FISHERIES RESEARCH & DEVELOPMENT CORPORATION

Auditing research effort on aquaculture species and industry adoption for production growth

Tung Hoang, Joshua Fielding, Henry King & Polly Hilder

October 2020

FRDC Project No **2017-171**

Please Note – Final Report Requirements – accessibility

Under the Disability Discrimination Act 1992, Australian Government agencies are required to ensure information and services are provided in a non-discriminatory accessible manner – the FRDC and as a result all content produced as part of our projects also need to meet these requirements.

The Web Content Accessibility Guidelines outlines ways to make digital content more accessible to the broadest audience – https://guides.service.gov.au/content-guide/accessibility-inclusivity/

While there are many aspects to this, a key focus for principal investigators is to ensure that PDF documents are accessible. To make a PDF accessible you must make sure structural elements such as headings are marked-up so that a screen reader can follow the logical order of the content. The FRDC will update the final report design standard to highlight these requirements. We are regularly working to improve what we deliver to end users and this is part of that.

Auditing research effort on aquaculture species and industry adoption for production growth

2017-171

2020

The Fisheries Research and Development Corporation plans, invests in and manages fisheries research and development throughout Australia. It is a statutory authority within the portfolio of the federal Minister for Agriculture, Fisheries and Forestry, jointly funded by the Australian Government and the fishing industry.

Researcher Contact Details

Name: Tung Hoang
Address: Bribie Island Research Centre
144 North Street, Woorim, QLD 4507
Phone: +61436 691 225
Fax:
Email: Tung.Hoang@csiro.au

FRDC Contact Details

Address: 25 Geils Court
Deakin ACT 2600
Phone: 02 6285 0400
Fax: 02 6285 0499
Email: frdc@frdc.com.au
Web: www.frdc.com.au

In submitting this report, the researcher has agreed to FRDC publishing this material in its edited form.

Table of contents

List of tables

List of figures

Acknowledgments

This research would not be possible without the valuable support of many individuals. We would like to express our sincere thanks to 116 contributors from Australia and 21 other countries for helping review research effort and/or industry adoption of aquaculture species. Without your inputs this project is simply not possible. Special thanks are given to Dr Patrick Hone (FRDC Director) and Dr Mathew Cook (CSIRO Aquaculture Research Director) for their advices and supports on project development; Ms. Angela Palmer and Ms. Suzanne Blankley for great assistance with financial management; CSIRO Human Social Committee for reviewing the proposal and granting permission to conduct the online surveys.

We are highly appreciated the initial advice of Mr. Pheroze Jungalwalla, Dr Craig Foster, Dr Nigel Preston and Dr Jennifer Crocroft (JCU Singapore) that helped shape the skeleton of this research. Our thanks are further extended to Dr Peter Kube, Dr Curtis Lind, Dr James Wynne, Dr Richard Taylor, Dr Mathew Hamilton, Dr Andrew Wood for their valuable helps in reviewing and improving the questionnaires. We would like to thank Dr Chris Barlow, Dr Ann Fleming and other ACIAR research fellows; Dr Simon Wilkinson (ENACA), Dr Wayne O'connor, Dr Ian Lyall and Dr Michael Dove at New South Wales Department of Primary Industries; Dr Paul Palmer, Dr Brian Peterson and Dr. Peter Lee at Queensland Department of Agriculture & Fisheries; Prof. Abigail Elizur and colleagues at University of Sunshine Coast; Dr Symon Dworjanyn at Southern Cross University, Dr. Nick Eliot (former CSIRO scientist), Dr Ngo Van Manh (Nha Trang University, Vietnam), Dr Meagan Davis (HBOI, US), Dr Brad Evan (Tassal), Mr. Dan Richard (Humpty Doo Barramundi), Dr Matthew Wassnig (Tassal), Mr Ian Charles (Aquna) and many anonymous seafood traders in Sydney, Melbourne, Hobart and Brisbane for their time sharing different insights of aquaculture development or market demand with us. This research has also received great support of Dr. Quyen Banh (Nha Trang University), Dr. Phan Thi Van (Director, Research Institute for Aquaculture No.1 in Vietnam), Dr Nguyen Tien Thong (Copenhagen Business School, Denmark), Ms. Petra Quezada Rodriguez and Mr. Joel Slinger (CSIRO Livestock & Aquaculture) regarding coordinating inputs or collecting additional information.

Finally, we would like to thank FRDC and CSIRO for this great opportunity. Our enriched knowledge of aquaculture species and the development contexts in Australia and overseas will be helpful to future R&D planning and implementation for the benefits of Australian aquaculture industries.

Brisbane 8 Oct 2020

The authors

Abbreviations

Acronyms	Definition
FRDC	Fisheries Research and Development Corporation
RD&E	Research, Development & Extension
R&D	Research & Development
DAWR	Department of Agriculture, Water and Resources
ABARES	Australian Bureau of Agricultural and Resource Economics
CSIRO	Commonwealth Scientific and Industrial Research Organization
FAO	Food and Agriculture Organization
PDI	Product diversity index (as percentage of processible product forms out of all the pre-defined ones)
RCI	Research Comprehensive Index (as percentage of the researched area out of 15 functional ones)
PRCI	Production-stage Research Coverage Index (percentage those targeted by research out of the 8 pre-defined production stages)
DSI	Desirable Score Index (percentage of desirable attributes of an individual species for aquaculture out of 9 pre-defined ones)
PAETI	Potential for Adoption of Existing Technologies Index (percentage of production stages that technology adoption is possible out of the 8 pre-defined ones)
BI	Barrier Index (percentage of identified barriers out of the 18 pre-defined ones to commercial aquaculture development)
HAI	Highly Accessible Index (percentage of the required inputs for farming that are highly accessible to aquaculture producers out of the 14 pre-defined ones)
AI	Availability Index (percentage of the required inputs for farming that are available to aquaculture producers out of the 14 pre-defined ones)
RDI	Research Demand Index (percentage of functional areas that still require substantial research effort out of the 15 pre-defined ones)

Executive Summary

What the report is about

This report presents the results of our FRDC 2017-171 Project entitled “Auditing research effort on aquaculture species and industry adoption for production growth”. Research effort and industry adoption on 44 species for aquaculture in Australia were audited to reveal both opportunities for and barriers to commercial aquaculture production. Similar audits were also conducted for 54 species overseas for reference purpose. The research was conducted by a team of CSIRO Aquaculture and FRDC staff. Data collection started in late 2018. Inputs were provided by scientists, aquaculture producers, experts, seafood traders and development officers both in Australia and 19 other countries. The report provides more insights about aquaculture development in Australia regarding research effort, research needs, barriers to further development and opportunities for growth. The information it provides is expected to be useful to aquaculture developers, producers and investors, scientists and research institutions, research management agencies, policy makers and governors.

Background

Australia is among the top countries with great potential for aquaculture. However, the Australian aquaculture industry is still small in scale. Aquaculture production has grown over time, but at different pace for different species and in general slower than expected. Thus, it is important to identify the barriers to further development of aquaculture, either commonly or species-specifically. Literature review show more than 90 species have been researched in Australia, either to assess aquaculture potential or to support commercial production. Nevertheless only 10% of the researched species have had commercially significant production or revenue. An audit of past research effort on aquaculture species and industry adoption is expected to reveal research progress and its application. Besides, understanding both opportunities and barriers collectively or for specific species would help prioritise RD&E to better supporting the growing aquaculture industry in Australia.

Objectives

1. To audit research effort on aquaculture species and industry adoption, and identify possible barriers to commercial production
2. To establish an open-access database that documents research progress, industry adoption and barriers to further development of aquaculture species in Australia

Methodology

Two online surveys one for scientists and the other for aquaculture producers/consultants were designed, tested and conducted from late 2018. The primary targets of the project are aquaculture species in Australia. In addition, interviews had been arranged with selected experts who are experienced in aquaculture development, aquaculture research or involved in industry development as key stakeholders. As this study also explore insights of market demand and customer’s preference, several visits had been made to fish markets in Sydney, Melbourne, Brisbane and Hobart to collect information about price range, most popular products, opinion of seafood traders about aquaculture product and future demands. For reference purpose, invitation to the two surveys was also extended to international scientists and aquaculture producers. The collected data are summarized and presented for 4 different groups of species namely finfish, crustaceans, molluscs and other species before being discussed collectively to drawn conclusions and recommendations.

Key findings

- Audit results of 44 aquaculture species in Australia and 54 species overseas show that species with consolidated commercial aquaculture production have received more research supports. Researches on potential species or less consolidated are still fragmented, thus requiring more investment in RD&E.
- The focuses of past research on the audited species include five functional areas: genetics/breeding, nutrition, health, husbandry and farming systems. Regarding production stages, grow-out, broodstock domestication and larval rearing have attracted more research.
- Research demand is high for both consolidated and potential species. The participating scientists indicated stronger interest in finfish. Also, they requested more funding for research and opportunities to partner with the industry.
- Insufficient supply of quality seed is identified as the top barrier to increasing commercial aquaculture production in Australia. Information collected from scientists and aquaculture producers through this study confirm the existence of this barrier, which is applicable to many species including those in the top 10 aquaculture species globally.
- The other major barriers are increasing risk of infectious diseases, unfavourable regulations and too small industry. Lack of production sites (as the result of unfavourable regulations), low profit or high production cost (due to too small industry and high costs), limited funding for R&D and lack of public interest are the other significant barriers to consider when developing aquaculture. Low accessibility to required inputs is an addition reason for lack of development of new species' aquaculture.
- This study reveals a great potential for aquaculture development in Australia in the long term especially if premium export markets are targeted and low-input farming models are established for carefully selected species.
- As seafood demand in Australia still needs more time to raise substantially, it is recommended that RD&E in the next 10 years should focus on improving production efficiencies for aquaculture of the more consolidated species or those with good demand for export markets. New species should only be considered if having unique advantages compared with the existing species or complimentary to the current aquaculture industry through integrated farming.
- Overall, we recommend Australia should aim to develop an aquaculture industry with high production efficiencies supplying both domestic and international markets with selected high-value species. Furthermore, Australia have all the required capabilities and conditions to lead global aquaculture via advanced technology development that sustainably supplies the world with not only quality products, but technologies and innovative inputs for farming and non-traditional aquaculture products such as pharmaceuticals.

Implications for relevant stakeholders

- Management: policy makers, governors, research management agencies and research sponsors could use our findings to develop strategies, prioritise RD&E activities and mobilize the required resources for aquaculture development.
- Industry and new investors can use our audit results to develop production strategies and plans or select an alternative species or farming/business models.

- Consumers can use the findings of this study to improve their awareness about the mandate of aquaculture, products it can supply and current barriers it has. These will be helpful to attract more support to Australian produces and aquaculture development.
- Scientists: to understand more about industry need and market demand in order to better orient research effort towards industry development.

Recommendations

- Organize FRDC-facilitated workshops to discuss the findings and formulate solutions/actions that could help direct RD&E effort and investment to assist the creation of a competitive aquaculture industry for Australia.
- Establish working groups to develop RD&E plans for selected species or industries of priority.
- Work with state governments to develop supporting policies for R&D start-ups, especially those could assist aquaculture development or marketing of aquaculture products; and call for investment.
- Explore the possibility to commission annual reviews of market demand, research advances and implications, technology development, industry performance, new opportunities for key aquaculture species in Australia.

Keywords

New species, aquaculture development, research effort, research needs, opportunities, barriers, Australia

Introduction

Australia is considered as one of the most potential countries for aquaculture development with nearly 1.9 million km^2 suitable for marine finfish aquaculture and 91,000 km^2 suitable for bivalve aquaculture (Gentry *et al.* 2017). In contrast, its aquaculture industry has remained relatively small in scale, accounting for approximately 1% of global aquaculture production (FAO 2019). Today, aquaculture in Australia, consisting of 1,030 businesses and nearly 5,700 employees, has an estimated annual revenue of $1.7 billion (Chapman 2020). Published in 2017 the National Aquaculture Strategy of Australia aimed to raise the value of its aquaculture industry to $2.0 billion by 2027 (DAWR 2017). In order to achieve this target a growth rate of 7% annually must be maintained during 2017 – 2027. However, annual growth rate of the Australian aquaculture industry was only 0.8% during 2016 – 2020 and is predicted around 2.0% for 2021 – 2026, far below the 7% target (Chapman 2020).

Literature review shows more than 90 candidate species for aquaculture have been researched in Australia over the last four decades. Less than 10% of these species have reached recognizable production in either tonnage (e.g. Atlantic salmon, oysters, tiger prawn and barramundi) or value (e.g. pearl oyster, tuna and abalone). Even with these more successful aquaculture species, development has not happened at the same space (ABARES 2018). In 2010 FRDC and large aquaculture companies projected that the finfish aquaculture industry could reach 100,000 tonnes by 2016 (FRDC 2010). Atlantic salmon, barramundi and yellowtail king fish are the major species included in this projection. However, only 50,000 tonnes of finfish were produced by 2019. Most of this growth was derived from just a single species – the Atlantic salmon. Similarly, it took the prawn industry 15 years to grow production from 1,500 to 7,000 tonnes (i.e. still less than 2% of global production) despite hundred thousand hectares suitable for prawn farming in Western and Northern Australia (Irvin *et al.* 2018). So, why aquaculture production has not grown as expected? What are the factors that enable or hamper its growth either collectively or for individual species?

Research plays a critical role to the development of aquaculture industries. Research outcomes either open opportunities for new-species start-ups or help transform existing industries via improvement of efficiencies by removing current barriers (Bostock et al., 2010). However, research alone is not enough to create or drive an aquaculture industry. Commercial farming of a species is only viable with an increasing market demand for it to attract long-term investments, and if farming technologies and required key inputs are available at costs that make it profitable. Furthermore, the new industry requires continuous support regarding regulation and policies. An FRDC snap-shot review in 2017 on 15 aquaculture species, mostly finfish and crustaceans has revealed both technical and non-technical barriers to commercial production of these species (FRDC, unpublished data). Non-technical barriers include market demand, profitability, regulation, availability of production site, social license and product form. Australia needs to identify and address these barriers in order to sustainably develop its aquaculture industry.

This FRDC 2017-171 project was conducted to explore both opportunities and barriers to the development of aquaculture for new species by auditing research effort and industry adoption. The project was jointly supported by FRDC and Commonwealth Scientific and Industrial Research Organisation (CSIRO). Both species that have been researched in Australia and, as references, in other countries were targeted by the project. Findings from the study are expected to help formulate/prioritise RD&E strategies that could eventually result in desirable increase of commercial aquaculture production in Australia.

Objectives

1. To audit research effort on aquaculture species and industry adoption, and identify possible barriers to commercial production
2. To establish an open-access database that documents research progress, industry adoption and barriers to further development of aquaculture species in Australia

Method

1. Auditing research effort on aquaculture species and industry adoption, and identifying possible barriers to commercial production

This study abbreviately named as Inventa 2018 was conducted via a combination of two on-line structured surveys: one for scientists and the other for aquaculture producers and depth interviews (Kelley *et al.* 2003) between May and December 2018. The questionnaires used for the surveys were designed based on the research questions formulated and in close consultation with a small group of two experienced scientists/consultants and two renown industry representatives in late 2017. They were then pilot-tested with staff of CSIRO Aquaculture – Southern Group in Hobart in early 2018 and revised for the application of an ethics clearance by CSIRO. Ethics clearance No. 046/18 for the study was granted by CSIRO Social and Interdisciplinary Science Human Research Ethics Committee (CSSHREC) on 28 May 2018 for an active research period from 15th of May to 30th of August, which was latterly extended to 31st of December 2018.

1.1. Survey designs

The first survey "Inventa 2018: Species Audit by Researchers" was designed for scientists to review research effort on aquaculture species and to provide evaluation on relevant opportunities and barriers to commercial production of the reviewed species. Key aspects included:

- **General information of researched species**: species name, distribution, country of research, current markets, product forms preferred by consumers, starting time of the research and research effort.
- **Potential for aquaculture**: favourable attributes, desirable attributes, current farming status, availability of essential inputs for the farming, possibility to adopt existing technologies.
- **Research effort**: reasons for research, by functional areas, by production stages
- **Barriers to aquaculture production**
- **Research plan**: confirmation of interest, need for funding and industrial partners, recommendation of functional research areas

The complete questionnaire used for this survey could be found in Appendix 4.

The second survey "Inventa 2018: Species Audit by Producers" was for aquaculture producers to assess the adoption of research results in commercial farming and to provide evaluation on relevant opportunities and barriers to commercial production of the reviewed species. Key aspects included:

- **General information of farmed species**: species name, country of production, reasons to farm, possession of favourable and desirable attributes

- **Farming experience**: starting year, production stages covered and proficient, availability of essential inputs for the farming, highest production achieved, possibility to adopt existing technologies, current status and markets
- **Technology development and adoption**: sources of know-how, contribution of adopted technologies
- **Barriers to aquaculture production**: reasons for ceasing farming if any, barriers for further development
- **Recommendation for research:** by functional areas, by production stages and specifically

The complete questionnaire used for this survey could be found in Appendix 4.

A significant degree of overlap between the two surveys were structured to allow cross-comparison, which help reveal potential differences in perspective over important issues such as research needs, farming status, adoption of research results, opportunities and barriers between scientists and aquaculture producers.

Table 1. Contribution approaches and relevant online forms

In order to facilitate contribution an invitation form was developed. This form allowed potential participants to understand the study's rationale and expected outcomes, review the ethics clearance, confirm their consents to participate, provide personal provide information and select contribution modes, i.e. completing an on-line survey or requesting an interview. In addition, several questions were asked to understand how potential species for aquaculture was selected for research and what are the possible linkages with experience, background of the researchers.

Table 2. Contributors of the Inventa 2018 study

	Australia	Overseas
Number of species audited	44	54
Audit attempts by scientist	69	78
Audit attempts by aquaculture producer/consultant	2	15
Interviews by the research team	15	3
Site/market visits by the research team	10	4

1.2. Survey implementation

The designed questionnaires were first transformed into Google Forms to facilitate online collection of data. Active links to these two questionnaires were then placed on the study's website www.inventa2018.com, on promotion articles or meeting presentations, and sent directly to potential contributors either initially identified by FRDC or later by the research team. Scientists and aquaculture producers in other countries were also invited to provide referential information about species and production context.

Data collection via the two surveys was conducted mainly from the 25th of June to the 31st of December 2018 and for additional overseas inputs in late 2019 early 2020. Followed up research activities including indepth interviews, site visits and market surveillance were made during March – November 2019. Indepth interviews were more focus on understanding better the opportunities and barriers to aquaculture development in general and few specific species. Market visits helped gather opinion of seafood traders as well as the availability and current prices of different species. The research team also conducted our own audit for the finfish group – the largest group of potential species revealed by the study and a snap-shot review of FRDC funded projects to support the interpretation of research results.

1.3. Data analysis

The collected data from the two surveys, available in Google Sheets format, were reviewed and validated for analysis. Duplicated attempts and wrongly-input data were removed. The 81 reviewed species were grouped into four groups: crustaceans, finfish, molluscs and others for convenience in data analysis and presentation of results. This included the data, where appropriate, of 15 species covered by a snapshot audit that FRDC conducted in 2017. Data were summarized using descriptive statistics. Where possible, inferential statistics were applied for comparisons (Sokal & Rohlf 1994; Quin & Keough 2002). Information obtained for Australian species is considered primary for presentation purpose. Referential information collected from overseas is presented, but merely used for discussion. The results of indepth interview and site visits are summarized and presented where appropriate.

2. Database development

An Excel database was developed to capture the results of the study. The Google Forms designed by the research team could be used by FRDC in the future to keep receiving reviews of new aquaculture species from scientists and aquaculture producers.

Results

PART 1: SELECTION CRITERIA FOR AQUACULTURE SPECIES & THE AUDITED SPECIES

1.1. Selection criteria for new aquaculture species

92 participants from 18 different countries had shared relevant information about their background, research or industry experience and more importantly their considerations when selecting new species for either research or commercial production (Table 2). Most of the participants are scientists (74%). Australia dominates with 47 participants. Of these 39 are scientists and 6 are aquaculture producers. The overseas participants come from all different continents. Vietnam has the highest contribution with 14 scientists, 9 aquaculture producers and 2 aquaculture consultants.

Nearly half of the participating scientist (45.6%) have worked for the aquaculture private sectors. The percentage of scientists with industrial experience in Australia (38.5%) is smaller than that in other countries (52.5%). Research on multiple species is common. More than half of the participating scientists in Australia and other countries reported that they have conducted research on five or more than five species (Figure 2). Among the participating producers and consultants, 55% are technical managers. The number of years involved in industry development or operation ranges from 5 to 40 with a mean of 17.7 ± 4.9 years in Australia and 19.6 ± 3.9 years overseas.

Table 3. Participating countries and participant backgrounds

Country	Number of participants	Scientists	Consultants	Producers	Other stakeholders
Australia	47	39	1	6	1
Viet Nam	25	19	3	3	
Mexico	3	2	1		
Colombia	2	1	1		
Egypt	2	1		1	
Algeria	1				1
Brazil	1	1			
Chile	1	1			
France	1		1		
India	1				1
Iran	1			1	
Malaysia	1	1			
New Zealand	1	1			
Philippines	1	1			
Singapore	1			1	
United Kingdom	1	1			
USA	1				1
Zambia	1		1		
TOTAL	92	68	8	12	4

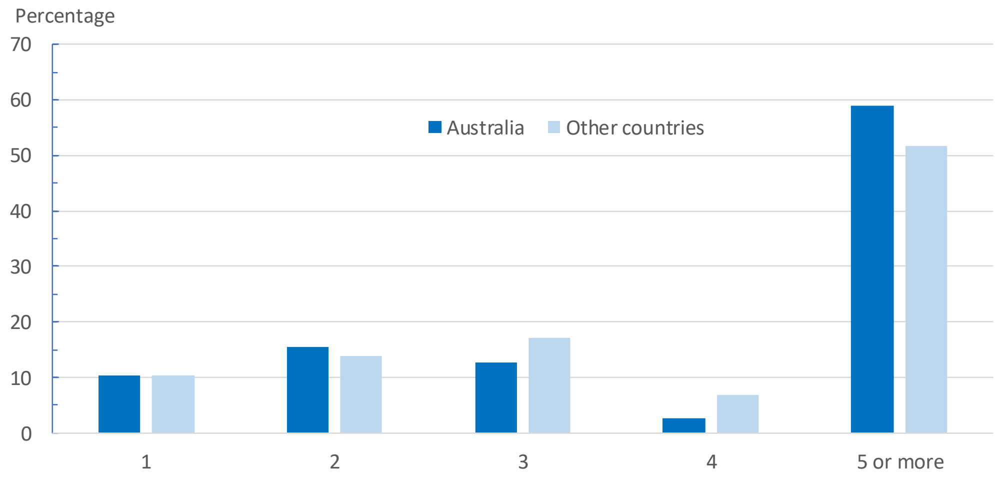


Figure 1. Number of species that have been researched by scientists in Australia (n = 39) and other countries (n = 29)

1.1.1. Consideration of scientists

a) Factors to consider

All the seven predefined factors are considered by Australian scientists with no weighing nor preference when selecting new aquaculture species (Figure 3). Consumer preference, regulation and biological attribute of the species are the most common ones. Social license and market demand receive less attention. Interestingly, overseas scientists pay more attention on R&D capital (i.e. the amount of research have been done globally), biological attribute and profitability. Less attention is paid on consumer preference, regulation and market demand. Regardless of countries, biological attribute (75.8%) and R&D capital (74.2%) are the most common factors for consideration when selecting new aquaculture species.

b) Most important factor

Scientists in Australia and overseas all consider market demand is the most important factor when selecting new species for aquaculture (Figure 4). The level of agreement is higher overseas, i.e. more than 80% of the participating scientists. Profitability and biological attribute are the other two factors for consideration by Australian scientists. Overseas, consumer preference is considered as important as profitability and biological attribute.

a) Future research intention

Interest on finfish (45.1%) and crustaceans (26.8%) are significantly higher than that for molluscs, algae/seaweed and others. Similar trends are reported for both Australia and other countries. However, Australian scientists tend to focus more on finfish and other species compared with their overseas counterparts (Figure 5).

