Cartonilho and de Jesus 2011). More recently, a programme to genetically select tambaqui that do not present these intramuscular bones started in Brazil (Perazza et al. 2017).

The aquaculture sector has invested in technologies to shift tambaqui production from conventional semi-intensive systems to more intensive production systems using RAS (Lima et al. 2019; Silva and Fujimoto 2015). However, only experimental results on the production of this species in RAS have been published so far. As reported for jundia, the investigations carried out with tambaqui used RAS as an experimental system to evaluate other productive management systems or parameters, and they were not specifically designed to evaluate the growth performance of tambaqui in such systems. These studies mainly focused on nutrition (Paulino et al. 2018; Júnior et al. 2017; Nwanna et al. 2008), reproduction (Gallego et al. 2017; Maria et al. 2015), management (Dantas et al. 2020; da Costa et al. 2019), behaviour (Reis et al. 2019; Barbosa et al. 2009), genetics (Ariede et al. 2020; da Silva et al. 2019) and health (Barbas et al. 2020; Paz et al. 2019). Lima et al. (2019) evaluated different stocking densities of tambaqui juveniles in RAS. Although these authors did not compare RAS with other production systems, they contrasted their findings with results reported for pond and cage systems and showed RAS as a potential system for intensive tambaqui production.

No published articles reporting the use of *C. macropomum* in aquaponics were found, except for a few abstracts presented at scientific conferences (Araújo et al. 2017; Cruz et al. 2015; Ibrahim et al. 2015), all of them with anecdotal and inconclusive results. However, researchers from the Brazilian Agricultural Research Corporation (EMBRAPA) described in a technical report the development of compact coupled systems for the aquaponics production of tambaqui and vegetables at the family production level, and in modular systems for large-scale production (Carneiro et al. 2015). They reported satisfactory growth of vegetables and the possibility of reaching the commercial weight of tambaqui in a similar period to that observed in conventional systems.

Snook (*Centropomus* sp.)

The species from genus *Centropomus* present favourable characteristics for aquaculture in recirculating systems, such as fast growth, acceptance of formulated diets, potential for very high biomass yields per unit volume in the nursery and grow-out systems and high market value (Pinho et al. 2016; Alvarez-Lajonchère and Tsuzuki 2008). The twelve snook species are known as “robalo” in Latin America. The common snook (*Centropomus undecimalis*) (Fig. 2e) is the fastest-growing snook species and, together with the fat snook (*Centropomus parallelus*), is the most cultivated species under experimental conditions (Alvarez-Lajonchère and Tsuzuki 2008). They are diadromous, euryhaline, stenothermic and estuarine-dependent fish found in rivers, estuaries and coastal lagoons and along rocky shores (Mello et al. 2015; Pope et al. 2006). Studies have demonstrated that snooks have high osmoregulatory capacity, which allows them to maintain their internal osmotic pressure practically independent of external salinity concentrations (0-40 ppt) and to be produced in fresh water (Michelotti et al. 2018; Liebl et al. 2016; Gracia-López et al. 2006). Moreover, they are highly prized for the quality of their meat and valued for sport fishing (Passini et al. 2019). Processing the fillet is easy, with high yield (~ 42%), and its market value is usually high (David et al. 2019b; Cerqueira 2010).

There are still some constraints to the commercial production of snooks, such as their carnivorous habit (requiring diets with high protein content) and difficulties during the hatchery phase. However, the experimental results of reproduction and growth out are promising (Passini et al. 2019; Michelotti et al. 2018; Alvarez-Lajonchère and Tsuzuki, 2008). Researchers from Mexico reported the production of 800 g snook in 1 year (Sanchez-Zamora et al., 2003). Most of the experiments conducted with snook have been carried out in RAS, and aimed at understanding their reproductive biology (Passini et al. 2018; 2019), nutrition (Michelotti et al. 2020; David et al. 2019b), adequate stocking densities (Sanches et al. 2011) and optimal water parameters, especially temperature and salinity (Michelotti et al. 2018; Mello et al. 2015). However, in the field of aquaponics, snooks are still unknown and no reports of their production in these systems were found.

Discussion

The South American fish species with the potential to be produced in aquaponics have been described. Moreover, the main productive data of these species along with required water quality have been tabulated to enable a comparison with the two most traditionally cultured aquaponic species, tilapia and catfish. Most of these novel species are already known to conventional aquaculture systems. For instance, in the last years, the production of tambaqui and pacu in ponds or cages has been widespread in the American continent (Valladão et al. 2018), as mentioned in the previous species descriptions. However, only a few studies have been carried out to evaluate their production in aquaponics. The reported aquaponics production of South American species was only performed in coupled systems. Among these species, pacu and jundia have been the most evaluated in aquaponics, and encouraging growth results were found in all studies (Pinho et al. 2017; Rocha et al. 2017; Araújo 2015).

Matching the physical-chemical parameters of the water that is tolerated by the respective fish species to those required by plants is a key factor in coupled systems. The optimal ranges or the maximum levels of these parameters for the suggested fish species were reviewed in this study (Table 1). In general, fish that tolerate a wide range of water parameters are desirable. More specifically, species are highly suitable for these system designs when (1) they can be reared in water with pH between 5.5 and 6.5, since this is the range when nutrients are mostly available to plants (Resh 2012), and (2) they tolerate high levels of nitrate, which is crucial in determining the plant-growing area (Goddek et al. 2016). Given these characteristics, jundia stands out most among the South American species, although the physiological ability of tambaqui to tolerate large pH variations and its better growth in acidic water (Aride et al. 2007) also make it an outstanding species for coupled aquaponics production. The resistance of tambaqui to an acidic environment is due to its adaption to the wide pH range of the Amazonian rivers, home of this species. This fish is naturally found in the Negro River (pH ~ 4.7) and Solimoes/Amazonas River (pH ~ 6.8) (da Silva et al. 2013). It is important to highlight that the values in Table 1 were obtained from experimental results in different production systems that, in some cases, did not evaluate specifically the parameters mentioned and only reported them as excellent for the species. Because of this, we assert that research designed to investigate the pH toleration level of each species in RAS or aquaponics should be encouraged. New results may show that these species tolerate wider ranges of water parameters and, consequently, have even more potential for production in aquaponics.