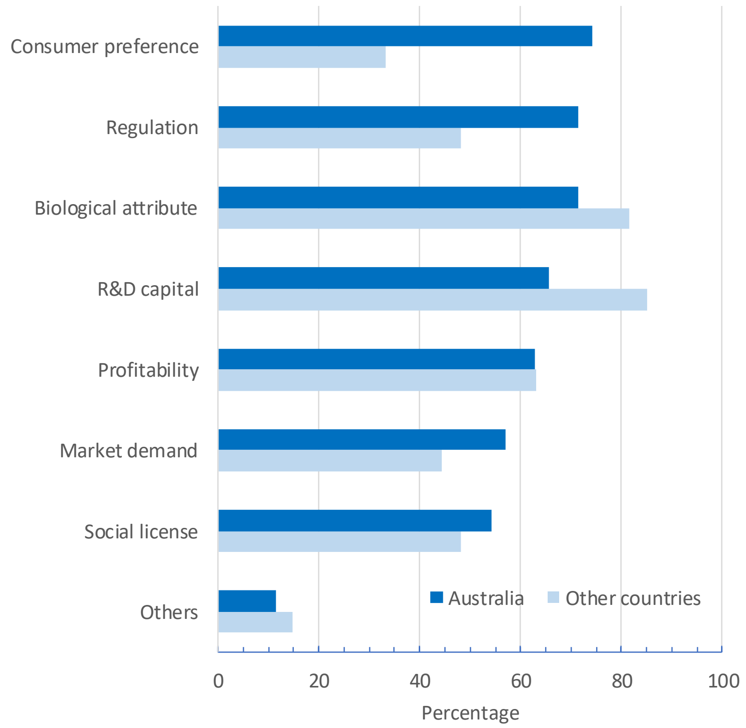


Figure 2. Factors considered when selecting new aquaculture species by scientist in Australia (*n* = 35) and other countries (*n* = 27)

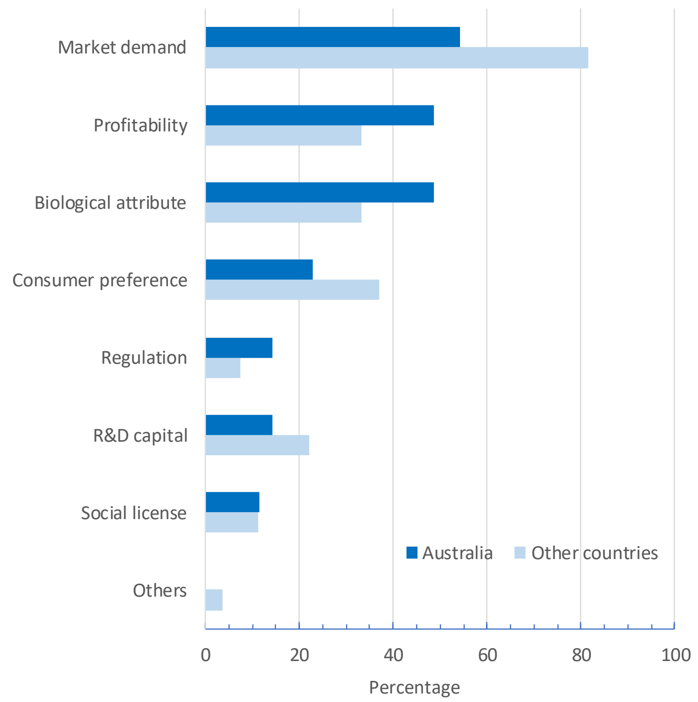


Figure 3. Most important factor when selecting new aquaculture species by scientist in Australia (n = 38) and other countries (n = 28)

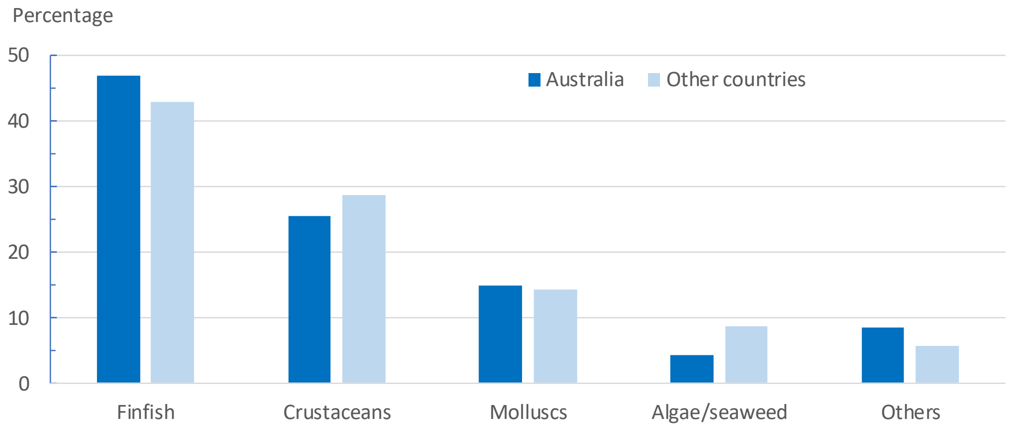


Figure 4. Research intention for the next 5 – 10 years by scientists in Australia (*n* = 47) and other countries (*n* = 35)

1.1.2. Considerations of aquaculture producers/consultants

a) Factors to consider

All the seven pre-defined factors are considered by Australian producers/consultant when selecting new species. Market demand is the most common factor for consideration (85.6%), followed equally by social license and biological attribute (57%) (Figure 6). Regulation and profitability receive the least attention (28.6%). In other countries, biological attribute and R&D capital are the most two common factors considered by aquaculture producers/consultants. Market demand and profitability are the other common factors for consideration.

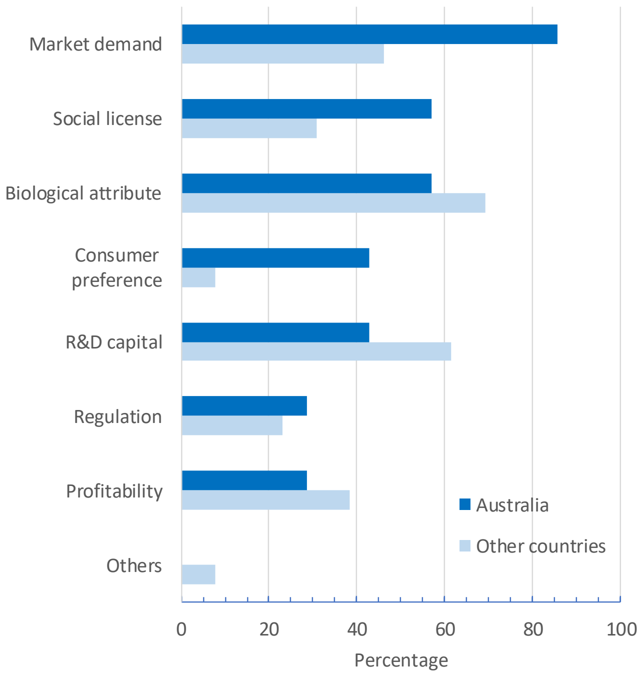


Figure 5. Factors considered when selecting new species for commercial aquaculture production by Australian producers (n = 7) and other countries (n = 13)

b) Most important factors

Only 4/7 of the pre-defined factors are considered as the most important factor for species selection (Figure 7). Market demand and profitability clearly outweigh biological attribute and consumer preference (i.e. 42.9% compared with 14.3%). Similar priorities are expressed by aquaculture producers/consultants in other countries with stronger emphasis on profitability. Furthermore, more attention is paid on consumer preference and biological attribute.

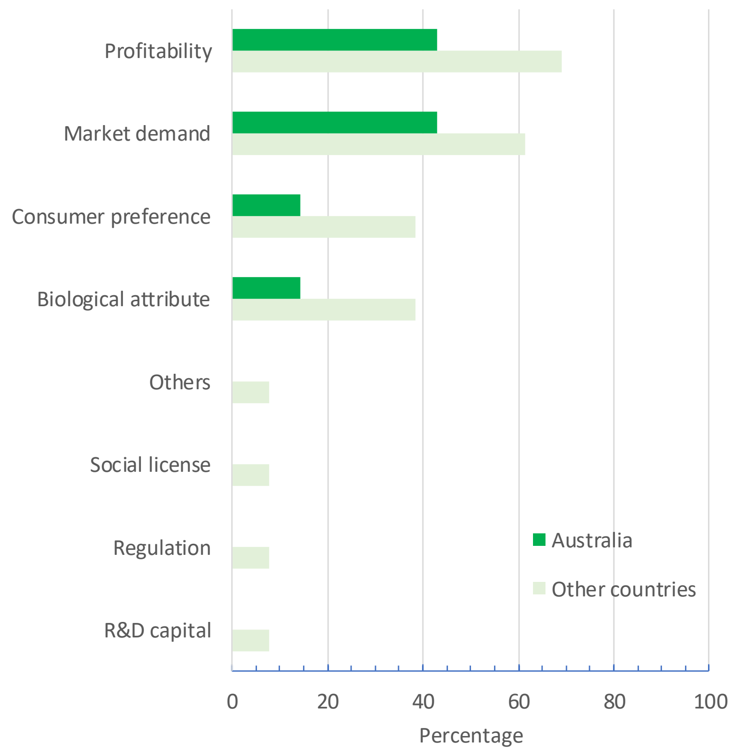


Figure 6. Most important factor when selecting new species for commercial aquaculture production by producers/consultants in Australia (n = 7) and other countries (n = 13)

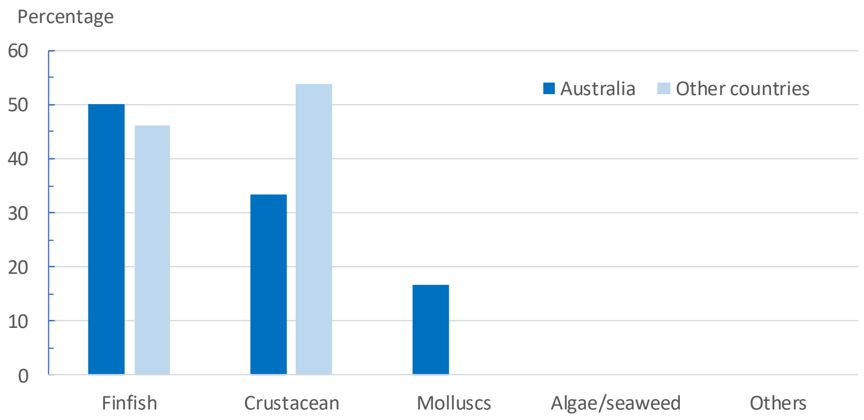


Figure 7. Farming intention for the next 5 – 10 years by aquaculture producers in Australia (*n* = 6) and other countries (*n* = 12)

a) Future production planning

Finfish aquaculture attracts the highest interest of the participating Australian producers regarding production plan for the next 5 – 10 years (Figure 8). No intention is expressed for the algae/seaweed and other species groups. Interest in crustacean aquaculture is nearly two folds higher than that for molluscs. Overseas, the participating producers only plan to produce finfish and crustaceans. Compared with Australia, there is more interest in crustacean aquaculture overseas.

1.2. The audited species

176 attempts have been made to audit 92 different species (Figure 9). Of these finfish is the largest group with 49 species or 53%. The number of audited species is similar between the crustacean and mollusc groups, 18 species or 19.6%. Other species account for 7.6%. Marine species are dominant with 77 species. Only 8 finfish and 6 crustaceans are freshwater. Interest is spread relatively even among finfish, crustaceans and molluscs in Australia but significantly skewed towards finfish overseas (i.e. 68.5% compared with only 14.8% for crustaceans and 11.6% for molluscs). Interest in other species is similar between Australia and the other countries included in this study. Most audits are conducted by scientists, 69 in Australian and 78 overseas (Figure 10). However, only two Australian producers helped audit redclaw and ornate lobster. Overseas, 24 audit attempts were made by aquaculture producers. Of these, 58.3% are for finfish and 41.7% for crustaceans. Diversity of the audited species is higher in Australia for crustaceans and molluscs, but lower for finfish.

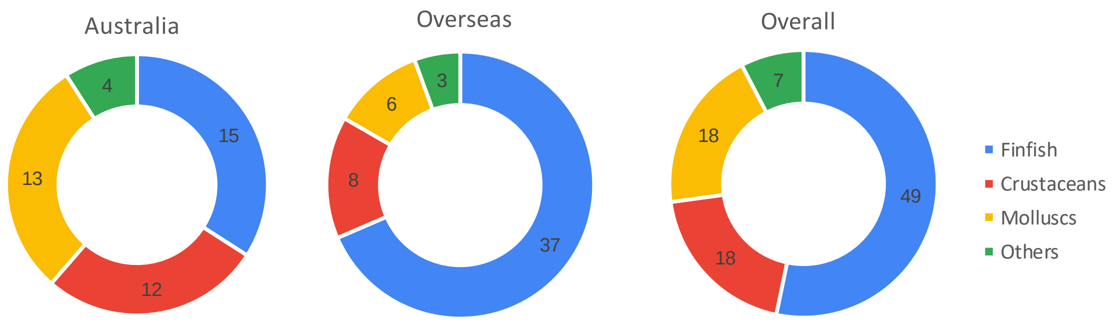


Figure 8. Number of species audited by FRDC 2017-171 project

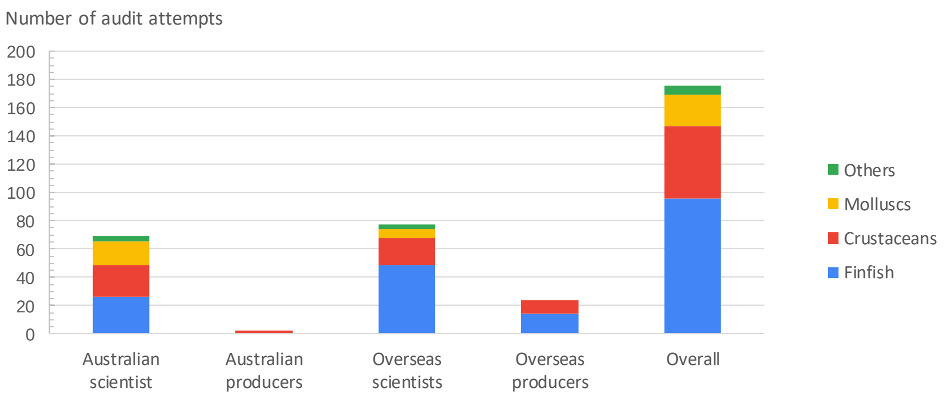


Figure 9. Contribution of Australian and overseas participants

Only few species are audited by both Australian and overseas participants, indicating global interest. These include barramundi (*Lates calcarifer*), cobia (*Rachycentron canadum*), snubnose pompano

(*Trachinotus blochii*), black tiger prawn (*Penaeus monodon*), redclaw (*Cherax quadricarinatus*) and the Portuguese oyster (*Crassostrea angulate*) (Tables 3, 4 and 5). Interest in both barramundi and cobia are higher overseas (Figure 11). In contrast, tiger prawn and redclaw attract less attention overseas than in Australia. Tilapia (*Oreochromis niloticus*) and whiteleg shrimp (*Penaeus vannamei*) are the most popular aquaculture species overseas, attracting the highest number of audits. Giant freshwater prawn (*Macrobrachium rosenbergii*) is another important species.

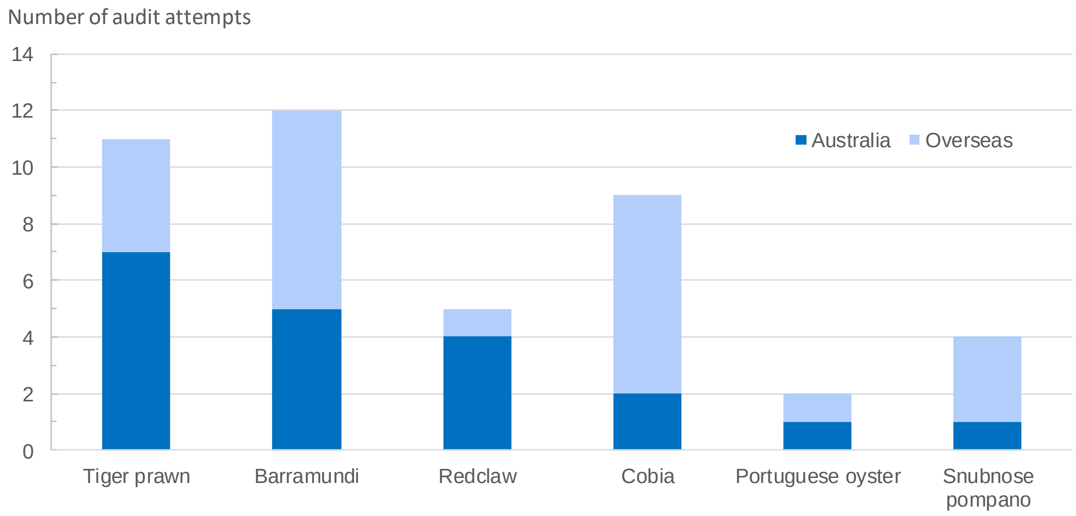


Figure 10. Species audited by both Australian and overseas participants

Ranked by the number of audits the top four species in Australia include two finfish (Atlantic salmon and barramundi) and two crustaceans (tiger prawn and redclaw) (Table 3). While commercial production of Atlantic salmon, tiger prawn and barramundi are already significant, that of redclaw is still limited. The top four species overseas include three finfish (tilapia, barramundi and cobia) and the whiteleg shrimp. Aquaculture production of these three finfish overseas are far more significant than in Australia. The common interest in barramundi, cobia and black tiger prawn confirm great potential for aquaculture of these species. However, it also implies potential competition in both domestic and international markets. Less interest in black tiger prawn overseas may imply better opportunity for this species Australia.

Table 4. Top species ranked by audit attempts in Australia and overseas

No.	Australia	No. of audits	No.	Overseas	No. of audits
1	Atlantic salmon	7	1	Tilapia	11
2	Black tiger prawn	7	2	White leg shrimp	10
3	Barramundi	5	3	Barramundi	7
4	Redclaw	4	4	Cobia	6
5	Ornate lobster	2	5	Giant freshwater prawn	5
6	Cobia	2	6	Tra catfish	4
7	Blue swimmer crab	2	7	Black tiger prawn	4
8	Yellowtail kingfish	2	8	Snubnose pompano	3
9	Pearl oyster	2	9	Indian shrimp	2
10	Blacklip abalone	2	10	California yellowtail	2

Table 5. Finfish species audited by scientists and aquaculture producers/consultants

No.	Common name	Scientific name	Number of audits	
			Australia	Overseas
1	Black bream	*Acanthopagrus butcheri*	1	
2	Mulloway	*Argyrosomus japonicus*	1	
3	Australasian snapper	*Chrysophrys auratus*	1	
4	Mahi-mahi	*Coryphaena hippurus*	1	
5	Barramundi	*Lates calcarifer*	5	7
6	Striped trumpeter	*Latris lineata*	1	
7	Golden snapper	*Lutjanus johnii*	1	
8	Pink snapper	*Pagrus auratus*	1	
9	Cobia	*Rachycentron canadum*	2	6
10	Atlantic salmon	*Salmo salar*	7	
11	Yellowtail kingfish	*Seriola lalandi*	2	
12	King George whiting	*Sillaginodes punctata*	1	
13	Sand whiting	*Sillago ciliata*	1	
14	Southern bluefin tuna	*Thunnus maccoyii*	1	
15	Snubnose pompano	*Trachinotus blochii*	1	3
16	Sturgeon	*Acipenser spp*		1
17	Climbing perch	*Anabas testudineus*		1
18	Silver barb	*Barbonymus gonionotus*		1
19	Snook	*Centropomus undecimalis*		1
20	Round fish	*Colossoma sp*		1
21	Common carp	*Cyprinus carpio*		1
22	European seabass	*Dicentrarchus labrax*		1
23	Fourfinger threadfin	*Eleutheronema tetradactylum*		1
24	Nassau grouper	*Epeniphelus striatus*		1
25	Atlantic goliath grouper	*Epinephelus itajara*		1
26	Hybrid grouper	*Epinephelus lanceolatus (male) x Epinephelus fuscoguttatus (female)*		2
27	Black grouper	*Epinephelus malabaricus*		2
28	Common galaxias	*Galaxias maculatus*		1
29	Golden trevally	*Gnathanodon speciosus*		3
30	Black seahorse	*Hippocampus kuda*		1
31	Ballan wrasse	*Labrus bergylta*		1
32	Nile perch	*Lates niloticus*		1
33	Mangrove red snapper	*Lutjanus agentimaculatus*		1
34	Mutton snapper	*Lutjanus analis*		1
35	Tarpon	*Megalops altanticus*		1
36	Shorthorn sculpin	*Myoxocephalus scorpius*		1
37	Blackspotted croaker	*Nibea diacanthus*		1
38	Tilapia	*Oreochromis niloticus*		11
39	Greater bony lipped barb	*Osteochilus melanopleurus*		1
40	Tra catfish	*Pangasianodon hypophthalmus*		4
41	Bonglau catfish	*Pangasius krempfi*		1
42	Cachama	*Piaractus sp.*		1
43	Red drum	*Sciaenops ocellatus*		1
44	California yellowtail	*Seriola dorsalis*		2
45	Florida pompano	*Trachinotus carolinus*		1
46	Permit	*Trachinotus falcatus*		2
47	Golden pompano	*Trachinotus ovatus*		1
48	Snakeskin gourami	*Trichopodus pectoralis*		1

Table 6. Crustacean species audited by scientists and aquaculture producers/consultants

No.	Common name	Scientific name	Number of audits	
			Australia	Overseas
1	Yabbies	*Cherax aldidus*	1	
2	Smooth marron	*Cherax cainii*	1	
3	Redclaw	*Cherax quadricarinatus*	4	1
4	Margaret River marron	*Cherax tenuimanus*	1	
5	Blackback land crab	*Gecarcinus lateralis*	1	
6	Ornate rock lobster	*Panulirus ornatus*	3	
7	Kuruma prawn	*Penaeus japonicus*	1	
8	Banana prawn	*Penaeus merguiensis*	1	
9	Tiger prawn	*Penaeus monodon*	7	4
10	Blue swimmer crab	*Portunus armatus*	2	
11	Mud crab	*Scylla serrata*	2	1
12	Moreton Bay bug	*Thenus orientalis*	1	
13	Giant freshwater prawn	*Macrobrachium rosenbergii*		5
14	Scalloped spiny lobster	*Panulirus homarus*		1
15	Indian shrimp	*Penaeus indicus*		2
16	Whiteleg shrimp	*Penaeus vannamei*		10
17	Mantis shrimp	*Harpio squilla harpax*		1
18	Mud crab	*Scylla paramamosain*		1

Table 7. Mollusc species audited by scientists and aquaculture producers/consultants

No.	Common name	Scientific name	Number of audits	
			Australia	Overseas
1	Ark cockle	*Anadara trapezia*	1	
2	Doughboy scallop	*Chlamys asperrima*	1	
3	Portuguese oyster	*Crassostrea angulata*	1	1
4	Hybrid abalone	*Haliotis hybrid species*	1	
5	Greenlip abalone	*Haliotis laevigata*	1	
6	Blacklip abalone	*Haliotis rubra*	2	
7	Australian flat oyster	*Ostrea angasi*	1	
8	Commercial scallop	*Pecten fumatus*	1	
9	Pearl oyster	*Pinctada maxima*	2	
10	Native rock oyster	*Saccostrea cuculatta*	1	
11	Spiny rock oyster	*Saccostrea echinata*	1	
12	Sydney rock oyster	*Saccostrea glomerata*	2	
13	Black-lip rock oyster	*Saccostrea mytiloides*	1	
14	Suminoe oyster	*Crassostrea arakensis*		1
15	Pacific oyster	*Crassostrea gigas*		1
16	Dredge oyster	*Ostrea chilensis*		1
17	Venerid clams	*Tapes dorsatus*		1
18	Blood cockle	*Anadara granosa*		1

Table 8. Other species audited scientists and aquaculture producers/consultants

No.	Common name	Scientific name	Number of audits	
			Australia	Overseas
1	Green algae	*Dunaliella salina*	1	
2	Torch Coral	*Euphyllia glabrescens*	1	
3	Purple sea urchin	*Heliocidaris erythrogramma*	1	
4	Tropical sea cucumber	*Holothuria scabra*	1	
5	Japanese palolo	*Tylorrhynchus heterochaetus*		1
6	Diatom	*Thalassiosira weissflogii*		1
7	Calanoid copepods	*Calanus spp., Acartia tonsa, Pseudodiaptomus annandalei*		1

PART 2: FINFISH GROUP

2.1. AUDIT OF RESEARCH EFFORT

2.1.1. The species

Overall, research effort on 49 finfish species are audited through 76 attempts: 26 by Australian scientists and 50 by their counterparts from 11 different countries. The 15 species audited for Australia are all marine (Table 8). Among them Atlantic salmon and barramundi attracted the highest number of audits by scientists, probably because aquaculture production of these two species in Australia are already significant. Overseas, most of the audited finfish species are marine. Only five are freshwater species such as tilapia, Tra catfish, cachama, sturgeon and, to some extent, barramundi. Cobia and tilapia are the top two species regarding number of audit attempts. Interestingly, pompano fish (*Trachinotus* spp.) attract significant interest of overseas scientists.

Table 9. Finfish species audited for Australia by scientists

*2018 production in tonnes (FAO 2020), ** Lee *et al.* (2018)

No.	Common name	Scientific name	Number of audits	Farming status in Australia by production (t)
1	Black bream	*Acanthopagrus butcheri*	1	-
2	Mulloway	*Argyrosomus japonicus*	1	Farmed
3	Australian snapper	*Chrysophrys auratus*	1	-
4	Mahi-mahi	*Coryphaena hippurus*	1	-
5	Barramundi	*Lates calcarifer*	5	5,668*
6	Striped trumpeter	*Latris lineata*	1	-
7	Golden snapper	*Lutjanus johnii*	1	-
8	Pink snapper	*Pagrus auratus*	1	-
9	Cobia	*Rachycentron canadum*	2	100**
10	Atlantic salmon	*Salmo salar*	7	61,227*
11	Yellowtail kingfish	*Seriola lalandi*	2	Farmed
12	King George whiting	*Sillaginodes punctate*	1	-
13	Sand whiting	*Sillago ciliate*	1	-
14	Southern bluefin tuna	*Thunnus maccoyii*	1	8,000*
15	Snubnose pompano	*Tradinotus blochii*	1	-

Table 10. Finfish species audited for other countries by scientists

No.	Species	Scientific name	Number of audits	Country audited for
1	Sturgeon	*Acipenser spp*	1	Vietnam
2	Snook	*Centropomus undecimalis*	1	Colombia
3	Cachama	*Colossoma sp*	1	Brazil
4	Hybrid cachama	*C. macropomum, P. mesopotamicus, P. brachypomus*	1	Brazil
5	European seabass	*Dicentrarchus labrax*	1	Belgium
6	Fourfinger threadfin	*Eleutheronema tetradactylum*	1	
7	Nassau grouper	*Epeniphelus striatus*	1	Colombia

8	Atlantic goliath grouper	*Epinephelus itajara*	1	Colombia
9	Black grouper	*Epinephelus malabaricus*	1	Vietnam
10	Hybrid grouper	*Epinephelus lanceolatus (male) x Epinephelus fuscoguttatus (female)*	2	
11	Withebait	*Galaxias maculatus*	1	Colombia
12	Golden trevally	*Gnathanodon speciosus*	3	Vietnam
13	Ballan wrasse	*Labrus bergylta*	1	Norway
14	Barramundi	*Lates calcarifer*	7	Vietnam
15	Mangrove red snapper	*Lutjanus agentimaculatus*	1	Vietnam
16	Mutton Snapper	*Lutjanus analis*	1	Colombia
17	Tarpon	*Megalops altanticus*	1	Colombia
18	Shorthorn sculpin	*Myoxocephalus scorpius*	1	Greenland
19	Blackspotted croaker	*Nibea diacanthus*	1	
20	Tilapia	*Oreochromis niloticus*	10	Fiji, PNG, Vanuatu, Samoa and Cook Islands, Brazil, Mexico, Vietnam
17	Tra catfish	*Pangasianodon hypophthalmus*		Vietnam
18	Cachama	*Piaractus sp.*	1	Brazil
19	Cobia	*Rachycentron canadum*	6	Brazil, Colombia, US, Vietnam
20	Red drum	*Sciaenops ocellatus*	1	Vietnam
21	California yellowtail	*Seriola dorsalis*	1	United States
22	Snubnose pompano	*Trachinotus blochii*	3	Vietnam
23	California pompano	*Trachinotus carolinus*	1	Colombia
24	Permit	*Trachinotus falcatus*	2	Vietnam

2.1.2. Reasons for species selection

In Australia, industry request (53%) is the most popular reason for species selection for research, followed by assignment of supervisor or employer (47%) and aquaculture potential (42%) (Figure 11). None of the audited research was originated from market studies' recommendation. Request of funding agencies or personal interest prompt a quarter of the audited research. Overseas, aquaculture potential (80%) and personal interest (51%) are the most popular reasons. The latter indicates the importance of individual motivation, which is highly essential for the development of new aquaculture species. Assignment by supervisor or employer is also a significant reason, accounting for 49%. A small proportion of research have been conducted as the results of market studies.

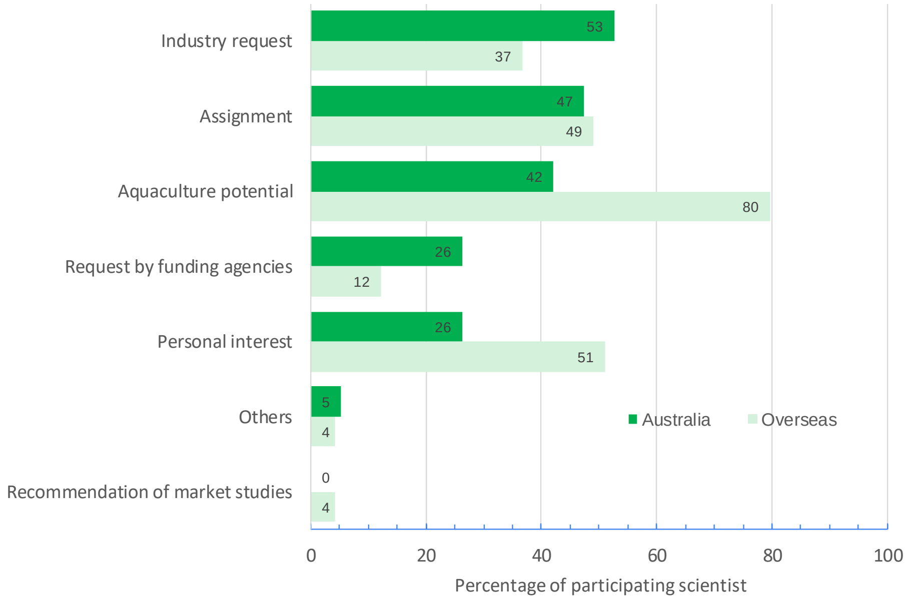


Figure 11. Reasons for species selection for research in Australia (n = 19) and overseas (n = 49)

2.1.3. Current market and consumer's preference

Most of the 15 audited Australian species are produced for domestic markets (Figure 12). Export markets are currently limited to one third of them. Australian species that could be exported include mulloway, Atlantic salmon, barramundi and yellowtail king fish. In contrast, 81% of the 26 audited species overseas could be exported. In addition, aquaculture species that are marketed both domestically and internationally account for 77% overseas, three folds higher than that in Australia. The long list of these species (18/26) include barramundi, cobia and snubnose pompano indicating some direct competitions to similar Australian aquaculture products.

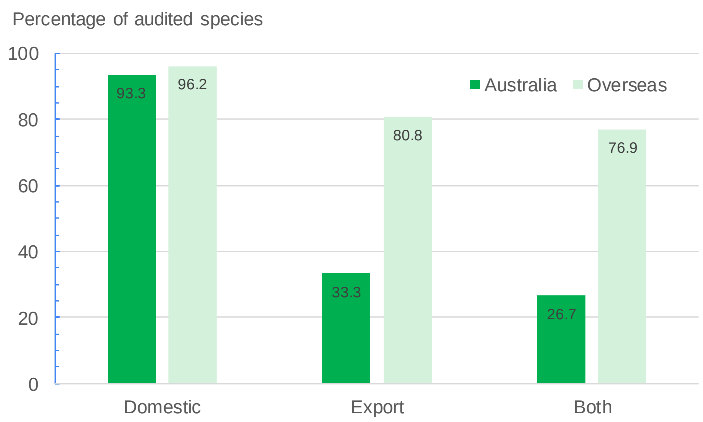


Figure 12. Current markets of the audited finfish species in Australia (n = 15) and overseas (n = 26)

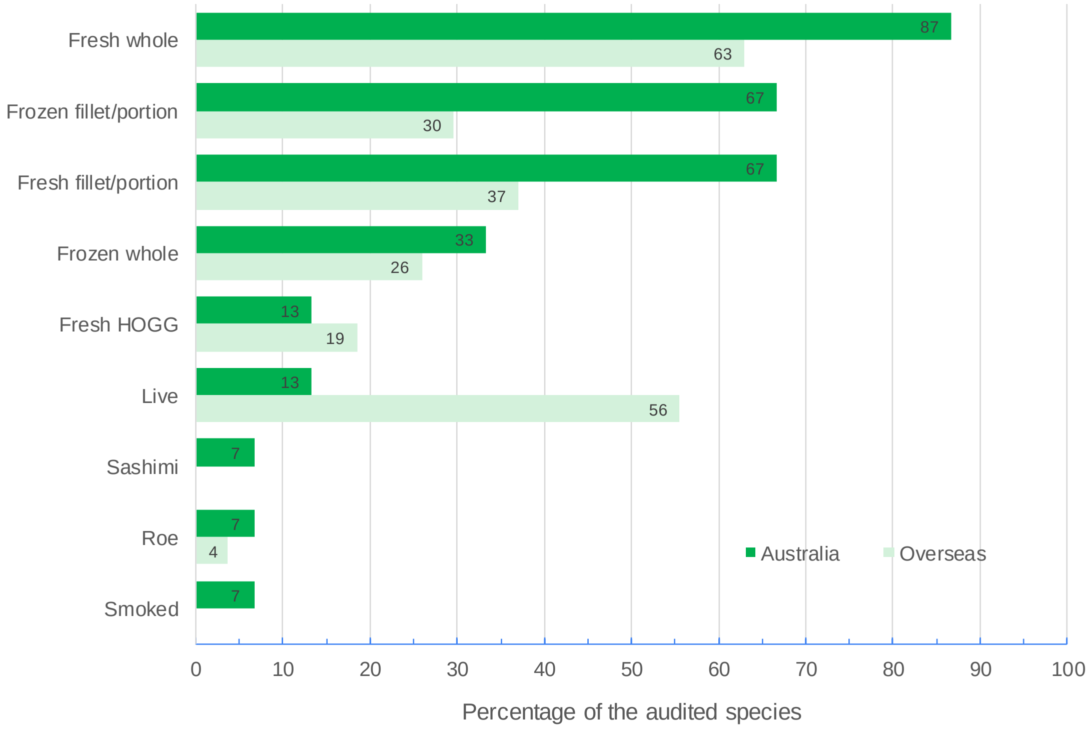


Figure 13. Preferred forms of finfish products in Australia (*n* = 15) and overseas (n = 27)

In Australia whole fresh fish is the most preferred product of the 15 audited species (Figure 13). Fresh and frozen fillet/portion are the two next choices. Frozen whole fish accounts for 33%. Preference for live fish is only 13%. Limited preference is given to products like sashimi, roe or smoked. Overseas, whole fresh fish and live fish are the top two choices. The preference rate for live fish (56%) is four folds higher than that in Australia. Fresh or frozen fillet/portion is acceptable, but at lower rates of 30 – 37%. Demand for smoked or sashimi products or fish roe varies from none to very limited. These observed differences should be considered for Australian finfish that are produced for export. Technically and economically it is challenging to deliver fresh products given the optimal window for finfish transportation is only 48 hours after harvesting. If frozen product is the only choice, lower value or profit should be expected due to the general lower price of frozen products.

Product diversity index (PDI – percentage of processible forms over the nine pre-defined forms of product) is 33% average for the audited Australian finfish species (Table 10). Atlantic salmon ranks highest with a PDI of 78%. PDIs of barramundi and pink snapper are above average (56%), followed by golden snapper and sand whiting (44%). Surprisingly, PDI of cobia is only 11% or much lower than that overseas. Overseas, PDI is 26% on average, indicating a current narrower range of preference by local consumers (i.e. towards live and fresh products) and plenty of room for product development (Table 11). Tilapia and cobia have the highest PDI of 56%. For cobia more products are preferred by consumers overseas than in Australia. PDI of barramundi is only 44%, slight lower than that in Australia because frozen products are not preferred.

Table 11. Product diversity index of the audited finfish species in Australia

Form of products: (1) live; (2) fresh whole; (3) fresh whole, gutted, gilled; (4) frozen whole ; (5) fresh fillet/portion, (6) frozen fillet/portion; (7) smoked; (8) roe; (9) sashimi.

No.	Audited species	PDI (%)	Preferred forms of product								
			1	2	3	4	5	6	7	8	9

1	Atlantic salmon	78									
2	Barramundi	56									
3	Pink snapper	56									
4	Golden snapper	44									
5	Sand whiting	44									
6	Mulloway	33									
7	Mahi mahi	33									
8	King George whiting	33									
9	Snubnose pompano	33									
10	Striped trumpeter	22									
11	Yellowtail kingfish	22									
12	Black bream	11									
13	Snapper	11									
14	Cobia	11									
15	Southern bluefin tuna	11									

Table 12. Product diversity index of the audited finfish species overseas

Form of products: (1) live; (2) fresh whole; (3) fresh whole, gutted, gilled; (4) frozen whole ; (5) fresh fillet/portion, (6) frozen fillet/portion; (7) smoked; (8) roe; (9) sashimi.

No.	Audited species	PDI (%)	Preferred forms of product								
			1	2	3	4	5	6	7	8	9
1	Tilapia	56									
2	Cobia	56									
3	Barramundi	44									
4	Sturgeon	33									
5	Cachama*	33									
6	Golden trevally	33									
7	Tra catfish	33									
8	California yellowtail	33									
9	Snubnose pompano	33									
10	Hybrid grouper	33									
11	Permit	33									
12	Red drum	33									
13	European seabass	22									
14	Black grouper	22									
15	Fourfinger thredfin	22									
16	Snook	11									
17	Nassau grouper	11									
18	Jewfish, atlantic goliat grouper	11									
19	Withebait	11									
20	Ballan wrasse	11									
21	Mutton Snapper	11									
22	Tarpon	11									
23	Shorthorn sculpin	11									
24	Pompano	11									
25	Mangrove red snapper	11									

** Cachama include Colossoma sp, Piaractus sp. and hybrid species*

2.1.4. Research history and time effort

In Australia, the audited research started as early as from 1985 – 1986 on barramundi and mahi-mahi. Research on new species like snubnose pompano just started in early 2020. Despite limited audit attempts some interesting trends are observed through this study. Significant effort has been made collectively for research on Atlantic salmon, barramundi and to a lesser extent yellowtail king fish (Table 12). Research effort by individual scientists on Atlantic salmon is lower than that of several species, implying the importance of collective effort on the success of this species' aquaculture. The average individual effort clearly show that Australia does have highly experienced scientists for research on barramundi, yellowtail King fish, striped trumpeter, mahi-mahi, sand whiting, cobia and Southern bluefin tuna.

Table 13. Research history and effort on the audited finfish in Australia

No	Audited species	Earliest start year reported	Individual effort (years)	No. of research	Total years of research
1	Atlantic salmon	1994	8.4	7	59
2	Barramundi	1985	11.8	4	47
3	Yellowtail kingfish	2006	10.5	2	21
4	Striped trumpeter	1997	14.0	1	14
5	Mahi-mahi	1986	12.0	1	12
6	Sand whiting	1994	10.0	1	10
7	Cobia	2008	10.0	1	10
8	Southern bluefin tuna	2009	9.0	1	9
9	Pink snapper	1999	5.0	1	5
10	Black bream	1996	4.0	1	4

Table 14. Research history and effort on the audited finfish overseas

No	Audited species	Earliest start year reported	Individual effort (years)	No. of research	Total years of research
1	Cobia	2004	7.6	7	53
2	Tilapia	1986	8.7	6	52
3	Barramundi	2002	6.3	4	25
4	Withebait	1996	22.0	1	22
5	Snubnose pompano	2010	5.7	3	17
6	Tra catfish	2005	7.0	2	14
7	Permit	2011	7.0	2	14
8	California yellowtail	2012	6.0	2	12
9	Sturgeon	2010	10.0	1	10
10	Golden trevally	2005	1.7	3	5
11	Mangrove red snapper	2012	4.0	1	4
12	Red drum	2014	4.0	1	4
13	Black grouper	2004	3.0	1	3
14	Cachama*	2012	3.0	1	3
15	Ballan wrasse	2015	3.0	1	3
16	Shorthorn sculpin	2015	3.0	1	3
17	Hybrid grouper	2017	1.5	2	3
18	Fourfinger thredfin	2015	2.0	1	2
19	European seabass	2008	1.0	1	1

** Cachama include Colossoma sp, Piaractus sp. and hybrid species*

Overseas, research on tilapia and whitebait were the earliest among the audited species. Research on many other species started later in mid 2000s (e.g. cobia, barramundi, Tra catfish) or the 2010s (e.g. subnose pompano, cachama, yellowtail, sturgeon). Significant effort has been made for research on cobia and tilapia, double that for barramundi. This might confirm the importance of tilapia or the potential of cobia. Today only tilapia and Tra catfish have commercial aquaculture production higher than 1 million tonnes annually (SOFIA 2020).

2.1.5. Functional areas that have been researched

Husbandry techniques is the functional area that has attracted more research, i.e. by 64% of the participating scientists (Figure 14). The next three most popular areas are biology/ecology, health/disease/biosecurity and nutrition (44 – 48%). Other areas such as environmental requirement or interactions, waste management, product development and market-related have received limited interest. None of the participating scientists report research activities on economics or law/policy/regulation areas. Overseas, the importance of husbandry techniques is confirmed. This area attracted research by 60% of the participating scientists. However, the next two most popular areas are nutrition (44% as in Australia) and farming system (44%, higher than that in Australia). Except economics, many of the other functional areas received less interest compared with Australia, e.g. animal welfare, genetics and selective breeding, biology/ecology and health/disease/biosecurity.

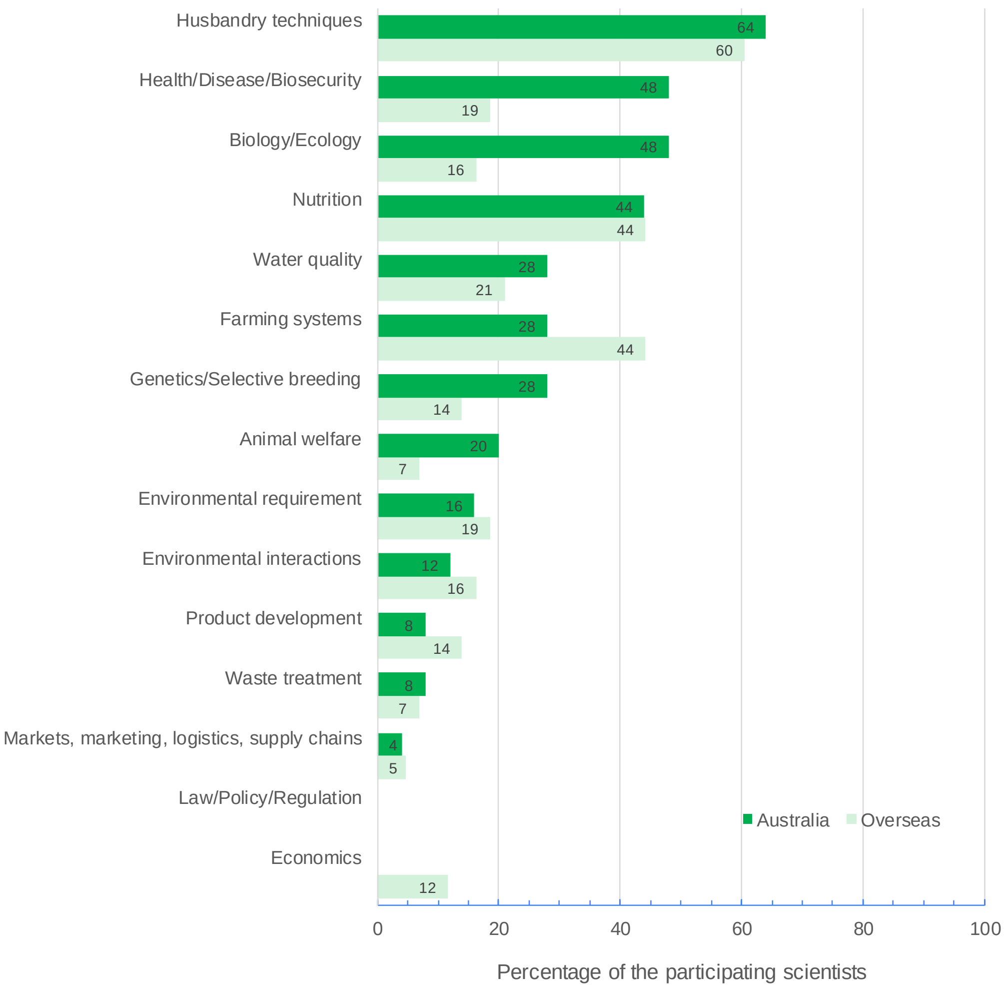


Figure 14. Functional areas targeted by finfish research in Australia (n = 25) and overseas (n = 43)

As for individual species Atlantic salmon and yellowtail king fish have the highest Research Comprehensive Index (RCI as percentage of the researched area out of 15 functional ones) of 53% (Table 14). RCI is 40 - 46% for barramundi, stripped trumpeter and cobia. Overseas, tilapia has the highest RCI (87%) among the audited species, higher than Atlantic salmon and yellowtail King fish in Australia. Interestingly, research on cobia is far more comprehensive with an RCI of 80%, indicating the potential for technology adoption for cobia farming in Australia. Research on snubnose pompano (*Trachinotus blochii*) and permit (*Trachinotus falcatus*) are more advanced from other species including barramundi. RCI of barramundi overseas is 40%, slightly lower than that in Australia. Research on more than 50% of the audited species is fragmented with low level of comprehensiveness, indicating more challenges for growing their aquaculture productions. Surprisingly RCI is only 7% for Tra catfish although the annual production of this species had exceeded 1.0 million tonnes since 2016 (SOFIA 2020). This species is quite special since its farming could benefit instantly from technologies and farming inputs developed for other species. Farming method and system are all simple, making production at scale feasible with limited R&D investment.

Table 15. Functional areas researched for the audited species in Australia

(1) biology/ecology, (2) genetics/selective breeding, (3) nutrition, (4) health/disease/biosecurity, (5) environmental requirements, (6) husbandry techniques, (7) farming system, (8) water quality, (9) waste treatment, (10) animal welfare, (11) market/marketing/logistics/supply chain, (12) product development, (13) economics, (14) environmental interactions and (15) law/policy/regulation.

No	Audited species	RCI (%)	Functional areas that have been researched														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Atlantic salmon	53	■	■	■	■		■	■			■				■	
2	Yellowtail kingfish	53	■	■	■	■	■	■		■						■	
3	Sand whiting	53	■		■	■		■	■	■			■	■			
4	Barramundi	47	■	■	■			■	■	■	■						
5	Striped trumpeter	40	■			■	■	■		■		■					
6	Cobia	40	■		■	■		■	■					■			
7	Snubnose pompano	33	■				■	■	■	■							
8	Pink snapper	27			■	■		■				■					
9	Southern bluefin tuna	27	■				■			■						■	
10	Black bream	20	■			■		■									
11	Mulloway	20	■		■			■									
12	Mahi-mahi	20	■		■			■									
13	Golden snapper	20			■			■	■								
14	Australian Snapper	7						■									
15	King George whiting	7						■									

Table 16. Functional areas researched for the audited species

(1) biology/ecology, (2) genetics/selective breeding, (3) nutrition, (4) health/disease/biosecurity, (5) environmental requirements, (6) husbandry techniques, (7) farming system, (8) water quality, (9) waste treatment, (10) animal welfare, (11) market/marketing/logistics/supply chain, (12) product development, (13) economics, (14) environmental interactions and (15) law/policy/regulation

No	Audited species	RCI (%)	Functional areas that have been researched														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Tilapia	87	■	■	■	■	■	■	■	■	■	■		■	■	■	
2	Cobia	80	■	■	■		■	■	■	■	■		■	■	■	■	
3	Snubnose pompano	67	■		■	■	■	■	■	■		■		■		■	
4	Permit	53			■	■		■	■	■		■		■		■	
5	Sturgeon	47	■		■		■	■	■	■						■	
6	Barramundi	40		■	■	■	■	■	■								
7	Hybrid grouper	40			■		■	■	■	■				■			

8	Withebait	33															
9	Black grouper	27															
10	Red drum	20															
11	European seabass	13															
12	Golden trevally	13															
13	Ballan wrasse	13															
14	California Yellowtail	13															
15	Cachama*	7															
16	Shorthorn sculpin	7															
17	Tra catfish	7															
18	Fourfinger thredfin	7															
19	Mangrove red snapper	7															

** Cachama include Colossoma sp, Piaractus sp. and hybrid species*

2.1.6. Production stages targeted by research

Research on the 15 audited finfish species in Australia strongly focus on grow-out stage (Figure 15). Broodstock maturation, larval rearing and to a lesser extent broodstock domestication are the other production stages that attract more research interest. Limited effort has been spent on harvest, processing and transport. Research on fingerling production receives less attention (33%). This might indicate existing challenges for the earlier stages and grow-out. In contrast, this area receives the strongest support by research overseas (79%), higher than the grow-out stage (62%). Compared with Australia, there have been more research on harvest and transport overseas.

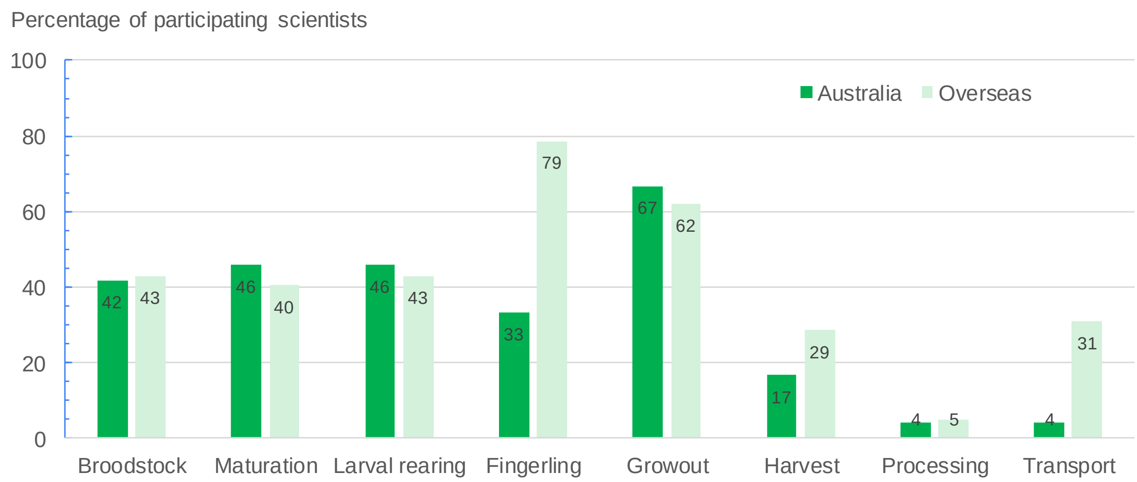


Figure 15. Production stages supported by the audited research in Australia (n = 24) and overseas (n = 42)

Table 17. Production stages targeted by research on the audited finfish species in Australia

(B) broodstock domestication, (M) maturation, (L) larval rearing, (F) fingerling production, (G) grow-out, (H) harvest, (P) processing, (T) transport. PRCI (%): production-stage research coverage index. R&D work on mahi-mahi was primarily industry bases.

No	Common name	PRCI (%)	Production stages							
			(B)	(M)	(L)	(F)	(G)	(H)	(P)	(T)
1	Sand whiting	100								

2	Black bream	63	■		■	■	■	■		
3	Mahi mahi	63	■	■	■	■	■			
4	Barramundi	63	■	■	■	■	■			
5	Mulloway	50	■		■	■	■			
6	Striped trumpeter	50	■	■	■	■				
7	Cobia	50	■	■	■		■			
8	Atlantic salmon	50	■	■			■	■		
9	Yellowtail kingfish	50	■	■	■	■				
10	Golden snapper	38		■	■		■			
11	King George whiting	25		■	■					
12	Snubnose pompano	25		■	■					
13	Australiasian snapper	13					■			
14	Pink Snapper	13					■			

As for individual species sand whiting is well supported by research across all the production stages, reflected by its PRCI of 100% (Production-stage Research Coverage Index). Black bream, mahi-mahi and barramundi all have PRCI of 63% (Table 16). The next group with an PRCI of 50% include Atlantic salmon, mulloway, striped trumpeter, cobia and yellowtail king fish. The Australiasian snapper and pink snapper have the lowest PRCI (13%) among the 15 audited finfish species in Australia.

Overseas, the audited researches are more comprehensive, thus better supporting commercial aquaculture. PRCI is 100% for tilapia and range from 75 – 88% for 50% of the audited species (Table 17). PRCI for barramundi and snubnose pompano are higher than that for cobia. Interesting, PRCI for Tra catfish and sturgeon are 63%, indicating more room for R&D activities on these species.

Table 18. Production stages targeted by research on the audited finfish species overseas

(B) broodstock domestication, (M) maturation, (L) larval rearing, (F) fingerling production, (G) grow-out, (H) harvest, (P) processing, (T) transport. PSCI (%): production-stage coverage index.

No	Common name	PSCI (%)	Production stages							
			(B)	(M)	(L)	(F)	(G)	(H)	(P)	(T)
1	Tilapia	100	■	■	■	■	■	■	■	■
2	Withebait	88	■	■	■	■	■	■	■	
3	Barramundi	88	■	■	■	■	■	■		■
4	Snubnose pompano	88	■	■	■	■	■	■		■
5	Hybrid grouper	88	■	■	■	■	■	■		■
6	Permit	88	■	■	■	■	■	■		■
7	Red drum	88	■	■	■	■	■	■		■
8	Golden trevally	75	■	■	■	■	■			■
9	Cobia	75	■	■	■	■	■	■		
10	Mangrove red snapper	75	■	■	■	■	■			■
11	Sturgeon	63	■	■	■	■	■			
12	Tra catfish	63	■	■	■	■	■			
13	Fourfinger thredfin	50		■	■	■	■			
14	Nassau grouper	25	■	■						
15	California yellowtail	25				■	■			
16	Cachama*	13				■				
17	Black grouper	13				■				
18	Ballan wrasse	13				■				

** Cachama include Colossoma sp, Piaractus sp. and hybrid species*

2.2. Industrial funding and adoption of research results

Information about the adoption of research results by the aquaculture industry is quite limited as it is generally hard to estimate if the audited research project did not directly link to the beneficial industries. Industrial funding has been made for some research on Atlantic salmon and, to a lesser extent, barramundi and pink snapper. These researches also have their results partly adopted for barramundi and pink snapper, and largely adopted for Atlantic salmon. Overseas, funding by the industry is also limited. Only 5 scientists reported industrial funding for their research on European seabass, tilapia, cobia, barramundi and Tra catfish. Industry adoption rate appears better. About 42% of the participating scientist claim that their research results have been adopted by the industry, largely for barramundi, hybrid grouper, snubnose pompano, permit, red drum, cobia, cachama, European seabass and sturgeon; and partly for tilapia, Tra catfish, golden trevally and mangrove red snapper.