For decoupled aquaponics systems or other aquaponics systems where fish is a relevant product, fish zootechnical performance must be considered. Reports of RAS production for all reviewed species are available. However, most of them were cultivated under experimental conditions that did not explore their productive potential. Pacu, snook and tambaqui stand out as the species that can be grown with the highest stocking density. The density for pacu rearing (75 kg m^{-3}) is higher than that commonly found for tilapia (70 kg m^{-3}) in aquaponics. On the other hand, catfish (*Clarias gariepinus*) culture density in aquaponics is significantly superior (300 kg m^{-3}, Baganz et al. 2020) as it is a rustic species and tolerates poor rearing conditions when compared to the other reviewed species. The production of jundia and yellowtail lambari is usually carried out in densities below 20 kg m^{-3}, three times lower than for tilapia. Research focused on increasing densities should be developed in order to make these species economically competitive in future RAS and aquaponics production. The FCR of lambari is the most desired among the species, ranging from 1.1 to 1.5. However, all the reviewed species show similar FCR and, because protein ingredients are the most expensive components of the diets, it is important to take into account the protein requirement of each species. In this sense, the lowest cost of feed would be for omnivore species, especially tambaqui, because it is the one with the lowest protein requirement. In contrast, although the FCR range for snook culture is comparable to the other species, it is a carnivorous fish and the amount of protein required in the diet would increase production costs.

The choice of fish species will depend on the demand and characteristics of the market where the aquaponics system will be located. For example, if the aim of production is to supply restaurants with differentiated fish cuts, the rearing of tambaqui and/or pacu should be considered. If the local market demands fish as a snack, yellowtail lambari will be the best option. For the supply of fillets, the snook can supply the high-end fish market while the jundia will be a more popular alternative. The market value and production cost of each species must also be taken into account. Table 2 shows the fish sale price according to CEAGESP, which is the biggest food warehouse in Latin America and sells fish from fisheries and aquaculture. The price of snook is four times higher than the others; however, its production is not yet at a commercial scale and there is no information on such costs. On the other hand, the sale price of the other novel species is higher or, at least, competitive in relation to the price of the traditional species. It should be noted that these prices are regional and will change according to the local market. Moreover, all these factors mentioned will influence the operational and economic planning of production.

Nutritious healthy food is usually understood as having low fat and high protein content (Jim et al. 2017). In this sense, the protein and fat content of the proposed South American species is more desirable than that reported for catfish, with the exception of pacu flesh which has 8.4% fat compared to 7.6% fat in catfish. On the other hand, protein content in tilapia fillet is surpassed only by snook. In addition to high muscle protein and low fat content, snook can offer an amount of *n*-3 highly unsaturated fatty acids (HUFA) higher than all other reviewed species. Freshwater tropical fish, generally, present lower concentrations of *n*-3 HUFA when compared to cold water marine fish. This fact encouraged research into *n*-3 HUFA supplementation in diets for freshwater fish grown in intensive systems (Stoneham et al. 2018), and this approach may be applicable to aquaponics systems in the future. In contrast to snook, the reported protein composition of yellowtail lambari is low. Although the protein content was analysed in different types of samples, that is, in the fillet for snooks and whole fish for lambari, they indicate the composition of the edible food. In this way, yellowtail lambari, as it is consumed, provides the least protein of the South American species. Nevertheless, it should be considered an important food for human consumption, since lambari can be a source of minerals, vitamins and other nutrients for vulnerable populations (Fonseca et al. 2017; Fiedler et al. 2016) and its *n*-3 to *n*-6 ratio is similar to the reported values for the traditional aquaponics species, i.e. around 0.40 and 0.49.

Aquaponics is not yet a well-represented food production system in South American countries (Emerenciano 2016). This may be related to the current high availability of fresh water and land in most of these countries, which results in the mistaken impression that incentives for sustainable aquaculture practices are not needed. Another relevant factor is the lack of political incentive, inspection or severe punishment for producers who degrade the environment (Azevedo et al. 2020). All these factors, in addition to the countries' current economic situation, result in low investment in advanced technologies for aquaculture and the predominance of production in conventional methods (ponds and cages). However, the growing need for food production technologies that minimize the use of natural resources should become the driving force for adopting more sustainable methods of production and stimulate the growth of aquaponics in these countries. At this point, knowing the feasibility of producing native fish species as well as encouraging research focused on evaluating the suitability of different regional species of plants in aquaponics is important. Until that happens, the information provided in this review will be useful to increase the variety of products and the satisfaction of different markets in countries where aquaponics is already a reality or is starting to grow.

Conclusions

The brief description of the South American species and the comparison with the traditionally reared species show that the five considered species (jundia, pacu, tambaqui, lambari and snook) are suitable for aquaponics production. The degree of their suitability, however, will depend on the system design, i.e. coupled or decoupled systems, as well as the characteristics of the regional market. It is recommended that future research focuses on understanding the optimal or tolerable water parameters and productive management, e.g. density and feeding rate, for each of the five species considered in recirculating aquaculture systems. In addition, practical applications of these species in aquaponics and their economic feasibility should be encouraged.

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