2.3. OPPORTUNITIES FOR DEVELOPMENT

2.3.1. Evaluation of species potential

The potential for commercial aquaculture is evaluated for the audited species by participating scientists (as favourable) against three different groups of criteria: market potential (market scale, domestic market price, potential for export and value add), biological potential (growth rate to market size, survival in grow-out phase, tolerance to high rearing densities, susceptibility to diseases/parasites and flesh yield) and enabling context (availability of broodstock, control of reproduction in captivity, consistent supply of quality seed, knowledge of nutritional requirement and access to feeds, access to production sites and possibility to adopt existing technologies). Market potential indicates how easy or difficult to grow large-scale commercial production. Species with high biological and market potentials should be promoted. High biological potential ensures farming success and profitability. Enabling technologies only allow to speed up the commercialization process and/or make it more attractive to investors.

In Australia, sand whiting, snubnose pompano and Atlantic salmon are the species with highest overall potential scores (Table 18). The difference between this group and the rest is high. Given that Atlantic salmon is already a successful species for aquaculture sand whiting and snubnose pompano should be considered for commercial aquaculture. Poor biological potential is reported for pink snapper, King George whiting, stripped trumpeter. That of Australian snapper, golden snapper, mulloway and yellowtail kingfish is only 40%. While market potential could be improved over time, poor biological potential is apparently an obstacle for further development. Market potential of 50% of the audited species is lower than 50%. Compared with Atlantic salmon, cobia and barramundi have lower market potentials, i.e. 31 - 50%.

Table 19. Aquaculture potential of the audited finfish species in Australia

Data are percentage of the criteria classified as favourable

No.	Common name	*n*	Market potential	Biological potential	Enabling factors	Overall potential
1	Sand whiting	*1*	100	100	83	283
2	Snubnose pompano	*1*	75	100	100	275
3	Atlantic salmon	*7*	96	74	86	256
4	Cobia	*1*	50	80	67	197
5	Barramundi	*4*	31	80	79	190
6	Australian snapper	*1*	75	40	67	182

7	Golden snapper	*1*	50	80	50	180
8	Black bream	*1*	25	60	83	168
9	Striped trumpeter	*1*	50	20	67	137
10	Mahi mahi	*1*	25	60	50	135
11	Pink snapper	*1*	25	0	83	108
12	Yellowtail kingfish	*2*	25	40	17	82
13	Mulloway	*1*	0	40	0	40
14	King George whiting	*1*	0	0	33	33

Overseas, the top three species include snubnose pompano, cachama and tilapia (Table 19). The first two species are favoured by the participating scientists even over tilapia, whose commercial production reached 6.5 million tonnes in 2018 (SOFIA, 2020). The overall potential for tilapia is very similar to that for Atlantic salmon in Australia. Market and biological potentials of barramundi and cobia are not evaluated as high as in Australia. Interestingly, only with an average market potential and above-average biological potential Tra catfish ranks seventh on the list. Its commercial aquaculture production is only second to tilapia, approximately around 1.2 million tonnes annually (SOFIA, 2020). Snubnose pompano and permit (*Trachinotus* spp.) have very good potential especially the market one. More than 50% of the audited finfish species overseas have very poor biological and/or market potentials. As a group the potential of the audited finfish species for aquaculture is just above average (Figure 16). Market potential and enabling context appears more favourable overseas than in Australia.

Table 20. Aquaculture potential of the audited finfish species overseas

Data are percentage of the criteria classified as favourable

No.	Common name	*n*	Market potential	Biological potential	Enabling factors	Overall potential
1	Cachama*		75	100	100	275
2	Black grouper		75	80	83	238
3	Tilapia		71	80	81	231
4	Snubnose pompano		83	67	78	228
5	California yellowtail		100	40	83	223
6	Permit		88	60	67	214
7	Tra catfish		50	60	83	193
8	Red drum		50	60	83	193
9	Withebait		25	100	67	192
10	Barramundi		25	60	100	185
11	Cobia		64	54	64	183
12	Hybrid grouper		63	60	50	173
13	Golden trevally		50	40	72	162
14	European seabass		0	40	100	140
15	Sturgeon		50	40	33	123
16	Snook		50	20	33	103
17	Atlantic goliath grouper		25	20	50	95
18	Nassau grouper		50	0	33	83
19	Mutton snapper		50	0	33	83
20	Tarpon		50	0	33	83
21	Pompano		25	0	33	58
22	Ballan wrasse		25	0	17	42
23	Mangrove red snapper		25	0	17	42
24	Fourfinger thredfin		0	0	33	33
25	Shorthorn sculpin		0	0	0	0

** Cachama include Colossoma sp, Piaractus sp. and hybrid species*

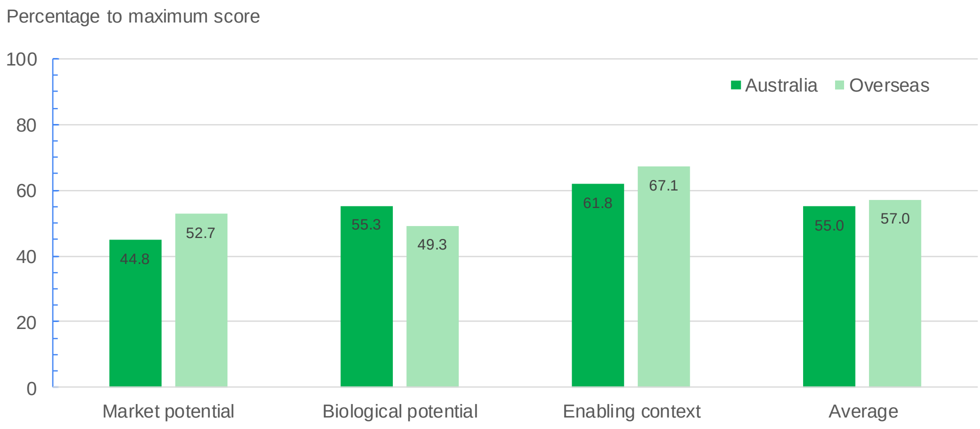


Figure 16. Potential for aquaculture of the audited finfish species in Australia (n = 25) and overseas (n = 36)

2.3.2. Possession of desirable attributes

Aquaculture species with more desirable attributes are more attractive to aquaculture producers or investors. The participating scientists helped evaluate the audited species against nine desirable attributes including easy reproduction in captivity, short grow-out period (≤12 mo.), intensive farming in sea cages, premium market price, substantial R&D interest, good growth on plant-protein-based diet, limited availability of wild catch, low production cost (≤US$3/kg) and history of regional or global trading.

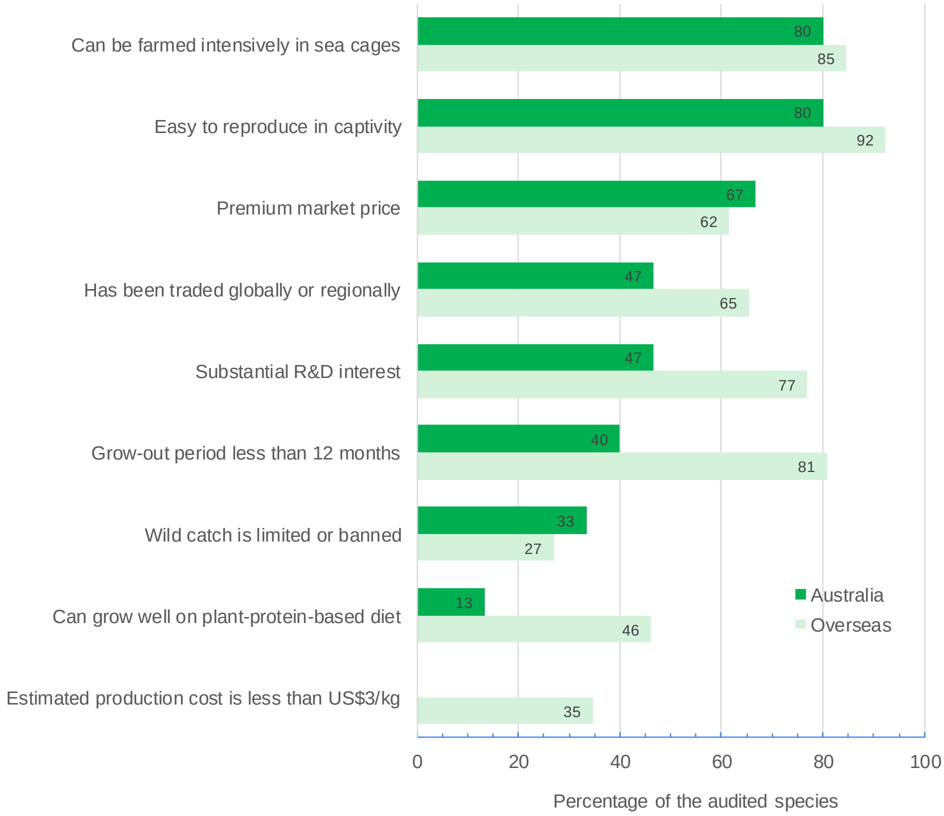


Figure 17. Possession of nine desirable attributes of the audited finfish species in Australia (n = 15) and overseas (n = 22)

In Australia, 80% of the species audited are easy to reproduce in captivity and could be farmed intensively in sea cages (Figure 17). Premium market price is the third most popular desirable attribute. Less than half of them have attracted substantial R&D interest or been traded in regional or global markets. 40% have their grow-out periods less than 12 months, indicating slower turnover rate and less profitability. Only 13% can grow on plant-protein-based diet. Production cost must be high since none has estimated production cost lower than US$3/kg.

Overseas, there are some remarkable differences that should be noted. First, 92% of the audited species can reproduce easily in captivity. The only exception is black grouper (Table 20). Second, 81% have grow-out periods less than 12 months while 77% have attracted substantial R&D interest. These probably help make production cost of 35% of the audited species lower than US$3.0/kg, which is not possible in Australia. Third, more species (65%) have been traded in regional and global markets. Export demand could encourage investors and producers to farm these species. Lastly, nearly half of the audited species could grow well on plant-protein-based diets. The contrasts between these audited species overseas and Australian species may indicate better species selection overseas and potential market competitions.

Table 21. Possession of desirable attributes and desirable score index (DSI) of the audited finfish species in Australia

Notes: (R) easy to reproduce in captivity, (G) grow-out period less than 12 months, (I) can be farmed intensively in sea cages, (M) premium market prices, (R&D) has attracted substantial R&D interest, (PP) grow well on plant-protein-based diet, (W) wild catch is limited or banned, (PC) estimated production cost less than US$3/kg, (T) has been traded regionally or globally.

No	Common name	DSI (%)	Desirable attributes								
			R	G	I	M	R&D	PP	W	PC	T
1	Atlantic salmon	78	■		■	■	■	■	■		■
2	Barramundi	78	■	■	■	■	■	■			■
3	Yellowtail kingfish	78	■	■	■	■	■		■		■
4	Cobia	67	■	■	■	■	■		■		
5	Striped trumpeter	56	■		■	■	■		■		
6	Snubnose pompano	56	■	■	■	■					■
7	Golden snapper	44	■		■	■	■				
8	Sand whiting	44	■	■		■			■		
9	Southern bluefin tuna	44			■	■	■				■
10	Mulloway	33			■	■					■
11	Mahi mahi	33	■	■	■						
12	Pink snapper	33	■		■						■
13	Black bream	11	■								
14	Australian snapper	11			■						
15	King George whiting	11	■								

Table 22. Possession of desirable attributes and desirable score index (DSI) of the audited finfish species overseas

Notes: (R) easy to reproduce in captivity, (G) grow-out period less than 12 months, (I) can be farmed intensively in sea cages, (M) premium market prices, (R&D) has attracted substantial R&D interest, (PP) grow well on plant-protein-based diet, (W) wild catch is limited or banned, (PC) estimated production cost less than US$3/kg, (T) has been traded regionally or globally.

No	Common name	DSI (%)	Desirable attributes								
			R	G	I	M	R&D	PP	W	PC	T
1	Cachama*	100	■	■	■	■	■	■	■	■	■

2	Tilapia	89									
3	Cobia	89									
4	Golden trevally	78									
5	Barramundi	78									
6	Snubnose pompano	78									
7	Permit	78									
8	Black grouper	67									
9	California yellowtail	67									
10	Hybrid grouper	67									
11	Red drum	67									
12	Sturgeon	56									
13	Snook	56									
14	European seabass	56									
15	Nassau grouper	56									
16	Withebait	56									
17	Tra catfish	56									
18	Pompano	56									
19	Atlantic goliath grouper	44									
20	Mutton snapper	44									
21	Tarpon	33									
22	Fourfinger thredfin	33									
23	Mangrove red snapper	33									
24	Ballan wrasse	11									

** Cachama include Colossoma sp, Piaractus sp. and hybrid species*

As for individual species, Atlantic salmon, barramundi and yellowtail kingfish all have the highest DSI (78%) (Table 20). Cobia ranks 4th, higher than snubnose pompano and striped trumpeter. Southern bluefin tuna, mulloway and Australian snapper are not easy to breed in captivity. 60% of the audited species have grow-out period longer than 12 months. DSIs for black bream, Australian snapper and King George whiting are only 11%. Overseas, DSI varies from 11 to 100 (Table 21). Cachama species are on top of the list with an DSI of 100%. Tilapia and cobia rank 2nd with a DSI of 89%, higher than than of the next group including barramuni, snubnose pompano, permit and golden trevally. Production cost of tilapia is lower than US$3.0/kg, which is not possible with cobia. DSI for barramundi is the same as evaluated in Australia (78%), but low production cost is considered as a desirable attribute instead the ability to grow well on plant-protein-based diet as reported in Australia. It should be noted that DSI for Tra catfish is only 56%, comprising of five desirable attributes: easy to reproduce in captivity, fast growing, growing well on plant-protein-based diet, low production cost and global trade.

2.3.3. Potential to adopt existing technologies

Adoption of existing technologies appears possible across all production stages of the audited finfish species in Australia (Figure 22). There is some limitation with larval rearing compared with the other stages, probably because of the intrinsic differences in biology, environmental or nutritional requirements of different species. The potential for adopting existing technologies is higher overseas, especially for broodstock maturation, larval rearing and broodstock domestication (Figure 16). Less potential is reported for processing and transport.

As for individual species, adoption of existing technologies is highly promising for Atlantic salmon, barramundi, sand whiting and snubnose pompano. PAETI of these species is 100% (Table). Lower PAETI is reported for striped trumpeter, cobia, pink snapper and yellowtail king fish. Interesting, technological adoption is not possible for broodstock maturation, larval rearing and fingerling production stages of the first three species of this group (Table 22). This may explain why their aquaculture development did not progress as fast as expected. Overseas, PAETI is 100% for 25% of the audited species (Table 22). These include tilapia, cobia, barramundi, snubnose pompano, permit, black grouper and golden trevally. In contrast, PAETI is zero for 7 species and only 13% (for grow-out phase) for Tra catfish.

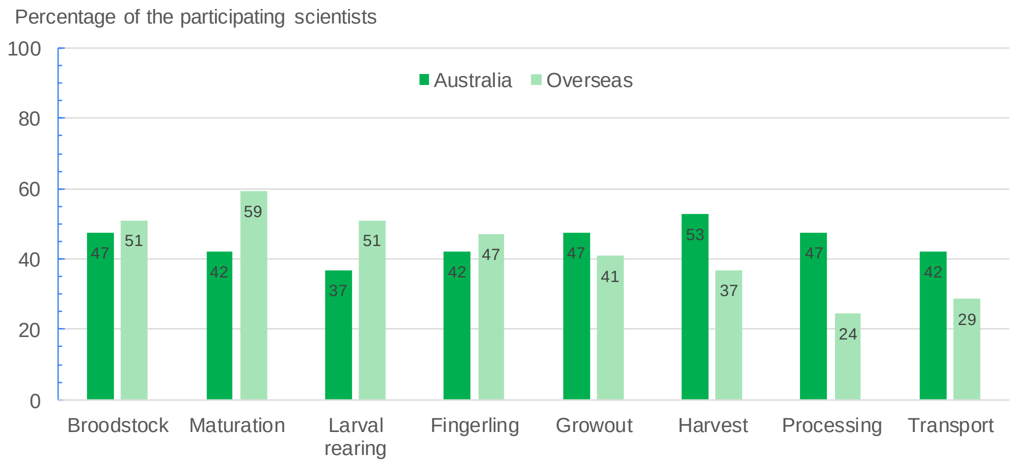


Figure 18. Potential for adoption of existing technologies across different production stages of the audited finfish species in Australia (n = 19) and overseas (n = 49)

Table 23. Production stages of the audited species in Australia that could benefit from technology adoption

(B) broodstock domestication, (M) maturation, (L) larval rearing, (F) fingerling production, (G) grow-out, (H) harvest, (P) processing, (T) transport. PAET (%): potential for adoption of existing technologies index.

No	Common name	PAETI (%)	Production stages (B)	(M)	(L)	(F)	(G)	(H)	(P)	(T)
1	Atlantic salmon	100								
2	Barramundi	100								
3	Sand whiting	100								
4	Snubnose pompano	100								
5	Striped trumpeter	63								
6	Cobia	50								
7	Pink snapper	38								
8	Yellowtail kingfish	38								

Table 24. Production stages of the audited species overseas that could benefit from technology adoption

(B) broodstock domestication, (M) maturation, (L) larval rearing, (F) fingerling production, (G) grow-out, (H) harvest, (P) processing, (T) transport. PAET (%): potential for adoption of existing technologies index.

No	Common name	PAETI (%)	Production stages (B)	(M)	(L)	(F)	(G)	(H)	(P)	(T)

1	Tilapia	100								
2	Barramundi	100								
3	Cobia	100								
4	Snubnose pompano	100								
5	Permit	100								
6	Black grouper	100								
7	Golden trevally	100								
8	Cachama*	88								
9	Red drum	88								
10	Hybrid grouper	75								
11	Atlantic goliath grouper	50								
12	Sturgeon	38								
13	European seabass	25								
14	Nassau grouper	25								
15	Mutton snapper	25								
16	Tarpon	25								
17	Pompano	25								
18	Tra catfish	13								
19	Snook	0								
20	Withebait	0								
21	Ballan wrasse	0								
22	Shorthorn sculpin	0								
23	California yellowtail	0								
24	Fourfinger thredfin	0								
25	Mangrove red snapper	0								

** Cachama include Colossoma sp, Piaractus sp. and hybrid species*

2.3.4. Technology readiness

Yellowtail kingfish, pink snapper and barramundi join Atlantic salmon in the commercially viable group with TRI higher than 2.8 (Table 24). This group accounts for only 27% of the audited species. Farming is technically feasible for sand whiting, black bream, striped trumpeter, Australian snapper and cobia. Further development of these species' aquaculture thus depends on other factors such as market demand, availability of production site, profitability or simply investment. All other species with TRI ranging from 0.6 to 1.3 would require more research, development or technology adoption.

Table 25. Technology readiness for each production stage by species in Australia

Experimental = 1.0; Technically feasible = 2.0; Commercially viable = 3.0. (BMA) broodstock maturation, (SPA) spawning, (LAR) larval rearing, (FIN) fingerling production, (GRO) grow-out, (HAV) harvest, (PRO) processing, (TRA) transportation.

No	Common name	*n*	TRI	Technology readiness							
			(%)	BMA	SPA	LAR	FIN	GRO	HAV	PRO	TRA
1	Barramundi	*4*	2.9	2.5	2.5	3.0	3.0	3.0	3.0	3.0	3.0
2	Pink snapper	*1*	2.9	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
3	Yellowtail kingfish	*2*	2.9	3.0	3.0	3.0	3.0	2.0	3.0	3.0	3.0
4	Atlantic salmon	*7*	2.8	2.7	2.7	2.7	2.7	2.9	2.9	2.9	2.9
5	Sand whiting	*1*	2.5	3.0	3.0	3.0	3.0	2.0	2.0	2.0	2.0
6	Black bream	*1*	2.4	2.0	2.0	2.0	2.0	2.0	3.0	3.0	3.0
7	Striped trumpeter	*1*	2.1	2.0	3.0	2.0	2.0	2.0	2.0	2.0	2.0
8	Australian snapper	*1*	2.0	3.0	3.0	3.0	3.0	2.0	2.0	0.0	0.0
9	Cobia	*1*	2.0	2.0	2.0	3.0	3.0	2.0	2.0	2.0	0.0
10	Mahi-mahi	*1*	1.3	1.0	1.0	2.0	2.0	2.0	2.0	0.0	0.0

11	Golden snapper	*1*	1.3	2.0	2.0	2.0	2.0	2.0	0.0	0.0	0.0
12	Southern bluefin tuna	*1*	1.1	0.0	0.0	0.0	0.0	3.0	3.0	3.0	0.0
13	Mulloway	*1*	1.0	1.0	1.0	2.0	2.0	2.0	0.0	0.0	0.0
14	King George whiting	*1*	0.6	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0
15	Snubnose pompano	*1*	0.6	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0
	Average	*25*	1.9	1.9	2.0	2.2	2.2	2.1	1.9	1.6	1.3

Overseas, the commercially viable group has 13 different species or 50% of the audited species with TRI of 2.7 and higher (Table 25). Of these tilapia, Tra catfish, barramundi, cachama and European seabass already have significant aquaculture productions globally (SOFIA 2020). Farming of cobia and black grouper is technically feasible. As withebait larval rearing is still problematic, the farming of this species is neither technically feasible nor commercially viable. Species such as mangrove red snapper, fourfinger thredfin, Atlantic goliath grouper, mutton snapper, Nassau grouper, Ballan wrasse, tarpon, California pompano and snook still need more research and development.

Table 26. Technology readiness for each production stage by species overseas

Experimental = 1.0; Technically feasible = 2.0; Commercially viable = 3.0. (BMA) broodstock maturation, (SPA) spawning, (LAR) larval rearing, (FIN) fingerling production, (GRO) grow-out, (HAV) harvest, (PRO) processing, (TRA) transportation.

No	Common name	*n*	TRI (%)	Technology readiness							
				BMA	SPA	LAR	FIN	GRO	HAV	PRO	TRA
1	European seabass	*1*	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
2	California yellowtail	*1*	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
3	Snubnose pompano	*3*	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.7	3.0
4	Permit	*2*	2.9	3.0	3.0	3.0	3.0	3.0	3.0	2.5	3.0
5	Barramundi	*4*	2.9	3.0	3.0	3.0	3.0	3.0	2.8	2.7	2.8
6	Tilapia	*6*	2.9	2.8	2.8	3.0	3.0	3.0	3.0	2.4	3.0
7	Sturgeon	*1*	2.9	3.0	3.0	3.0	3.0	3.0	3.0	2.0	3.0
8	Cachama*	*1*	2.9	2.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
9	Red drum	*1*	2.9	3.0	3.0	3.0	3.0	3.0	3.0	2.0	3.0
10	Tra catfish	*2*	2.8	3.0	3.0	2.5	2.5	2.5	2.5	3.0	3.0
11	Golden trevally	*3*	2.7	2.7	2.7	2.7	2.7	2.7	2.7	3.0	2.7
12	Withebait	*1*	2.6	2.0	3.0	1.0	3.0	3.0	3.0	3.0	3.0
13	Hybrid grouper	*2*	2.2	2.0	2.0	2.0	2.5	2.5	2.5	2.0	2.0
14	Cobia	*7*	2.1	2.4	2.6	2.7	2.6	2.1	2.0	1.4	1.3
15	Black grouper	*1*	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
16	Mangrove red snapper	*1*	1.1	2.0	2.0	1.0	1.0	1.0	0.0	0.0	2.0
17	Fourfinger thredfin	*1*	1.0	1.0	1.0	2.0	2.0	1.0	0.0	0.0	1.0
18	Atlantic goliath grouper	*1*	0.8	2.0	2.0	2.0	0.0	0.0	0.0	0.0	0.0
19	Mutton snapper	*1*	0.6	2.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0
20	Nassau grouper	*1*	0.5	2.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0
21	Ballan wrasse	*1*	0.5	0.0	0.0	2.0	2.0	0.0	0.0	0.0	0.0
22	Tarpon	*1*	0.3	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	California pompano	*1*	0.3	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	Snook	*1*	0.1	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Average	*47*	2.0	2.1	2.1	1.9	1.9	1.8	1.8	1.7	1.8

2.4. BARRIERS TO FURTHER DEVELOPMENT

2.4.1. Identified barriers

In Australia, 17/18 pre-defined barriers are considered by the participating scientists. The most common barrier is insufficient supply of quality seed, applicable for 54% of the audited species (Figure 24). Unfavourable regulation ranks 2nd. The next two barriers are too-small industry and low profit (due to high production cost) reported for 38% of the audited species. Other major barriers include lack of production sites, poor growth rate and limited funding for R&D. Interestingly, the lack of skilled labour is not considered by any of the participating scientists.

Overseas, limited funding for R&D and poor downstream capacity are the top two barriers applicable for 77% of the audited species. The next two barriers include insufficient supply of quality seed and lack of investment throughout the supply chain (both at 69%). The magnitude of all these four barriers are all higher than the top four in Australia. Other major barriers are low profit (due to high production cost) (58%), lack of public support (58%) and increasing threat of infectious diseases (46%). The lack of skilled labour is more obvious overseas. Technical barriers exist for only 20 – 30% of the audited species in both countries. This observation indicates that increasing commercial aquaculture production requires a lot more than addressing technical challenges of farming.

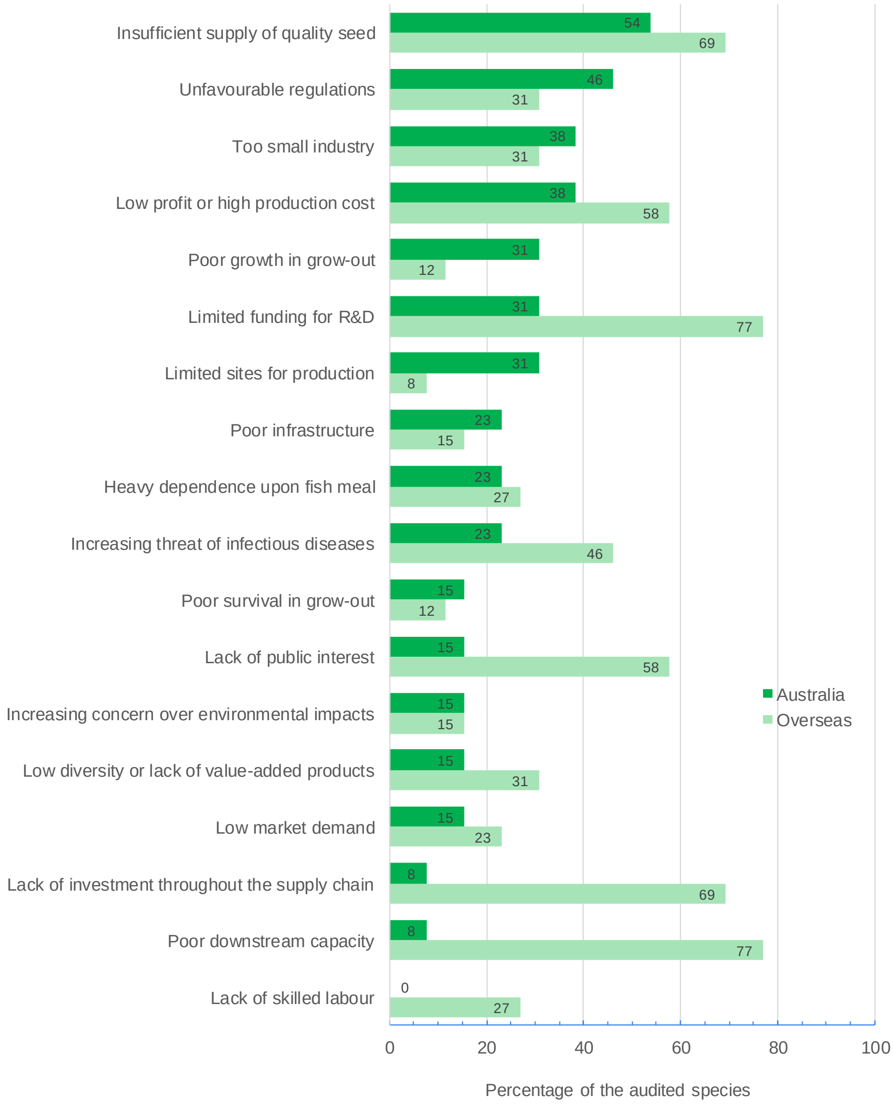


Figure 19. Identified barriers to development of finfish aquaculture in Australia (n = 13) and overseas (n = 26)

As for individual species in Australia barramundi has the highest Barriers Index (BI) of 67%. Interestingly, Atlantic salmon – the most successful aquaculture finfish in Australia ranks 2nd with a BI of 55.6%, implying that increasing commercial production is not easy despite of advanced aquaculture technologies. BI for yellowtail kingfish (50%) is more than two folds higher than that for cobia, golden snapper and snubnose pompano (22%). Compared with barramundi and yellowtail kingfish Atlantic salmon aquaculture does not have barriers such as low market demand or inconsistent supply of quality seed. Several new species have fewer barriers to development reported, probably because their commercial farming has not taken place yet.

Table 27. Barriers to aquaculture development of the audited finished species in Australia

No	Common name	n	BI (%)	Barriers to development																	
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Barramundi	4	67	■	■	■	■		■	■		■	■	■		■	■		■		
2	Atlantic salmon	7	56	■		■	■		■		■	■			■				■	■	■
3	Yellowtail kingfish	2	50	■		■			■	■	■	■	■		■		■				
4	Golden snapper	1	22		■		■			■								■			
5	Cobia	1	22			■				■		■						■			
6	Snubnose pompano	1	22	■						■		■							■		
7	Mahi-mahi	1	17				■			■											■
8	Pink snapper	1	11			■					■										
9	King George whiting	1	11							■										■	
10	Sand whiting	1	11	■															■		
11	Southern bluefin tuna	1	11	■													■				
12	Black bream	1	6																	■	
13	Snapper	1	6																	■	

n: number of audits;

BI (%): barriers index, i.e. percentage of the number of identified barriers over 18 pre-defined ones;

(1): Unfavourable regulations; (2) Low market demand; (3) Low profit or high production cost;

(4) Limited sites for production; (5) Lack of skilled labour; (6) Increasing threat of infectious diseases;

(7) Insufficient supply of quality seed; (8) Heavy dependence upon fish meal; (9) Too small industry;

(10) Low diversity or lack of value-added products; (11) Poor downstream capacity; (12) Increasing concern over environmental impacts;

(13) Lack of investment throughout the supply chain; (14) Poor infrastructure; (15) Lack of public interest;

(16) Limited funding for R&D; (17) Poor growth in grow-out; (18) Poor survival in grow-out;

Table 28. Barriers to aquaculture development of the audited finished species overseas

No	Common name	n	BI (%)	Barriers to development																	
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Tilapia	6	67																		
2	Cobia	7	61											3							
3	Barramundi	4	56																		
4	Golden trevally	3	50																		
5	Tra catfish	2	50																		
6	Snubnose pompano	3	50																		
7	Permit	2	50																		
8	Sturgeon	1	44																		
9	Black grouper	1	44																		
10	Hybrid grouper	2	44																		
11	Cachama*	1	33																		
12	Snook	1	33																		
13	Nassau grouper	1	33																		
14	Atlantic goliath grouper	1	33																		
15	Mutton snapper	1	33																		
16	Tarpon	1	33																		
17	Pompano	1	33																		
18	Mangrove red snapper	1	33																		
19	California Yellowtail	2	28																		
20	Red drum	1	28																		
21	Fourfinger thredfin	1	28																		
22	European seabass	1	22																		
23	Withebait	1	17																		
24	Ballan wrasse	1	17																		

ı: number of audits; BI (%): barriers index, i.e. percentage of the number of identified barriers over 18 pre-defined ones; *cachama include *Colossoma* sp., *Piaractus* sp. and hybrid of these

1): Unfavourable regulations; (2) Low market demand; (3) Low profit or high production cost;

4) Limited sites for production; (5) Lack of skilled labour; (6) Increasing threat of infectious diseases; (7) Insufficient supply of quality seed; (8) Heavy dependence upon fish meal; (9) Too small industry;

10) Low diversity or lack of value-added products; (11) Poor downstream capacity; (12) Increasing concern over environmental impacts; (13) Lack of investment throughout the supply chain; (14) Poor infrastructure;

15) Lack of public interest; (16) Limited funding for R&D; (17) Poor growth in grow-out; (18) Poor survival in grow-out;

Overseas, cobia, tilapia and Tra catfish are the three species that have highest BIs. Even with million tons of commercially annually, the lack of quality seed still exists with both tilapia and Tra catfish in addition to disease problem. None of the audited species has poor growth rate in grow-out considered as a barrier. This may imply the importance of biological attribute in selecting candidate species for aquaculture. Barramundi and snubnose pompano rank lowly on the list. BI is only 22% for barramundi and 17% for snubnose pompano.

2.4.2. Availability of required inputs for commercial production

Farming of a species could only take place and scale up if all required inputs are available and easy to source. This is extremely important for new species' aquaculture that are either technical feasible or even commercially viable. The required inputs for farming include primarily production site, labour, broodstock, fingerlings, feeds, drugs and chemicals and farming systems. The other essential inputs are finance, technical support, transport to market and processing facilities.

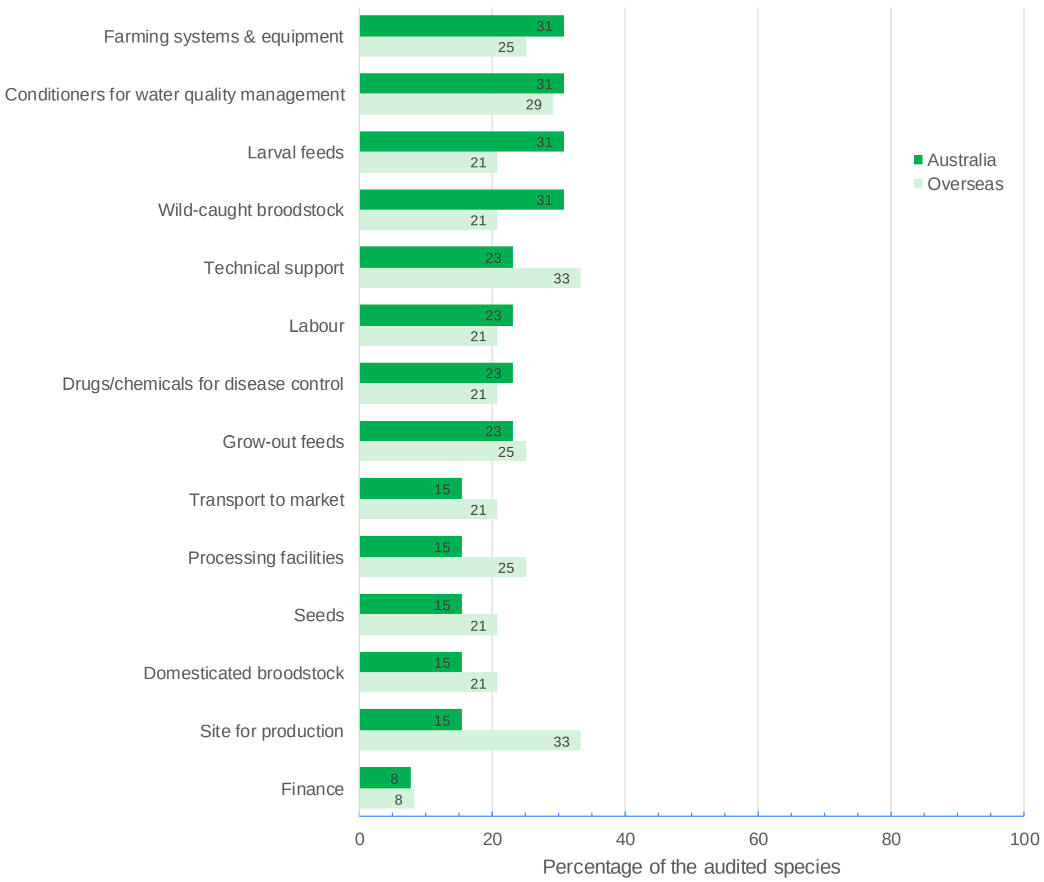


Figure 20. Access to required inputs for commercial farming of finfish in Australia (n = 13) and overseas (n = 24)

In Australia, the percentage of audited species could easily access to 14 required inputs range from 8 – 31%. Finance is the most limited input for finfish aquaculture in Australia (Figure 23). The other inputs for farming that are currently still limited include production site, domesticated broodstock, seed, processing facilities and transport. These essential inputs are considered highly accessible for only 17% of the audited species. Overseas, higher availability of technical support and production site are reported. Finance is also considered as the most limited input. Interestingly, the inputs that are less available in Australia have slightly higher availability overseas. In contrast, farming systems and equipment, larval feed and wild-caught broodstock are less available compared to Australia.

Table 29. Availability of required inputs for farming of finfish species in Australia

a: available, ha: highly accessible, AI(%): availability index, HAI(%): high accessibility index; (1) site for production, (2) wild-caught broodstock, (3) domesticated broodstock, (4) seeds, (5) larval feeds, (6) grow-out feeds, (7) drugs/chemicals for disease control, (8) conditioners for water quality management, (9) farming systems & equipment, (10) processing facilities, (11) transport to markets, (12) labour, (13) finance, (14) technical support

No	Audited species	HAI (%)	AI (%)	Required inputs for farming													
				1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Barramundi	93	7	ha	ha	ha	ha	ha	ha	ha	ha	ha	ha	ha	ha	a	ha
2	Atlantic salmon	79	21	a	a	ha	ha	ha	ha	a	ha	ha	ha	ha	ha	ha	ha
3	Cobia	57	21	a	ha	a	a	ha	ha	ha	ha	ha			ha		ha
4	Sand whiting	43	57	ha	ha	a	a	ha	a	ha	ha	ha	a	a	a	a	a
5	Striped trumpeter	7	50		ha			a	a	a		a	a	a			a
6	Yellowtail kingfish	0	100	a	a	a	a	a	a	a	a	a	a	a	a	a	a
7	Pink snapper	0	86	a	a		a	a	a	a	a	a	a	a	a		a
8	Snubnose pompano	0	57	a	a			a	a	a	a	a				a	
9	Golden snapper	0	36	a		a	a	a		a							
10	Mahi-mahi	0	29	a		a	a										a
11	Black bream	0	21	a		a	a										
12	Southern bluefin tuna	0	21	a	a												a
13	King George whiting	0	14			a	a										

Table 30. Availability of required inputs for farming of finfish species overseas

a: available, ha: highly accessible, AI(%): availability index, HAI(%): highly accessibility index; (1) site for production, (2) wild-caught broodstock, (3) domesticated broodstock, (4) seeds, (5) larval feeds, (6) grow-out feeds, (7) drugs/chemicals for disease control, (8) conditioners for water quality management, (9) farming systems & equipment, (10) processing facilities, (11) transport to markets, (12) labour, (13) finance, (14) technical support

No	Audited species	HAI (%)	AI (%)	Required inputs for farming													
				1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Barramundi	86	14	ha	a	ha	ha	ha	ha	ha	ha	ha	ha	ha	ha	a	ha
2	Tilapia	86	14	ha	a	ha	ha	ha	ha	ha	ha	ha	ha	ha	a	ha	ha
3	Cobia	86	14	ha	ha	ha	ha	ha	ha	a	ha	ha	ha	ha	ha	a	ha
4	Snubnose pompano	86	14	ha	ha	a	ha	ha	ha	ha	ha	ha	ha	a	ha	ha	ha
5	Withebait	71	29	ha	ha	ha	a	a	ha	ha	ha	ha	ha	ha	a	a	ha
6	Black grouper	64	36	ha	ha	a	a	ha	ha	a	ha	ha	ha	ha	ha	a	a
7	California yellowtail	36	64	ha	ha	ha	ha	a	a	a	a	a	a	a	a	a	ha
8	Sturgeon	21	79	ha	a	a	a	a	a	a	a	a	a	a	ha	a	ha
9	Permit	14	71	a		a	a	a	a	ha	ha	a	a	a	a		a
10	Golden trevally	7	93	a	a	a	a	a	a	a	a	a	a	a	a	a	ha
11	Cachama*		100	a	a	a	a	a	a	a	a	a	a	a	a	a	a
12	Tra catfish		93	a	a	a	a	a	a	a	a	a	a	a	a		a
13	Red drum		79	a		a	a	a	a	a	a	a		a	a		a
14	Ballan wrasse		71	a	a	a	a	a	a	a	a	a	a				
15	Hybrid grouper		71	a	a	a	a	a	a	a	a	a		a			
16	Mangrove red snapper		64	a	a	a		a	a	a	a	a		a			
17	Fourfinger thredfin		57	a				a	a	a	a	a		a	a		
18	European seabass		43			a	a	a	a		a						a
19	Nassau grouper		29		a	a		a									a

20	Snook		7														a
21	Mutton snapper		7														a
22	California pompano		7														a

** Cachama include Colossoma sp, Piaractus sp. and hybrid species*

Species that have good accessibility to the 14 required inputs for farming include barramundi, Atlantic salmon, cobia, sand whiting and to a lesser extent yellowtail king fish, pink snapper, striped trumpeter (Table 28). Overseas, tilapia, barramundi, cobia and snubnose pompano have the highest HAI of 86% (Table 29). Other species whose farming are well supported include withebait and black grouper

2.5. FUTURE RESEARCH

2.5.1. Research planning and demand for industrial partnership

In Australia 65% of the participating scientists would like to continue research on finfish (Figure 25). Another 13% indicate they may. Research is not recommended for black bream, mulloway, pink snapper and King George whiting due to limited potentials (see Appendix 1). More than 50% of the participating research request funding from FRDC while 67% would like to have industrial partners supporting the research projects. The need for industrial partners is very similar overseas. So does the intention to do more research on finfish. This intention appears stronger than that in Australia as none of the participating scientists plan to stop doing research on finfish.

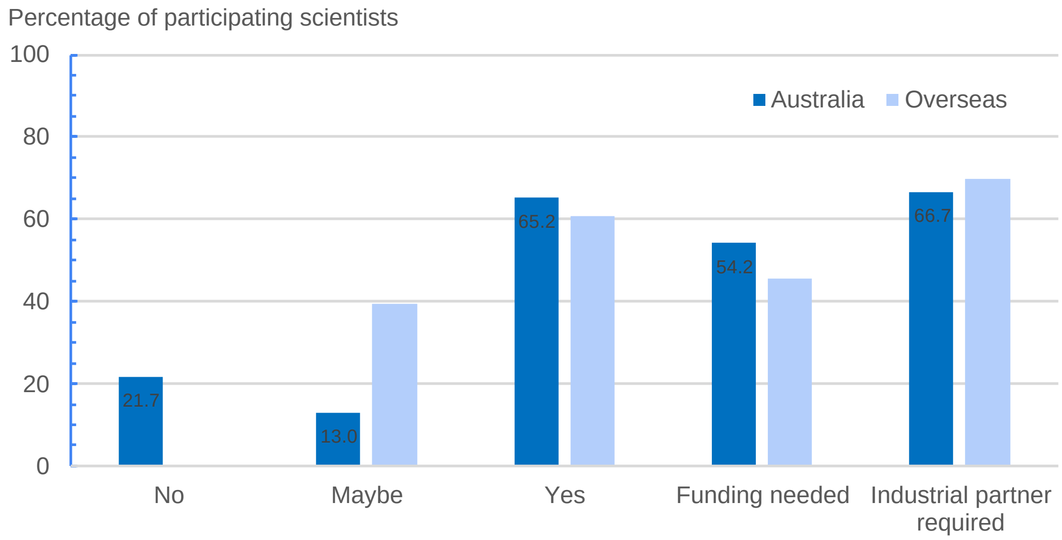


Figure 21. Intention for future research on finfish species and requests for support

2.5.2. Functional areas that require more research

Research is recommended for 9 species by 19 scientists in Australia (Figure 26). Three functional areas that receive high recommendation rate include health/disease/biosecurity, genetics/selective breeding and nutrition. Important areas such as husbandry techniques and waste treatment received limited recommendation. Overseas, genetics/selective breeding is the most recommended area for research, followed by market/marketing/logistics/supply chain and health/disease/biosecurity. Nutrition and production development rank fourth and fifth. Less research is required on farming system.

As for species Atlantic salmon and cobia have the highest Research Demand Index (RDI as percentage of recommended area out of 15) (Table 30). These recommendations do emphasize the importance to support the largest finfish aquaculture industry in Australia and, at the same time, to explore the potential of cobia for commercial aquaculture. RDI of new species such as snubnose pompano (53%) and pink snapper (47%) are higher than that of more established species like barramundi (40%) and yellowtail King fish (33%).

Similar trends are observed through the recommendation of scientists overseas (Table 30). Cobia and tilapia have the highest RDIs, i.e. 93 and 80%. It is quite clear that cobia is considered an important species for marine aquaculture. Aquaculture production of tilapia reached 6.5 mil tons in 2017 with sales value of US$12 billion (FAO 2018). Great demand for research on this species is likely due to the need for further improvement of production efficiencies. Golden trevally and permit *(Trachinotus falcatus)* are the next two species that require more research for 60% of the surveyed functional areas. Among the 18 finfish species recommended for research overseas barramundi has the lowest RDI (13%). The two functional areas that require more research for barramundi are genetics/selective breeding and product development.

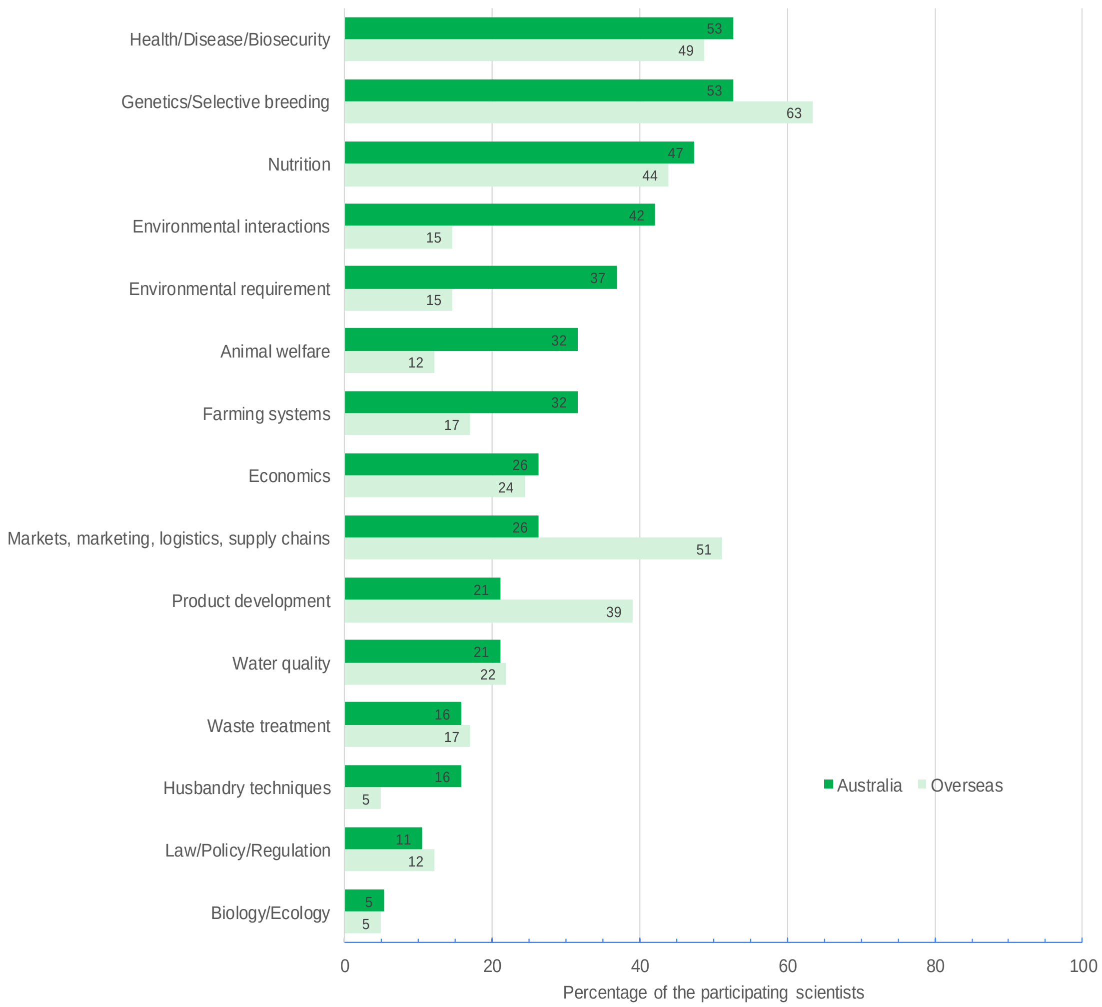


Figure 22. Functional areas that require substantial research effort to assist commercial aquaculture as recommended by Australian (n = 19) and overseas scientists (n = 41)

Table 31. Functional areas that still require substantial research effort for finfish in Australia

(1) biology/ecology, (2) genetics/selective breeding, (3) nutrition, (4) health/disease/biosecurity, (5) environmental requirements, (6) husbandry techniques, (7) farming system, (8) water quality, (9) waste treatment, (10) animal welfare, (11) market/marketing/logistics/supply chain, (12) product development, (13) economics, (14) environmental interactions and (15) law/policy/regulation.

No	Audited species	RDI (%)	Functional areas														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Atlantic salmon	80	■	■	■	■	■		■	■	■	■			■	■	■
2	Cobia	67		■	■	■	■	■		■			■	■	■	■	
3	Snubnose pompano	53		■	■	■						■	■	■	■		■
4	Pink snapper	47		■	■			■	■			■	■		■		
5	Barramundi	40		■	■	■		■	■					■			
6	Yellowtail kingfish	33		■	■	■	■									■	
7	Sand whiting	33			■				■				■	■	■		
8	Striped trumpeter	13							■				■				
9	Southern bluefin tuna	13					■									■	

Table 32. Functional areas that still require substantial research effort for finfish overseas

(1) biology/ecology, (2) genetics/selective breeding, (3) nutrition, (4) health/disease/biosecurity, (5) environmental requirements, (6) husbandry techniques, (7) farming system, (8) water quality, (9) waste treatment, (10) animal welfare, (11) market/marketing/logistics/supply chain, (12) product development, (13) economics, (14) environmental interactions and (15) law/policy/regulation

No	Audited species	RDI (%)	Functional areas														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Cobia	93	■	■	■	■	■		■	■	■	■	■	■	■	■	■
2	Tilapia	80		■	■	■			■	■	■	■	■	■	■	■	■
3	Golden trevally	60		■	■	■	■	■	■	■			■	■			
4	Permit	60		■	■	■					■		■	■	■	■	■
5	Cachama*	47		■	■	■				■			■	■	■		
6	Snubnose pompano	47		■	■						■		■	■		■	■
7	Hybrid grouper	47		■	■	■			■	■			■				■
8	Black grouper	33		■	■	■							■	■			
9	Withebait	33	■	■	■		■			■							
10	Fourfinger thredfin	33		■	■		■						■	■			
11	Mangrove red snapper	33		■	■		■			■			■				
12	Tra catfish	27			■			■	■		■						
13	California yellowtail	27		■		■						■			■		
14	Red drum	27		■		■							■	■			
15	Sturgeon	20		■		■							■				
16	Barramundi	13		■										■			

** Cachama include Colossoma sp, Piaractus sp. and hybrid species*

2.6. REMARKS

Although not covering all the finfish species that have been researched in Australia and overseas, this study has revealed some important findings

- The audited researches show strong focus on marine finfish including those with established commercial aquaculture productions and new species. About half of the audited researches were prompted from industry request and assignment of the employer. None was associated with recommendation from market studies. Research overseas are more driven by aquaculture potential and personal interest. This indicates stronger entrepreneurship mindset of scientists overseas, which is highly important to drive commercial production of new species.

- Most Australian species are produced for domestic markets which are growing but has not far exceeded aquaculture growth to create a strong market pull. Export of aquaculture products, although could only target premium international markets, must be considered to create more incentives to aquaculture producers as Australian agriculture products are preferred thanks to premium quality. Export does help aquaculture start-ups if the selected (new) species is of good demand for both domestic and international markets. Overseas, 76.9% of the audited species are produced for both export and domestic consumption.
- Whole fresh fish and their fresh/frozen fillets are preferred by consumers in Australia. The preference of live fish overseas suggests that this form of product should be considered as Asian communities are growing in Australia. Species that could be sold live, usually at plate-size and much higher prices should be considered.
- The top 4 functional areas that have attracted research on finfish are husbandry techniques, health, biology and nutrition. The importance of husbandry techniques and nutrition are echoed overseas, but much stronger focus is reported for farming systems and economics which are helpful to the selection and development of new species.
- Significant research effort has been invested on more established species like Atlantic salmon, yellowtail king fish, barramundi and new species such as striped trumpeter, sand whiting and cobia. Among these species, researches on Atlantic salmon and yellowtail king are more complete. Overseas, researches on cobia and snubnose pompano are more advanced and comprehensive, suggesting great potential for technology transfer or adoption for these two species in Australia.
- Research focus more on grow-out and the earlier stages of production (broodstock domestication, maturation, larval rearing and fingerling) than on harvest, processing and transport. This clearly indicates aquaculture development for many species is still in the early stages. Overseas, fingerling production and grow-out stage attract the highest attention of scientists, probably to support further expansion of the finfish aquaculture industry.
- Industrial funding is only reported for more established aquaculture species like Atlantic salmon and barramundi with an exception of pink snapper. Industrial funding is also limited overseas, but more scientists overseas than in Australia claimed that their research results were adopted by the aquaculture industry.
- Evaluated by the participating scientists, barramundi and yellowtail king fish both have the same desirable score index (DSI) as for Atlantic salmon. However, these two species have much lower market potential compared with Atlantic salmon. Interesting, market potential of barramundi is also low overseas. In Australia, sand whiting, snubnose pompano and cobia are considered having high overall potential for commercial aquaculture. Overseas scientists have similar evaluation for subnose pompano and cobia. Other species with high DSIs that Australia may consider include golden trevally, permit and groupers.
- Adoption of existing technologies is possible across all different production stages, but less promising for larval rearing. This may imply significant difference in biology and thus nutritional/environmental requirements of the audited species. As stated above more research on hatchery production should be beneficial to Australian aquaculture industry. Furthermore, biological similarities (to existing species) could be beneficial when considering new species.
- Regarding technology readiness grow-out of pink snapper and Southern bluefin tuna are commercially viable. Other species such as cobia, yellowtail king fish, sand whiting, black

bream, Australian snapper and striped trumpeter all require more commercial research. However, the current availability of critical farming inputs only favour cobia and sand whiting. Generally, limited accessibility to domesticated broodstock, fingerlings and production site all make it difficult to increase aquaculture production of both more established and new species.

- Barriers to development are common to all different species regardless of how established their commercial aquaculture productions are. Examples include Atlantic salmon and barramundi in Australia or tilapia, Tra catfish and barramundi overseas. Barriers appear to be production scale dependent. For finfish aquaculture in Australia, insufficient supply of quality seed and unfavourable regulations are the most common barriers. Australia has not had many hatchery businesses while importing seed from other countries is almost impossible thanks to stringent biosecurity regulations. Without a reliable supply of seed, especially of new species, it is impossible to implement more research or to support commercial trials. At the same time, market demand and public interest are not high enough to influence political will, which could help create favourable regulations for aquaculture development. Low profit (or high production cost) and too small industry are the other common barriers. It does take time to obtain economy of scale and improve production efficiencies to ensure profit or stay competitive. Unavailability of production sites (due to regulations and general concerns of the public regarding environmental impacts) and poor proximity to the current major markets are the other barriers. While the former limits expansion, the latter increase logistics costs thus significantly reducing profitability not to mention potential degradation of product quality due to long distance for transportation.
- The selection of finfish species for aquaculture relies on four key variables: market demand, (estimated) profitability, consumer preference and biological attribute. Biological constraints such as slow growth rate is difficult to know when selecting species. A significant proportion of finfish species in Australia do not grow fast enough, thus are less attractive to producers or investors. Aquaculture in other countries often started with the collection of wild animals for grow-out trials. If the performance of wild-caught stock in aquaculture system is acceptable, significant improvements by research could be expected. This practice is not possible in Australia when evaluating new species.
- For Australian producers, competitiveness on global market is limited due to high prices of product while domestic market demand has not grown high enough. Relatively abundant wild-caught and low-cost imported supplies altogether make aquaculture neither necessary (to the public or governors) nor attractive to producers/investors. Market potential indicates how easy or difficult to grow large-scale commercial production. Species with high biological and market potentials should be promoted. In fact, high biological potential ensures farming success and profitability. Enabling technologies only allow to speed up the commercialization process and/or make it more attractive to investors.
- As for future research on finfish, few needs are identified:
    - ✓ More research on new aquaculture site evaluation for existing species (e.g. Atlantic salmon, yellowtail king fish, cobia), economics and policies/regulation research are needed to inform policies makers and the public. Together with market studies and advances in waste management these will help make favourable policies for aquaculture development.

- ✓ Market research and promotion campaign are required for less developed finfish species such as barramundi, cobia and yellowtail king fish or new species like sand whiting, groupers or snubnose pompano.
- ✓ Intensive research on hatchery production in general and more specifically for cobia, and, if selected to promote, stripped trumpeter and pink snapper since technology transfer/adoption is not possible. Consideration for further investment in R&D on stripped trumpeter and pink snapper should be carefully assessed against the biological constrainsts of these two species. Alternatively, research can exlore if these biological constraints are removable.

PART 3: CRUSTACEANS GROUP

3.1. AUDIT OF RESEARCH EFFORT

3.1.1. The audited species

In Australia 12 crustacean species were audited via 22 attempts by scientists. Of these species 41.6% are freshwater including yabbies, redclaw, marrons and black back land crab (Table 32). Species that are currently farmed in Australia include black tiger prawn, banana prawn, redclaw, marrons, yabbies and Moreton Bay bug. Overseas, except the Mantis shrimp *Harpiosquilla harpax* all the other audited species are current farmed at commercial scale (Table 33).

Table 33. Audited finfish species in Australia and aquaculture status

* 2018 production in tonnes (FAO 2020)

No.	Common name	Scientific name	Number of audits	Aquaculture status Australia*
1	Black tiger prawn	*Penaeus monodon*	7	4,205
2	Banana prawn	*Penaeus merguiensis*	1	(inc above)
3	Redclaw	*Cherax quadricarinatus*	4	49
4	Margaret River marron	*Cherax tenuimanus*	1	-
5	Smooth marron	*Cherax cainii*	1	66
6	Yabbies	*Cherax aldidus*	1	-
7	Moreton Bay bug	*Thenus orientalis*	1	-
8	Kuruma prawn	*Penaeus japonicus*	1	-
9	Ornate spiny lobster	*Panulirus ornatus*	1	-
10	Blue swimmer crab	*Portunus armatus*	2	-
11	Mud crab	*Scylla serrata*	1	-
12	Black back land crab	*Gecarcinus lateralis*	1	-

Table 34. Audited finfish species in overseas and aquaculture status

No.	Common name	Scientific name	Number of audits	Audited for country
1	Whiteleg shrimp	*Penaeus vannamei*	5	Vietnam
2	Black tiger prawn	*Penaeus monodon*	3	Vietnam
3	Indian shrimp	*Penaeus indicus*	2	Vietnam
4	Giant freshwater prawn	*Macrobrachium rosenbergii*	3	Vietnam, PICs
5	Redclaw	*Cherax quadricarinatus*	1	Mexico
6	Ornate spiny lobster	*Panulirus ornatus*	1	Vietnam
7	Scalloped spiny lobster	*Panulirus homarus*	1	Vietnam
8	Mud crab	*Scylla paramamosain*	1	Vietnam
9	Mantis shrimp	*Harpiosquilla harpax*	1	Vietnam

*** PICs: The Pacific Island Countries (Fiji, PNG, Vanuatu, Samoa and Cook Islands)

3.1.2. Reasons for species selection

Aquaculture potential of the species and assignment by employer/supervisor are the most common reasons for research on the audited crustacean species (Figure 26). About 27% of the audited researches (on black tiger prawn, mud crab and Margaret River marron) were conducted in response to industry request. Research that follow recommendation of market studies account for only 13% for mud crab and blue swimmer crab. Overseas, aquaculture potential of the candidate species is the most common reason for research (72%). Research prompted by personal interest and by request of funding bodies account for 44 and 33%, respectively. Only 22% of the audited researches were requested by the aquaculture industry.

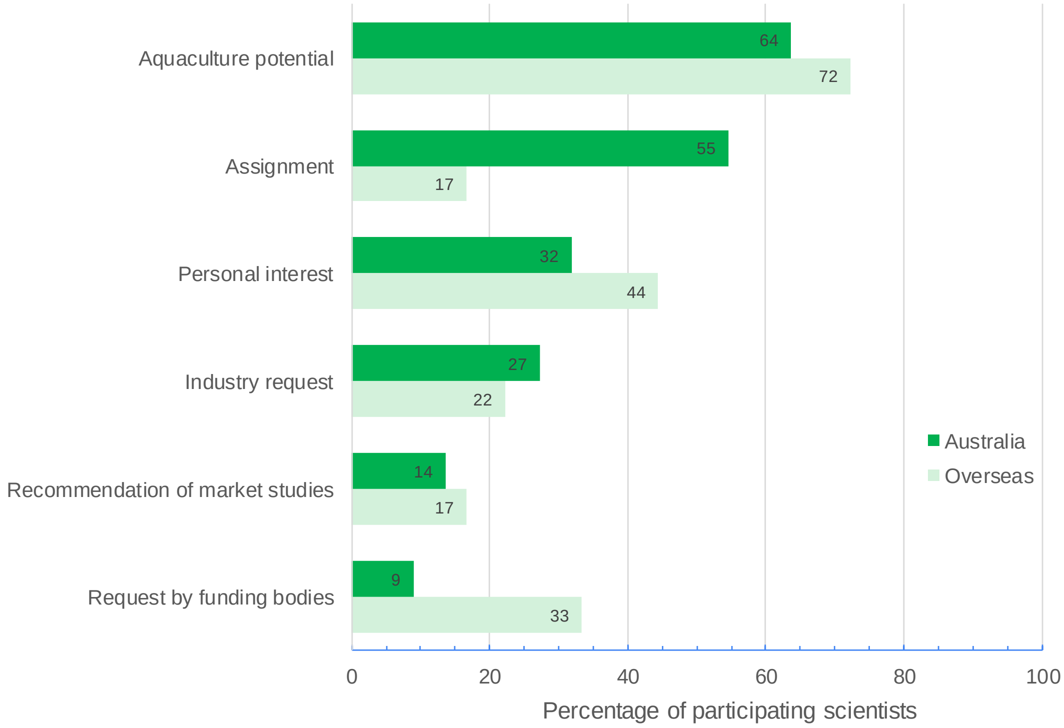


Figure 23. Reasons for species selection for research in Australia (n = 23) and overseas (n = 18)

3.1.3. Current market and consumer's preference

In Australia, all species except the smooth marron are marketed domestically. Species that could be exported include black tiger prawn, kuruma prawn, ornate rock lobster, mud crab and Margaret River marron (Table 34). The percentage of species that could be marketed both domestically and internationally is 45.5%, lower than that overseas (77.8%). Onverseas, redclaw and mantis shrimp are the only two species produced only for domestic markets. Whitelegs shrimp, black tiger prawn and ornate rock lobsters have been exported globally, indicating potential competition with Australian products (Table 35).

Live animals are most preferred by Australian consumers, i.e. for 90% of the audited species in Australia except Moreton Bay bug (Figure 28). Furthermore, fresh products are preferred to frozen ones. Value-added products are species specific, including cooked black tiger prawn and softshell blue swimmer crab or Moreton Bay bug. Overseas, preference for live animals is 100% while that for whole fresh animals is 89%, significantly higher than reported for Australia. Frozen products are less preferred and applicable only for penaeid prawns, giant freshwater prawn and redclaw.

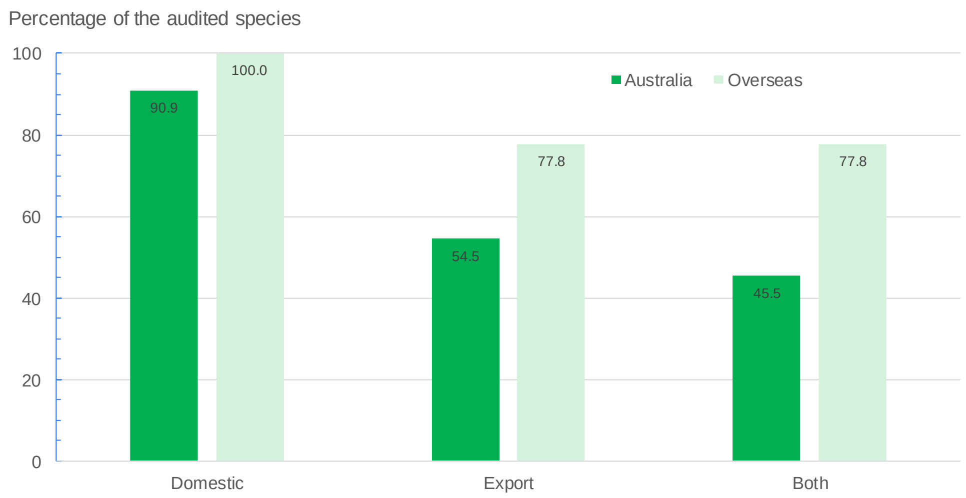


Figure 24. Current markets of the audited crustaceans in Australia and overseas

Table 35. Current market of the audited crustaceans in Australia

No.	Audited species	Local market	National market	Limited export	Globally export
1	Black tiger prawn	■	■	■	
2	Ornate spiny lobster	■	■		■
3	Mud crab	■	■	■	
4	Margaret River marron	■	■	■	
5	Kuruma prawn		■	■	
6	Banana prawn	■	■		
7	Redclaw	■	■		
8	Smooth marron			■	
9	Moreton Bay bug		■		
10	Yabbies		■		
11	Blue Swimmer Crab		■		

Table 36. Current market of the audited crustaceans overseas

No.	Audited species	Local market	National market	Limited export	Globally export
1	Whiteleg shrimp	■	■	■	■
2	Indian shrimp	■	■	■	
3	Black tiger prawn		■		■
4	Giant freshwater prawn		■	■	
5	Scalloped spiny lobster		■	■	
6	Ornate spiny lobster		■		■
7	SA mud crab		■	■	
8	Redclaw		■		
9	Mantis shrimp		■		

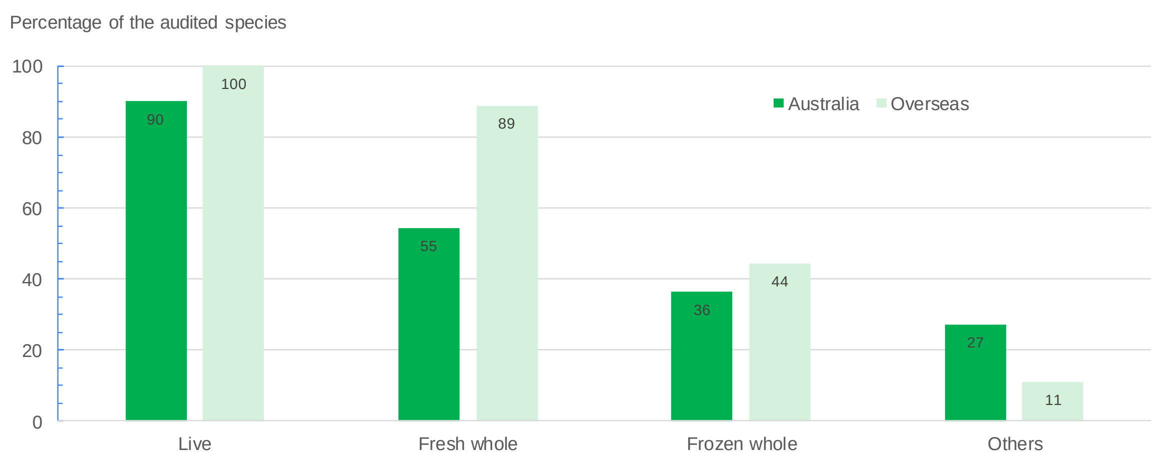


Figure 25. Preferred forms of crustacean products in Australia and overseas

Table 37. Preference diversity index (PDI) of audited crustacean species in Australia. Fresh and frozen means fresh whole and frozen whole

No.	Species	PDI (%)	Preferred form of product			
			Live	Fresh	Frozen	Value-added
1	Black tiger prawn	100				cooked
2	Banana prawn	75				
3	Ornate spiny lobster	75				
4	Blue swimmer crab	75				softshell
5	Moreton Bay bug	75				softshell
6	Redclaw	50				
7	Kuruma prawn	25				
8	Mud crab	25				
9	Yabbies	25				
10	Hairy marron	25				
11	Smooth marron	25				

Table 38. Preference diversity index (PDI) of audited crustacean species overseas. Fresh and frozen means fresh whole and frozen whole.

No.	Species	PDI (%)	Preferred form of product			
			Live	Fresh	Frozen	Value-added
1	Whiteleg shrimp	100				
2	Black tiger prawn	75				
3	Giant freshwater prawn	75				
4	Redclaw	75				
5	Scalloped spiny lobster	50				
6	Indian shrimp	50				
7	Mantis shrimp	50				
8	Southeast Asia mudcrab	50				
9	Ornate spiny lobster	25				

Preference diversity index (PDI – percentage of preferred forms over the four common product forms of crustaceans) is 52.3% on average for the audited crustacean species in Australia (Table 36). Black tiger prawn ranks first with 100% available product forms preferred by the consumers. PDI is 75% for banana prawn, ornate rock lobster, blue swimmer crab and Moreton Bay bug. Five species including kuruma prawn, mud crab, yabbies and marrons are preferred only as live making their PDI only 25%. Overseas, the average PDI is 61.1%. Whiteleg shrimp has the highest PDI, followed by a group of three species: black tiger prawn, giant freshwater prawn and redclaw (Table 37). Ornate spiny lobster is preferred live, making its PDI only 25%. Fresh lobster has very low market prices.

3.1.4. Research history and time effort

In Australia, among the reported research, the earliest one is for tiger prawn back in 1982. Furthermore, more research effort has been spent on black tiger prawn, i.e. 17.4 years/scientist on average significantly higher than what reported for all other species. Research on Moreton Bay bug started in 1992, earlier than that for blue swimmer crab, banana and kuruma prawns and mud crab (1998 – 2001). Compared with other species redclaw, smooth marron and black back land crab could be considered as new candidate species with research starting in 2016 – 2017. Marginal research effort is reported for these species.

Table 39. Research history and effort on the audited crustaceans in Australia

No	Common name	n	Start year	Individual effort (years)	Total years of research
1	Black tiger prawn	7	1982	17.4	122
2	Moreton Bay bug	1	1992	3.0	3
3	Blue swimmer crab	2	1998	6.0	12
4	Yabbies	1	1998	NA	NA
5	Banana prawn	1	1999	3.0	3
6	Kuruma prawn	1	1999	8.0	8
7	Mud crab	1	2001	7.0	7
8	Ornate spiny lobster	1	2009	6.0	6
9	Redclaw	4	2016	2.3	7
10	Smooth marron	1	2016	3.0	3
11	Black back land crab	1	2017	2.0	2

Table 40. Research history and effort on the audited crustaceans overseas

No	Common name	n	Start year	Individual effort (years)	Total years of research
1	Giant freshwater prawn	3	1983	9.7	29
2	Whiteleg shrimp	5	1987	13.4	67
3	Redclaw	1	1994	24.0	24
4	Black tiger prawn	3	2003	8.3	25
5	Ornate spiny lobster	1	2007	1.0	1
6	Indian shrimp	2	2015	3.5	7
7	Scalloped spiny lobster	1	2016	3.0	3
8	Mantis shrimp	1	2008	3.0	3
9	Southeast Asia mud crab	1	1998	10.0	10

Overseas, research on giant freshwater prawn and whiteleg shrimp started earlier than the other species. Significant collective effort is reported for whiteleg shrimp, making it the most successful crustacean species for today aquaculture. Global production of whiteleg shrimp has reached 5.0 million tonnes in 2018 (SOFIA 2020). This must be the results of favourable biological attributes, technological advances (especially breeding programs), profitability (short crop, better cash flow, high density) and market demand for lower price species. Black tiger prawn, ornate spiny lobster and redclaw are the other species that have attracted significant research effort. Research on ornate rock lobster started earlier than that in Australia.

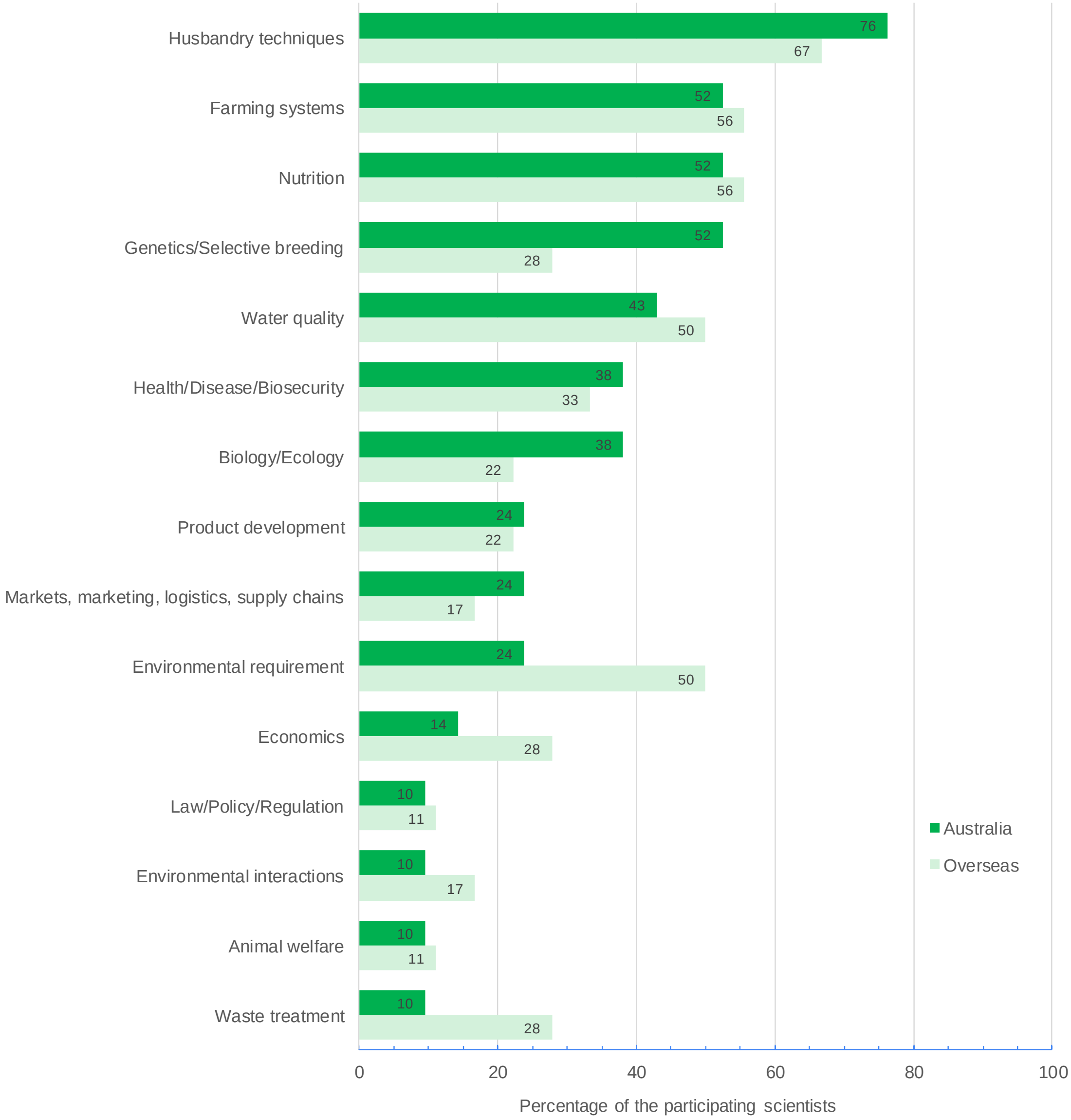


Figure 26. Functional areas targeted by crustacean research in Australia and overseas

3.1.5. Researched functional areas

In Australia, research has focused very much on husbandry techniques (Figure 29). The next three most popular functional areas for research include farming systems, nutrition and genetic/selective breeding. Water quality, health and biology are the other functional areas that have attracted research by 38 – 43% of the participating scientists. However, research attention is minimal on economics, law/policy/regulation, environmental interactions, animal welfare and waste management. Overseas, similar focuses are reported for husbandry techniques, farming systems and nutrition. However, there have been more research interest in environmental requirement, waste management and economics overseas than in Australia. In contrast, research in in genetics/selective breeding and biology/ecology are more limited.

As for specific species research on black tiger prawn in Australia is the most comprehensive one. This species has the highest research comprehensiveness index (RCI) of 100%, almost double that of ornate rock lobster (Table 40). The number of researches audited by this study for black tiger prawn is much more than that for other species. This may explain why black tiger prawn aquaculture is far more advanced than other species. Research on the other species are still fragmented with more focus on areas required for early development stages of aquaculture. It is interesting that research on market-related area has been conducted for three species namely tiger prawn, blue swimmer crab and redclaw. Except for black tiger prawn and ornate spiny lobster all the other species audited in this study still have few gaps for functional areas (3) to (8) which directly relate to aquaculture production (Table 40).

Table 41. Researched functional areas by species in Australia

No	Common name	RCI (%)	Functional areas for research														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Black tiger prawn	100	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
2	Ornate spiny lobster	60		■	■	■	■	■	■	■				■	■		
3	Blue swimmer crab	33			■			■	■				■	■			
4	Smooth marron	33			■	■	■	■		■							
5	Redclaw	27	■	■				■					■				
6	Mud crab	20			■			■	■								
7	Moreton Bay bug	20						■	■	■							
8	Margaret River marron	20		■				■	■								
9	Banana prawn	13	■			■											
10	Kuruma prawn	13		■				■									

(1) biology/ecology, (2) genetics/selective breeding, (3) nutrition, (4) health/disease/biosecurity, (5) environmental requirement, (6) husbandry techniques, (7) farming systems, (8) water quality, (9) waste treatment, (10) animal welfare, (11) markets/marketing/logistics/supply chains, (12) product development, (13) economics, (14) environmental interactions, (15) law/policy/regulation. RCI is Research Comprehensiveness Index calculated as the percentage of researched areas out of total 15 functional areas surveyed.

Table 42. Researched functional areas by species overseas

No	Common name	RCI (%)	Functional areas for research														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Whiteleg shrimp	93	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
2	Redclaw	80	■	■	■		■	■	■	■	■	■	■	■	■		
3	Black tiger prawn	73		■	■	■	■	■	■	■	■				■	■	■
4	Scalloped spiny lobster	47	■		■		■	■	■	■	■						
5	Giant freshwater prawn	27		■			■	■	■								
6	Mantis shrimp	27						■	■				■	■			
7	Ornate spiny lobster	13			■			■									
8	Indian shrimp	13	■			■											
9	SA mud crab	13			■			■									

(1) biology/ecology, (2) genetics/selective breeding, (3) nutrition, (4) health/disease/biosecurity, (5) environmental requirement, (6) husbandry techniques, (7) farming systems, (8) water quality, (9) waste treatment, (10) animal welfare, (11) markets/marketing/logistics/supply chains, (12) product development, (13) economics, (14) environmental interactions, (15) law/policy/regulation. RCI is Research Comprehensiveness Index calculated as the percentage of researched areas out of total 15 functional areas surveyed.

Overseas, whiteleg shrimp *Penaeus vannamei* has the highest RCI (93%), followed by redclaw (80%) and black tiger prawn (73%) (Table 41). However, the number of researches audited in this study for whiteleg shrimp is three times higher than that for redclaw or five times higher than that for lobster.

Accordingly, global production of redclaw is only 20% of that of whiteleg shrimp (SOFIA 2020). For ornate lobster the focus of the audited researchers has been on nutrition and farming systems. This is in agreement with observations that lobster aquaculture overseas is simply the fattening of wild-caught perulii or sub-adults in sea cages using trash fish and other low-value species as feeds. RCI is relatively low (27%) for an established aquaculture species like *Macrobrachium*.

3.1.6. Production stages targeted by research

In Australia, research on the audited species had a clear focus on grow-out stage (73%) (Figure 30). Broodstock domestication and maturation were the next two stages that attract high level of interest. i.e. 59% of the audited research. Larval rearing and nursery stages received lesser attention, but significantly higher than that on harvest, processing and transport stages. Similar focus of research on grow-out stage is also reported overseas. 67% of the audited research target nursery stage, showing how important this stage is in order to support commercial production. Among the three initial stages of production, larval rearing attracts more research (50%) than broodstock domestication (39%) and maturation (44%). Research effort on all post-farming stages has been minimal.

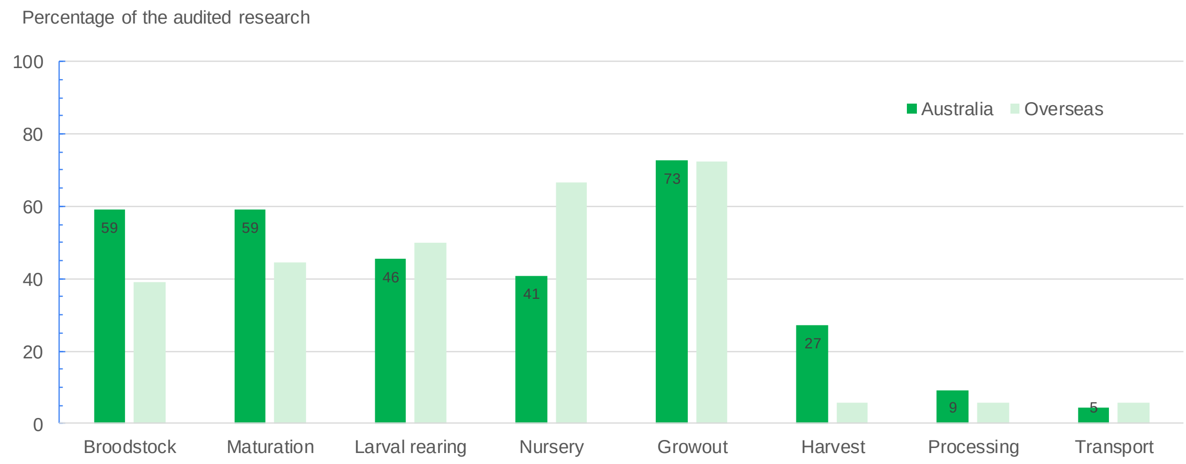


Figure 27. Production stages supported by the audited research in Australia and overseas

As for individual species, research on tiger prawn in Australia have covered all production stages except transportation (Table 43). The production-stage coverage index (PSCI) is highest for this species (88%), followed by that for ornate spiny lobster and blue swimmer crab (75%). Except broodstock domestication research cover all the pre-harvesting stages for mud crab. PSCI for all the other species is low and research has been fragmented. Broodstock maturation, larval rearing and nursery stages are generally not supported by the audited research for redclaw, kuruma prawn, marrons, Moreton Bay bug and yabbies.

Overseas, black tiger prawn and whiteleg shrimp have the highest PSCI of 75%. The difference between these two species is that research has targeted processing for whiteleg shrimp, but transport for black tiger prawn. This is understandable as black tiger prawn is highly preferred for live fish market while a significant amount of farmed whiteleg shrimp is for export. Redclaw ranks third with an PSCI of 63%, but there is a research gap in larval rearing (similar to what reported for Australia) as seen for spiny lobsters and Indian shrimp, which likely hamper further development. PSCI of mudcrab is only 50% but all the essential farming stages are supported.

Table 43. Production stages targeted by research on the audited crustaceans in Australia

(B) broodstock domestication, (M) maturation, (L) larval rearing, (N) nursery, (G) grow-out, (H) harvest, (P) processing, (T) transport. PSCI (%): production-stage coverage index.

No	Common name	PSCI (%)	Production stages (B)	(M)	(L)	(N)	(G)	(H)	(P)	(T)
1	Black tiger prawn	88	■	■	■	■	■	■	■	
2	Ornate spiny lobster	75	■	■	■	■	■			■
3	Blue swimmer crab	75	■	■	■	■	■	■		
4	Mud crab	63		■	■	■	■	■		
5	Banana prawn	50	■	■	■		■			
6	Redclaw	50	■	■			■	■		
7	Kuruma prawn	25	■	■						
8	Hairy marron	25	■				■			
9	Smooth marron	25	■				■			
10	Moreton Bay bug	13			■					
11	Yabbies	13					■			

Table 44. Production stages targeted by research on the audited crustaceans overseas

(B) broodstock domestication, (M) maturation, (L) larval rearing, (F) fingerling production, (G) grow-out, (H) harvest, (P) processing, (T) transport. PSCI (%): production-stage coverage index.

No	Common name	PSCI (%)	Production stages (B)	(M)	(L)	(F)	(G)	(H)	(P)	(T)
1	Black Tiger Prawn	75	■	■	■	■	■			■
2	Whiteleg shrimp	75	■	■	■	■	■		■	
3	Redclaw	63	■	■		■	■	■		
4	Giant Freshwater Prawn	50	■	■	■	■				
5	Southeast Asia mud crab	50		■	■	■	■			
6	Scalloped spiny lobster	38		■		■	■			
7	Indian shrimp	38	■			■	■			
8	Mantis shrimp	25			■	■				
9	Ornate spiny lobster	13				■				

3.1.7. Industrial funding and adoption of research results

Like what reported for the audited finfish species, information about industry adoption of results from crustacean research is limited. Scientists tend of be aware of this only if their research projects had industrial partners or they have involved in technology transfer. The participating scientists report that research results have been adopted largely for kuruma prawn and partly for tiger prawn and ornate spiny lobster. These researches were supported financially by the industry. Funding from FRDC has been made available for the audited research on tiger prawn. Overseas, the participating scientists reported that research results have been adopted largely for giant freshwater prawn. Also, this species was the only one among the audited species received funding from the industry. Unlike Australia, the producers of aquaculture species overseas are mostly growers. The aquaculture industry consists of different segments. A lot of RD&E are carried out by the supporting industries who provide essential inputs for farming such as seeds, feeds, chemicals and equipment or collect raw materials for processing. Thus, growers generally benefit from R&D but not to fund research.

3.2. OPPORTUNITIES FOR FURTHER DEVELOPMENT

3.2.1. Evaluation of species potential

In Australia, Margaret River marron and yabbies rank top on the list with an overall potential score of 280, higher than banana prawn and even black tiger prawn - the major aquaculture species. Among the other species, ornate spiny lobster and banana prawn are better than the rest. However, ornate spiny lobster has excellent market potential. Mud crab and blue swimmer crab do have some limitations in either biological or market potentials. Moreton Bay bug has low potential across all the three different categories.

Table 45. Potential for aquaculture of the audited crustaceans in Australia. Data are percentage of the criteria classified as favourable.

No.	Common name	*n*	Market potential	Biological potential	Enabling factors	Overall potential
1	Yabbies	*1*	100	80	100	280
2	Magaret River marron	*1*	100	80	100	280
3	Banana prawn	*1*	75	60	100	235
4	Black tiger prawn	*7*	89	74	62	225
5	Ornate spiny lobster	*2*	100	50	42	190
6	Mud crab	*1*	75	40	67	182
7	Blue swimmer crab	*2*	38	50	84	171
8	Smooth marron	*1*	100	20	50	170
9	Kuruma prawn	*1*	25	40	83	148
10	Redclaw	*4*	25	40	71	136
11	Moreton Bay bug	*1*	25	0	17	42
12	Black back land crab	*1*	0	0	0	0

Table 46. Potential for aquaculture of the audited crustaceans overseas. Data are percentage of the criteria classified as favourable.

No.	Common name	*n*	Market potential	Biological potential	Enabling factors	Overall potential
1	Redclaw	*1*	100	80	100	280
2	Whiteleg shrimp	*4*	80	56	77	213
3	Black tiger prawn	*3*	92	40	61	197
4	Scalloped spiny lobster	*1*	75	60	50	185
5	Indian shrimp	*2*	63	30	75	168
6	Giant freshwater prawn	*3*	50	33	67	150
7	Southeast Asia mud crab	*1*	75	20	50	145
8	Mantis shrimp	*1*	75	40	17	132
9	Ornate spiny lobster	*1*	100	0	0	100

Overseas, redclaw has the highest potential for commercial aquaculture, even higher than that of whiteleg shrimp or black tiger prawn. There are few noticeable contrasts to the evaluations made by Australian scientists. First, biological potential of black tiger prawn is considered lower (40%) than that in Australia (74%). Second, Indian shrimp (*Penaeus indicus*) a very similar species to banana prawn (*Penaeus merguiensis*) ranks lower than black tiger prawn due to inferior market and biological potentials. Third, ornate spiny lobster *(Panulirus ornatus)* has the lowest potential among the audited species. Scalloped spiny lobster *(Panulirus homarus)* appears to be a better choice than ornate spiny lobster thanks to higher biological potential. Low biological potential significantly reduces the potential for commercial aquaculture of Indian shrimp, giant freshwater prawn, mud crab and mantis shrimp.

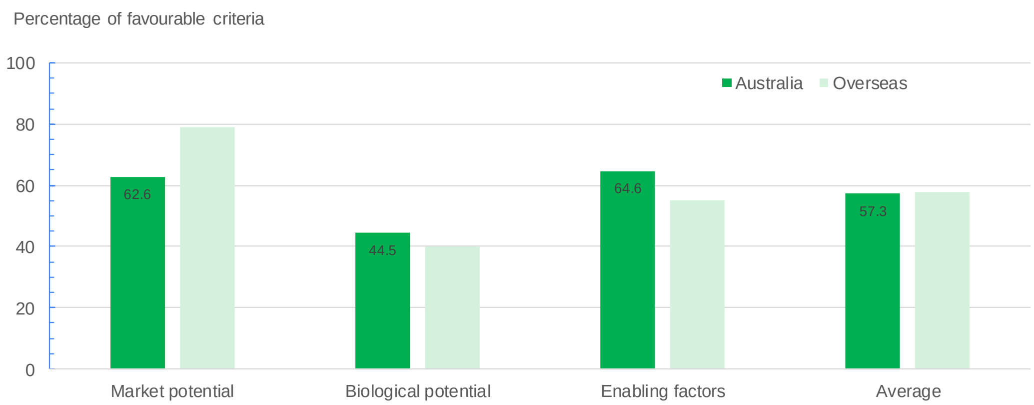


Figure 28: Potential for aquaculture of the audited crustaceans in Australia and overseas

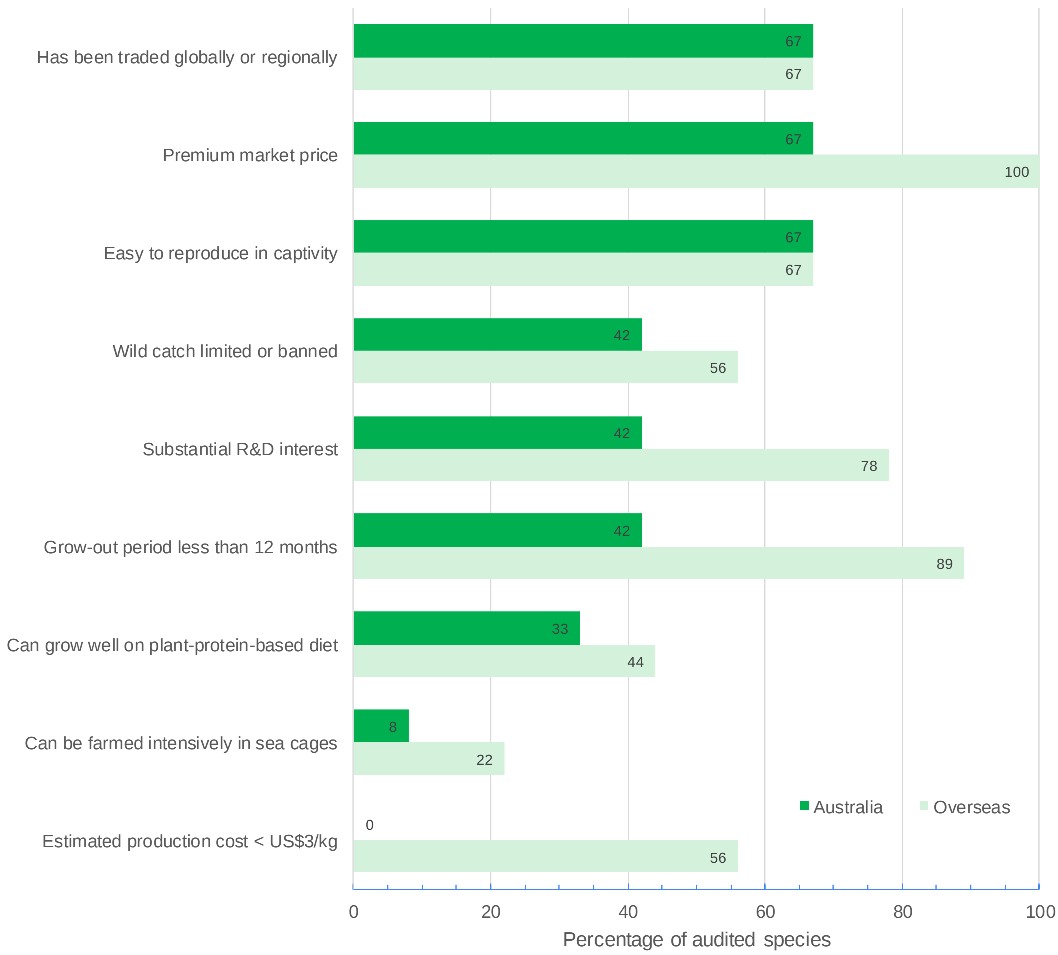


Figure 29. Possession of desirable attributes of the audited species in Australia and overseas

The average potential of 12 audited crustacean species in Australia is 57.3%. Biological potential is lower than market potential (Figure 31). The evaluation of enabling factors indicate favourable conditions for increasing commercial aquaculture production in Australia. Compared with Australia, market potential for the audited species overseas is significantly higher. This may indicate that species selection overseas is more market oriented. Lower evaluation for enabling factors overseas is probably the results of large-scale production of key aquaculture species.

3.2.2. Possession of desirable attributes

The audited crustacean species in Australia are characterized for their high values, export potential, high production cost (i.e. none has estimated production at or lower than US$3.0/kg) and long crop. The most common desirable attributes include premium prices in domestic markets, potential for export markets and easy reproduction in captivity (Figure 32). More than 50% of the audited species have grow-out period longer than 12 months. About 25% of the audited species can grow on plant-protein-based diet namely tiger prawn, redclaw and smooth marron. Only ornate spiny lobster could be farmed in sea cages. Overseas, there are some noticeable differences about the audited species. First, all fetch premium prices in domestic markets. Second, 89% has grow-out less than 12 months, indicating either good growth rate or high turnover or both. Third, 78% are supported by substantial R&D interest. These and low labour cost altogether make the estimated production costs of 56% of the audited species could be as low as US$ 3.0/kg. This is apparently a competitive advantage regarding exportation and, at the same time, a great incentive to producers/investors. The percentage of species that has been traded globally or easy to reproduce in captivity is like what reported for Australia.

As for individual species, black tiger prawn has the highest Desirable Score Index (DSI) of 78%, distinctly higher than all the other audited species in Australia. The only two desirable attributes that black tiger prawn does not have is the option for sea-cage production and low production cost. The next group with a DSI of 56% include redclaw, banana and kuruma prawns, ornate spiny lobster and smooth marron. For ornate spiny lobster growth rate and hatchery production are the two most obvious limitations. DSI is very low for yabbies, Moreton Bay bug and hairy marron. The black back land crab has no desirable attributes.

Table 47. Possession of desirable attributes and desirable score index (DSI) by species

(Re) easy to reproduce in captivity, (Gr) grow-out period less than 12 months, (SC) can be farmed intensively in sea cages, (MP) premium price in domestic markets, (R&D) has attracted substantial R&D interest, (Pt) grow well on plant-protein-based diet, (Wi) wild catch is limited or banned, (PC) estimated production cost less than US$3/kg, (Tr) has been traded regionally or globally.

No	Species	DSI	Desirable attributes								
		(%)	Re	Gr	SC	MP	R&D	Pt	Wi	PC	Tr
1	Black tiger prawn	78	■	■		■	■	■	■		■
2	Redclaw	56	■	■		■		■			■
3	Banana prawn	56	■	■		■			■		■
4	Kuruma prawn	56	■	■		■			■		■
5	Ornate spiny lobster	56			■	■	■		■		■
6	Smooth marron	56	■			■		■	■		■
7	Blue swimmer crab	44	■	■		■	■				
8	Mud crab	44				■	■	■			■
9	Yabbies	22	■								■
10	Moreton Bay bug	11					■				
11	Hairy marron	11	■								
12	Black back land crab	0									

Overseas, the average DSI of those overseas is 64.2%, significantly higher than that of those in Australia (41%). Black tiger prawn, whiteleg shrimp and giant freshwater prawn have the highest DSI of 89% (Table 47). Farming in sea cages is not a viable option yet for the first two species although it has been experimented for whiteleg shrimp. Redclaw and scalloped spiny lobster rank next with a DSI of 67%. Both species have production cost higher than US$ 3.0/kg. Scalloped spiny lobster is less potential than redclaw because of limitations in captive reproduction and utilization of plant-based protein. It should be noticed that DSI of redclaw overseas higher than that in Australia as this species has attracted substantial R&D interest in other countries. Ornate spiny lobster, mud crab and mantis shrimp have lower DSIs compared with the other species.

Table 48. Possession of desirable attributes and desirable score index (DSI) by species

(Re) easy to reproduce in captivity, (Gr) grow-out period less than 12 months, (SC) can be farmed intensively in sea cages, (MP) premium price in domestic market, (R&D) has attracted substantial R&D interest, (Pt) grow well on plant-protein-based diet, (Wi) wild catch is limited or banned, (PC) estimated production cost less than US$3/kg, (Tr) has been traded regionally or globally.

No	Species	DSI	Desirable attributes								
		(%)	Re	Gr	SC	MP	R&D	Pt	Wi	PC	Tr
1	Black tiger prawn	89	■	■		■	■	■	■	■	■
2	Giant freshwater prawn	89	■	■		■	■	■	■	■	■
3	Whiteleg shrimp	89	■	■		■	■	■	■	■	■
4	Scalloped spiny lobster	67		■	■	■	■		■		■
5	Redclaw	67	■	■		■	■	■			■
6	Indian shrimp	56	■	■		■	■				■
7	Ornate spiny lobster	44			■	■	■		■		
8	Southeast Asia mudcrab	44	■	■		■				■	
9	Mantis shrimp	33		■		■				■	

3.2.3. Technology readiness

In Australia, the farming of five species (kuruma prawn, tiger prawn, yabbies, banana prawn and blue swimmer crab) are considered commercially available with Technology Readiness Index (TRI) ranging from 2.8 – 3.0. Farming is technically feasible for ornate spiny lobster, hairy and smooth marron. However, technology development/improvement is still needed for mud crab (grow-out stage), redclaw (nursery and grow-out stages) and Moreton Bay bug (broodstock maturation and spawning). The average TRI of audited species is 2.1, higher than that for finfish species (1.9) in Australia.

Table 49. Technology readiness level for each production stage by species in Australia

No	Common name	*n*	TRI	Technology readiness level							
			(%)	BMA	SPA	LAR	NUR	GRO	HAV	PRO	TRA
1	Kuruma prawn	*1*	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
2	Yabbies	*1*	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
3	Black tiger prawn	*7*	2.9	2.6	2.9	3.0	2.9	3.0	3.0	3.0	3.0
4	Banana prawn	*1*	2.9	3.0	3.0	3.0	3.0	3.0	2.0	3.0	3.0
5	Blue swimmer crab	*2*	2.8	3.0	3.0	3.0	3.0	2.5	2.5	2.0	3.0
6	Mud crab	*1*	2.6	3.0	3.0	3.0	3.0	1.0	2.0	3.0	3.0
7	Ornate spiny lobster	*1*	2.5	2.0	3.0	2.0	2.0	2.0	3.0	3.0	3.0
8	Redclaw	*4*	2.1	2.0	2.0	2.0	1.8	1.8	2.0	2.7	2.5
9	Smooth marron	*1*	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
10	Hairy marron	*1*	1.3	2.0	2.0	2.0	2.0	2.0	-	-	-
11	Moreton Bay bug	*1*	1.0	1.0	1.0	2.0	2.0	2.0	-	-	-
12	Black back land crab	*1*	-	-	-	-	-	-	-	-	-
	Average		**2.1**	1.9	2.0	2.2	2.2	2.1	1.9	1.6	1.3

(BMA) broodstock maturation, (SPA) spawning, (LAR) larval rearing, (FIN) nursery, (GRO) grow-out, (HAV) harvest, (PRO) processing, (TRA) transportation. Technology readiness levels: 3.0 = commercially viable, 2.0 = technically feasible, 1.0 = experimental.

Overseas, the farming of five species (whiteleg shrimp, tiger prawn, Indian prawn, redclaw and giant freshwater prawn) are considered commercially viable. TRI of these species ranges from 2.6 to 3.0. Technology development/improvement is still needed for broodstock maturation of tiger prawn and transportation of giant freshwater prawn. TRI of redclaw is 3.0, significantly higher than that in Australia (2.1) indicating great opportunities for technology transfer. Less advancement is reported for the two tropical rock lobsters and mantis shrimp. Among the 8 production stages, broodstock maturation, transport and processing are all required more technological improvements. Generally, aquaculture technologies for crustaceans overseas are more advanced than Australia reflecting through higher average TRI (2.5).

Table 50. Technology readiness level for each production stage by species overseas

No	Common name	*N*	TRI (%)	Technology readiness							
				BMA	SPA	LAR	NUR	GRO	HAV	PRO	TRA
1	Redclaw	1	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
2	Whiteleg shrimp	5	2.9	3.0	3.0	3.0	3.0	3.0	2.6	2.6	3.0
3	Black tiger prawn	3	2.8	2.3	3.0	3.0	3.0	3.0	2.7	3.0	2.7
4	Indian shrimp	2	2.8	3.0	3.0	3.0	2.5	2.5	2.5	2.5	3.0
5	Giant freshwater prawn	3	2.6	3.0	2.7	3.0	3.0	3.0	3.0	2.0	1.0
6	Southeast Asia mudcrab	1	2.3	-	2.0	3.0	3.0	3.0	2.0	3.0	2.0
7	Ornate spiny lobster	1	1.5	-	2.0	2.0	2.0	3.0	3.0	-	-
8	Scalloped spiny lobster	1	1.4	1.0	2.0	1.0	3.0	2.0	2.0	-	-
9	Mantis shrimp	1	1.4	-	1.0	1.0	2.0	3.0	2.0	-	2.0
	Average		**2.5**	2.0	2.7	2.9	2.8	2.9	2.7	2.3	2.1

(BMA) broodstock maturation, (SPA) spawning, (LAR) larval rearing, (NUR) nursery, (GRO) grow-out, (HAV) harvest, (PRO) processing, (TRA) transportation. Technology readiness levels: 3.0 = commercially viable, 2.0 = technically feasible, 1.0 = experimental.

3.2.4. Potential to adopt existing technologies

Adoption of existing technologies is possible across all different production stages. Adoption rate is production stage dependent, ranging from 27 to 46% of the audited species (Figure 33). Broodstock maturation has the highest rate while broodstock domestication has the lowest rate. Overseas, the potential for adopting existing technologies is much higher, probably thanks to the similarities in biology of the audited species. Grow-out ranks first with an adoption rate of 78% of the audited species, follow by broodstock maturation, nursery and harvest (all at 67%). Larval rearing is the only production stage with limited potential (33%).

In Australia, adoption of existing technology is possible for 6/11 audited species (Table 50). Tiger prawn, banana prawn and blue swimmer crab all rank top on the list with a PAETI of 100%. Less potential is reported for Moreton Bay bug (PAETI of 50%) and ornate spiny lobster stay (PAETI of 38%). Between these two species, technology adoption is possible for the four more important production stages (i.e. maturation, larval rearing, nursery and grow-out) for Moreton Bay bug, but not for the ornate spiny lobster probably. This is probably because of the unique biological requirements of ornate spiny lobster. Potential for technology adoption restricts to only broodstock maturation stage for redclaw. Species that have no recommendation for technology adoption probably warrant more research.

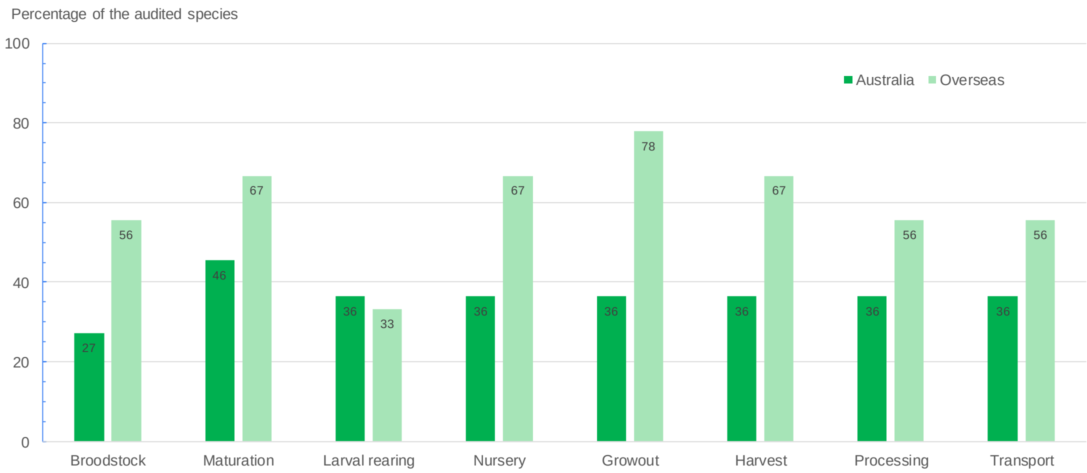


Figure 30. Potential for adoption of existing technologies across different production stages of the audited crustaceans in Australia and overseas

Table 51. Production stages targeted by research on the audited crustaceans in Australia and potentially benefited from technology adoption

(B) broodstock domestication, (M) maturation, (L) larval rearing, (N) nursery, (G) grow-out, (H) harvest, (P) processing, (T) transport. PAET (%): potential for adoption of existing technologies index

No	Species	PAETI (%)	Production stages							
			(B)	(M)	(L)	(N)	(G)	(H)	(P)	(T)
1	Black tiger prawn	100								
2	Banana prawn	100								
3	Blue swimmer crab	100								
4	Moreton Bay bug	50								
5	Ornate spiny lobster	38								
6	Redclaw	13								
7	Kuruma prawn	-								
8	Mud crab	-								
9	Yabbies	-								
10	Margaret River marron	-								
11	Smooth marron	-								

Table 52. Production stages targeted by research on the audited crustaceans in Australia and potentially benefited from technology adoption

(B) broodstock domestication, (M) maturation, (L) larval rearing, (N) nursery, (G) grow-out, (H) harvest, (P) processing, (T) transport. PAET (%): potential for adoption of existing technologies index

No	Species	PAETI (%)	Production stages							
			(B)	(M)	(L)	(N)	(G)	(H)	(P)	(T)
1	Black Tiger Prawn	100								
2	Whiteleg shrimp	100								
3	Indian shrimp	100								
4	Giant Freshwater Prawn	88								
5	Redclaw	88								
6	Scalloped spiny lobster	38								
7	Mantis shrimp	25								

8	Ornate spiny lobster	-									
9	Southeast Asia mud crab	-									

Overseas, technology adoption is possible for 7/9 audited species. PAETI is 100% for whiteleg shrimp and Indian prawn or 88% for giant freshwater prawn and redclaw (Table 51). There is no potential for technology adoption for larval rearing stage of the last two species and scalloped spiny lobster. Potential for technology adoption is suggested for three production stages scalloped spiny lobster: broodstock maturation, nursery and grow-out. The latter two stages are enough to increase commercial aquaculture production using wild-caught perulii as being practised these days. Technology adoption for Mantis shrimp is small and not possible for ornate spiny lobster and Southeast Asia mud crab.

3.3. Barriers to development

3.3.1. Identified barriers

Insufficient supply of quality seed is the top barrier for crustacean aquaculture in Australia (i.e. for 57% of the audited species), followed by increasing threat of infectious diseases (for 43% of the audited species) (Figure 34). The other major barriers include limited sites for production, unfavourable regulations and too-small industries. Poor growth, limited funding for R&D and high production are a few more barriers.

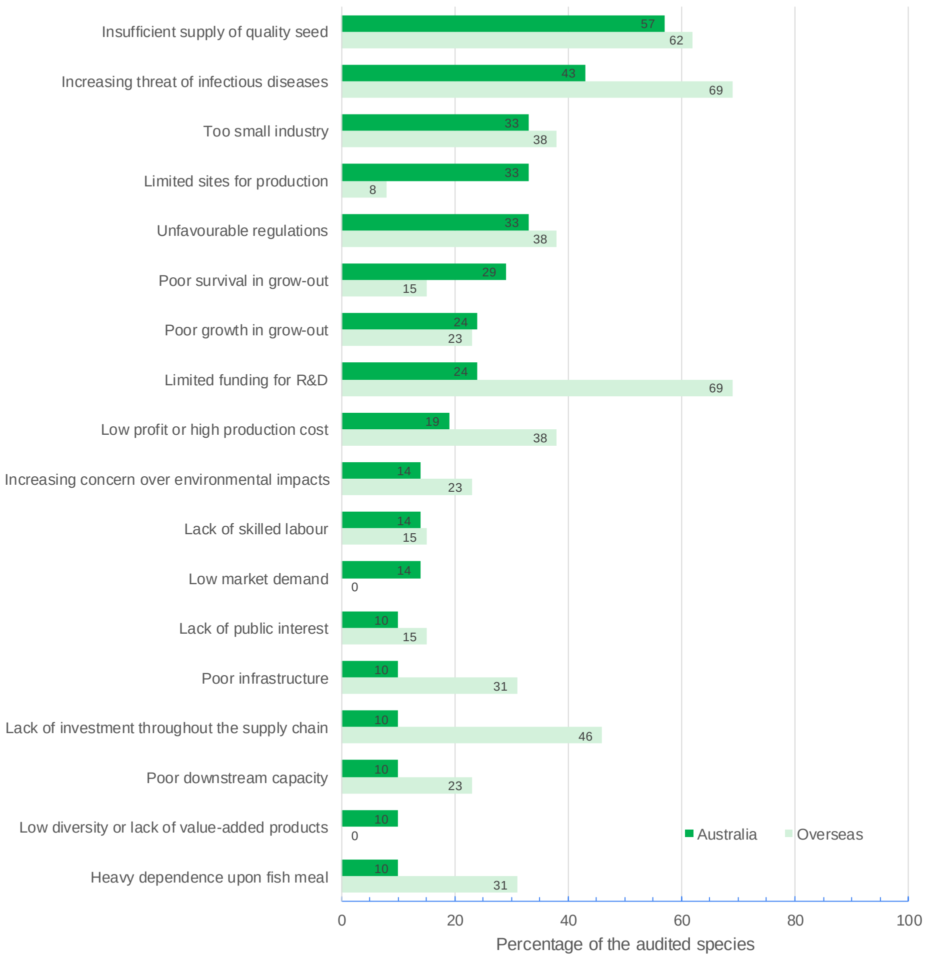


Figure 31. Identified barriers to development of crustacean aquaculture in Australia and overseas

Table 53. Barriers to aquaculture development of the audited crustacean species in Australia

No	Common name	n	BI (%)	Barriers to development																	
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Black tiger prawn	7	72	■	■		■	■	■	■	■	■			■	■	■	■	■		
2	Smooth marron	1	39	■			■			■			■						■	■	■
3	Ornate spiny lobster	2	39					■	■	■	■				■					■	■
4	Blue swimmer crab	2	33			■	■		■			■								■	■
5	Mud crab	1	33			■	■	■				■								■	■
6	Redclaw	4	28		■				■			■	■	■							
7	Banana prawn	1	22							■		■						■	■		
8	Kuruma prawn	1	22		■	■						■								■	
9	Moreton Bay bug	1	17							■									■		■
10	Margaret River marron	1	17	■												■	■				
11	Yabbies	1	11							■					■						
		Ave	**30.3**																		

n: number of audits;

BI (%): barriers index, i.e. percentage of the number of identified barriers over 18 pre-defined ones;

(1): Unfavourable regulations; (2) Low market demand; (3) Low profit or high production cost;

(4) Limited sites for production; (5) Lack of skilled labour; (6) Increasing threat of infectious diseases;

(7) Insufficient supply of quality seed; (8) Heavy dependence upon fish meal; (9) Too small industry;

(10) Low diversity or lack of value-added products; (11) Poor downstream capacity; (12) Increasing concern over environmental impacts;

(13) Lack of investment throughout the supply chain; (14) Poor infrastructure; (15) Lack of public interest;

(16) Limited funding for R&D; (17) Poor growth in grow-out; (18) Poor survival in grow-out;

Table 54. Barriers to aquaculture development of the audited crustacean species overseas

No	Common name	n	BI (%)	Barriers to development																	
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Whiteleg shrimp		61	■		■			■	■	■			■	■	■	■		■		■
2	Giant freshwater prawn		44			■		■		■	■	■		■			■		■		
3	Black tiger prawn		39					■	■	■		■		■		■				■	
4	Indian shrimp		39	■			■			■		■						■	■	■	
5	Scalloped spiny lobster		33	■					■	■						■			■		■
6	Redclaw		28	■						■		■				■			■		
7	Ornate spiny lobster		22						■	■					■				■		
8	Southeast Asia mud crab		17				■					■	■								
9	Mantis shrimp		11							■		■									
		Ave	**32.7**																		

n: number of audits;

BI (%): barriers index, i.e. percentage of the number of identified barriers over 18 pre-defined ones;

(1): Unfavourable regulations; (2) Low market demand; (3) Low profit or high production cost;

(4) Limited sites for production; (5) Lack of skilled labour; (6) Increasing threat of infectious diseases;

(7) Insufficient supply of quality seed; (8) Heavy dependence upon fish meal; (9) Too small industry;

(10) Low diversity or lack of value-added products; (11) Poor downstream capacity; (12) Increasing concern over environmental impacts;

(13) Lack of investment throughout the supply chain; (14) Poor infrastructure; (15) Lack of public interest;

(16) Limited funding for R&D; (17) Poor growth in grow-out; (18) Poor survival in grow-out;

Overseas, increasing threat of infectious diseases, limited funding for R&D and insufficient supply of quality seed are the most common barriers. There are few other differences that should be noticed when compared with Australia. Market demand and product diversity are not barriers. Only 8% of the audited species has problem with limited production sites. Barriers like low profit, poor infrastructure and poor investment are more significant overseas than in Australia.

As for individual species in Australia tiger prawn has the highest BI of 72% (Table 52). Increasing threat of infectious diseases, insufficient supply of quality seed, unfavourable regulations and limited site for production are the barriers to further development of black tiger prawn aquaculture. BIs of smooth marron, ornate spiny lobster, blue swimmer crab, mud crab, and redclaw are lower, ranging from 28 to 39%. Poor grow-out performance (growth, survival), limited site for production and too-small industry are the common barriers of these species. Yabbies, Moreton Bay bug, Margaret River marron and kuruma prawn have less barriers to further development. Insufficient supply of quality seed is the most common barrier for these species. In addition, poor survival in grow-out and unfavourable regulations are identified as barrier for commercial aquaculture of Moreton Bay bug and smooth marron, respectively. Lack of funding for R&D is considered as a barrier for black tiger prawn, banana prawn, smooth marron and Moreton Bay bug.

Overseas, whiteleg shrimp ranks top on the list with a DI of 61%, lower than that for tiger prawn in Australia (Table 53). For whiteleg shrimp, low profit and increasing threat of infectious diseases are the two major barriers for further development. Giant freshwater prawn and black tiger prawn still have several barriers to further development. For giant freshwater prawn lack of funding for R&D and low profit are identified as the barriers. Black tiger prawn has a DI of 39%, only half of what reported for Australia. This species has similar barriers as for whiteleg shrimp. However, market demand for black tiger prawn is still high. Farming of ornate spiny lobster is less challenging overseas. It is noticeable that 100% of audited species overseas have problem with insufficient supply of quality seed while 86% have received limited funding for R&D.

3.3.2. Availability of required inputs for commercial production

A review of input availability can help explore both barriers and opportunities for commercial aquaculture of a certain aquaculture species. Finance and site for production site are only highly accessible to 17% of the audited crustacean species in Australia. Domesticated broodstock, seeds and grow-out feeds are the other required inputs that can be highly accessible for 33% of the audited species. These five inputs are all essential to commercial aquaculture. This observation probably helps explain why crustacean aquaculture in Australia has not developed fast to capitalize premium prices and good demand. Overseas, more species can easily access to site for production and grow-out feeds while finance availability is similarly a constraint. The percentage of audited species that can easily access to the other inputs are either lower or similar to what reported to Australia. This is probably because of much larger scales of commercial aquaculture of crustaceans overseas.

As for individual species, black tiger prawn and banana prawn have the highest HAIs, explaining why commercial aquaculture production of these two species have been established in Australia (Table 54). All the other audited species have significantly lower HAIs. These species have more challenges for development due to poorer availability of domesticated broodstock, seed and site for production. Overseas, similar trends are observed. Whiteleg shrimp farming has high accessibility to all the required inputs. That’s why its commercial aquaculture production has exceeded 5 million tonnes globally recently (SOFIA 2020). All the other audited species have some limitations for further development, particularly those that have poorer availability of domesticated broodstock and seeds. Compared with giant freshwater prawn, Indian shrimp and reclaw black tiger prawn aquaculture has less challenges, but accessibility to technical support for this species is poor, indicating low level of research effort.

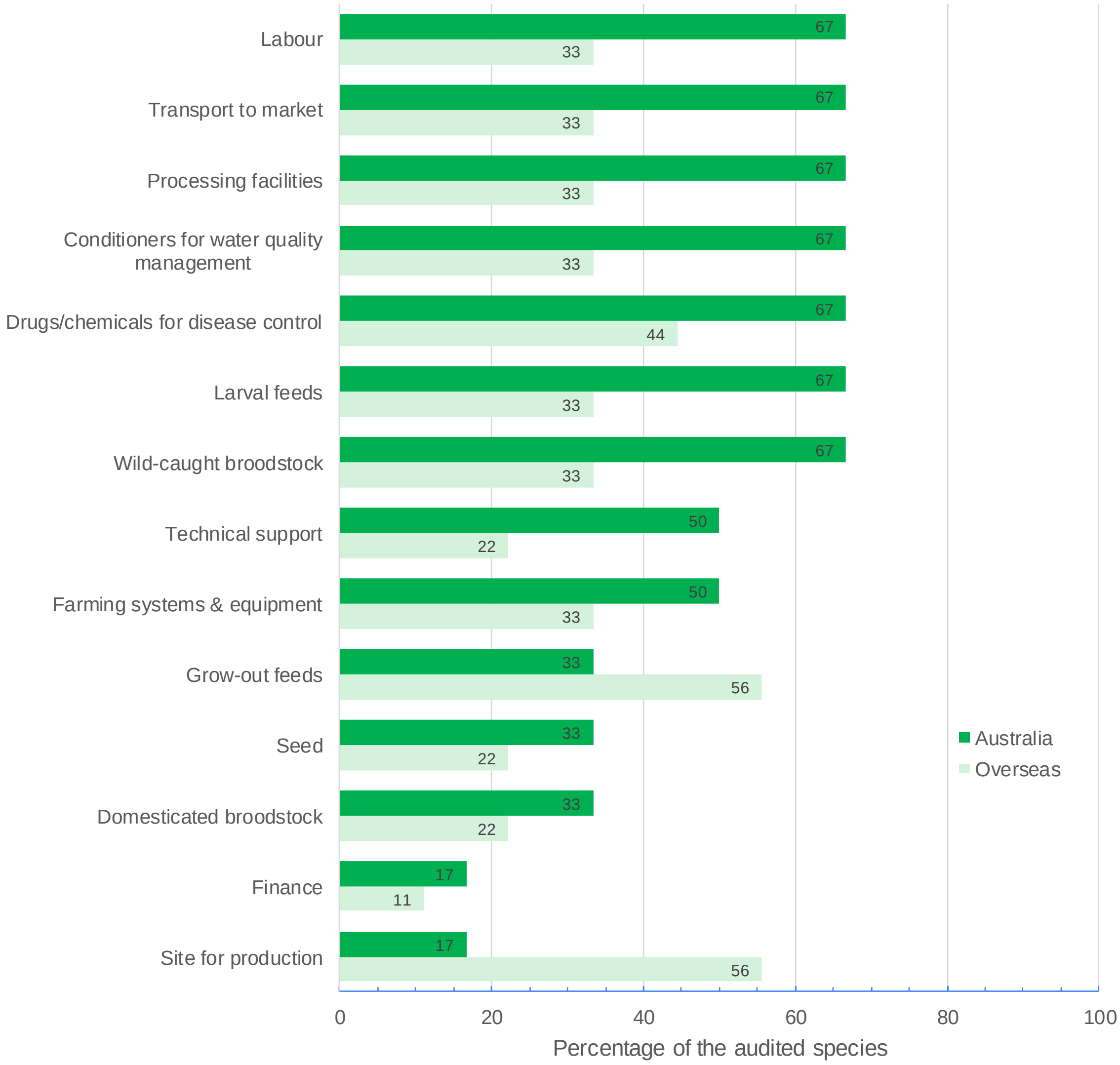


Figure 32. High availability rate of required inputs for commercial aquaculture production of the audited crustacean species in Australia and overseas

Table 55. Availability of required inputs for farming of finfish species in Australia

a: available, ha: highly accessible, AI(%): availability index, HAI(%): high accessibility index; (1) site for production, (2) wild-caught broodstock, (3) domesticated broodstock, (4) seeds, (5) larval feeds, (6) grow-out feeds, (7) drugs/chemicals for disease control, (8) conditioners for water quality management, (9) farming systems & equipment, (10) processing facilities, (11) transport to markets, (12) labour, (13) finance, (14) technical support

No	Audited species	HAI (%)	AI (%)	Required inputs for farming													
				1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Black tiger prawn	93	7	a	ha	ha	ha	ha	ha	ha	ha	ha	ha	ha	ha	ha	ha
2	Banana prawn	71	29	ha	ha	a	a	ha	ha	ha	ha	ha	ha	ha	ha	a	a
3	Blue swimmer crab	43	43	a	ha	a	a	ha	a			a	ha	ha	ha	a	ha
4	Mud crab	36	36	a	ha		a	a	a			a	ha	ha	ha		ha
5	Kuruma prawn	29	50		a		a	ha	a	ha	ha	ha	a	a	a		a
6	Ornate spiny lobster	14	64	a	a	a				ha	ha	a	a	a	a	a	a
7	Margaret R marron	14	21			ha	ha					a	a	a			

				1	2	3	4	5	6	7	8	9	10	11	12	13	14
8	Smooth marron	0	100	a		a	a	a	a			a	a	a			
9	Redclaw	0	57	a	a	a	a	a	a	a	a	a	a	a	a	a	a

Table 56. Availability of required inputs for farming of finfish species overseas

a: available, ha: highly accessible, AI(%): availability index, HAI(%): highly accessibility index; (1) site for production, (2) wild-caught broodstock, (3) domesticated broodstock, (4) seeds, (5) larval feeds, (6) grow-out feeds, (7) drugs/chemicals for disease control, (8) conditioners for water quality management, (9) farming systems & equipment, (10) processing facilities, (11) transport to markets, (12) labour, (13) finance, (14) technical support

No	Audited species	HAI (%)	AI (%)	Required inputs for farming													
				1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Whiteleg shrimp	100	0	ha	ha	ha	ha	ha	ha	ha	ha	ha	ha	ha	ha	ha	ha
2	Indian shrimp	71	29	ha	ha	a	a	ha	ha	ha	ha	ha	ha	ha	ha	a	a
3	Redclaw	64	29	ha	a	a	a		ha	ha	ha	ha	ha	ha	ha	a	ha
4	Black tiger prawn	43	43	ha	ha	ha	ha	ha	ha	a	a	a	a	a	a		
5	Giant freshw. prawn	14	79	ha	a	a	a	a	a	ha	a	a	a	a	a		a
6	Scalloped spiny lobster	7	79	a	a	a	a		ha	a	a	a		a	a	a	a
7	Ornate spiny lobster	0	50	a					a		a	a	a	a	a		
8	Mantis shrimp	0	64	a	a		a	a	a	a	a	a		a			
9	SA mud crab	0	79	a	a		a	a	a	a	a	a		a	a		a

3.4. FUTURE RESEARCH

3.4.1. Research intention

In Australia 75% of the participating scientists confirm to continue research on crustaceans, higher than that for the audited finfish species. Of those who plan to do more research on crustaceans 67% request funding from FRDC while 83% would like to seek for industrial partners. About 19% of the participating scientists do not plan for further research on kuruma prawn, mud crab and blue swimmer crab (see Appendix 2). Overseas, all the participating scientists either confirm their future research on crustaceans or express they may. The needs for funding for R&D and partnership development with industrial partners are also as high as reported for Australia.

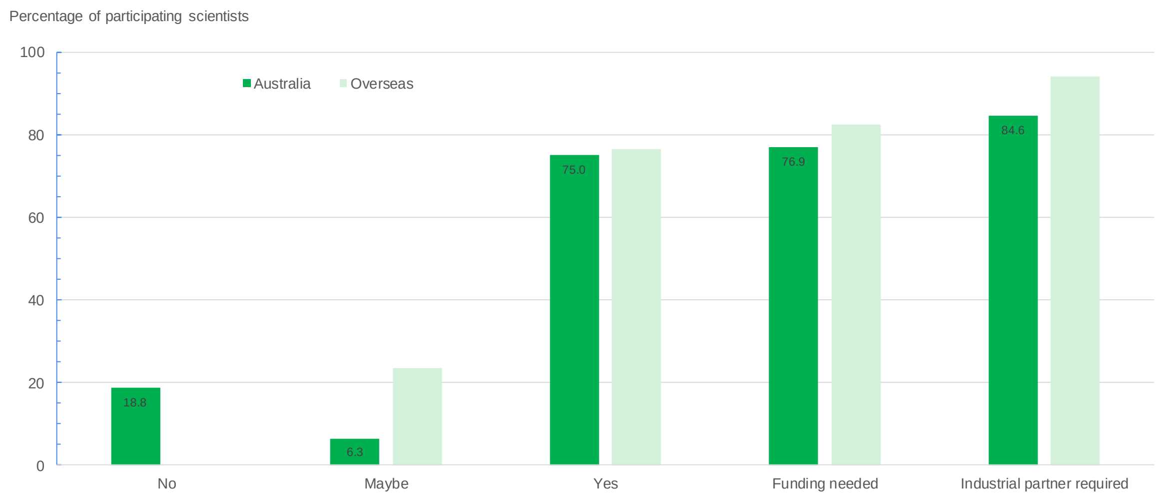


Figure 33. Intention for future research on crustacean species and requests for support

3.4.2. Functional areas that still require substantial effort

In Australia, research on nutrition is highly recommended, followed by those on genetics/selective breeding (Figure) for five species including black tiger prawn, banana prawn, ornate rock lobster, blue swimmer crab and redclaw (Table). Research on husbandry techniques, farming systems and health are the other major functional areas recommended by the participating scientists. Similar trends are reported overseas for 9 species. Nutrition and genetics/selective breeding receive the highest number of recommendations. Other important areas include husbandry techniques, health and farming systems.

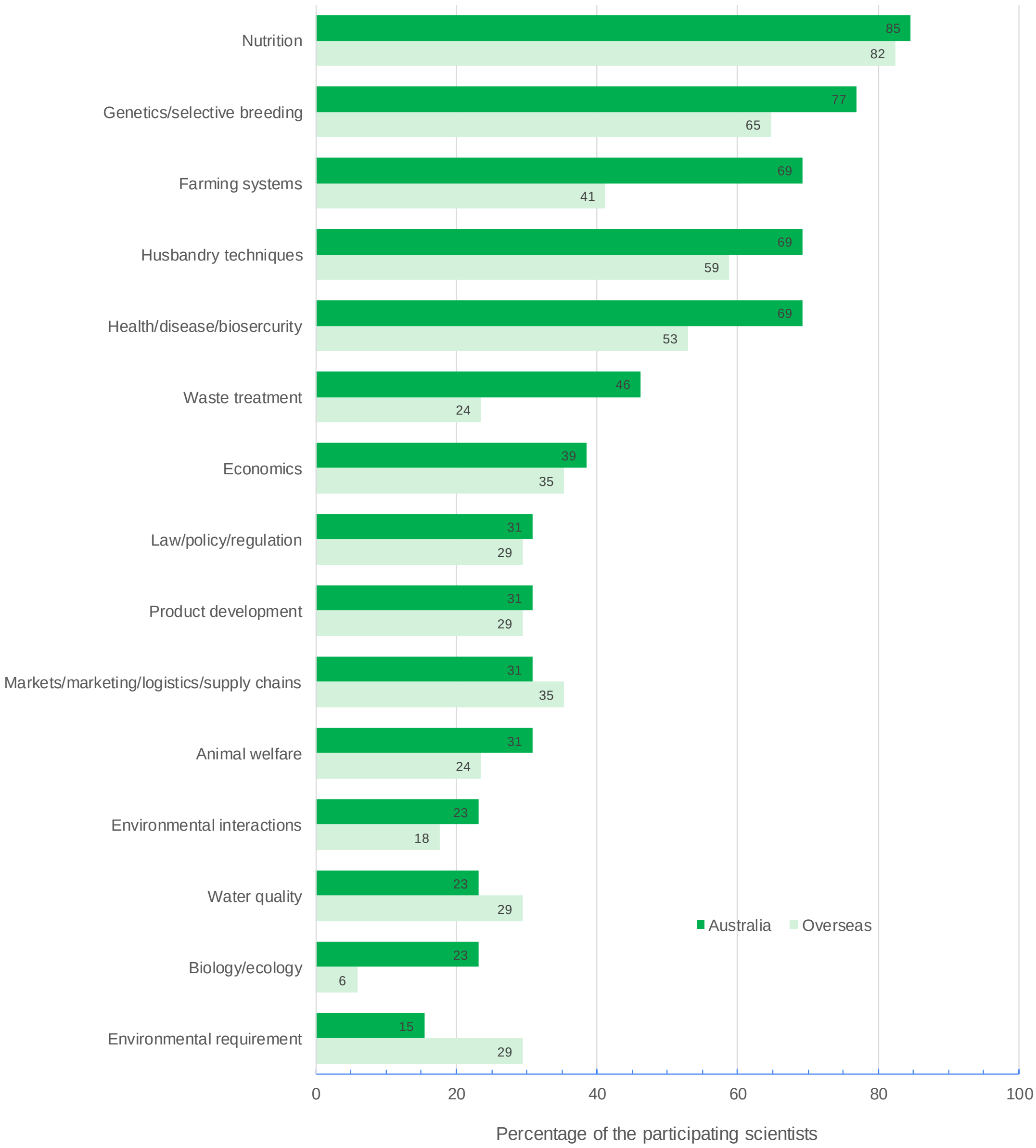


Figure 34. Functional areas that require substantial research effort to develop crustacean aquaculture in Australia and overseas

Research demand is highest for black tiger prawn in all functional areas (Table 56). Its RDI is 100%. Ornate spiny lobster and blue swimmer crab are the next two species that require more research. Both species have an RDI of 40%. The four common areas for these two species are genetics/selective breeding, nutrition, health/disease/biosecurity and economics. While research on husbandry techniques and farming systems are in need for ornate spiny lobster, that for blue swimmer crab rests with markets/marketing/logistics/supply chains and product development. For redclaw the participating scientist recommends more research on fundamental areas such as biology/ecology, genetics/selective breeding and nutrition and on market-end ones such as product development and economics. No research is recommended for kuruma prawn (due to unreliable market demand) and mud crab.

Overseas, research demand is highest for all the major aquaculture species: whiteleg shrimp, black tiger prawn and giant freshwater prawn (Table 57). Recommendations for research on redclaw and scalloped spiny lobster have few overlaps with what recommended for these two species in Australia. Only nutrition research is recommended for ornate spiny lobster.

Table 57. Functional areas requiring substantial research effort by species in Australia

No	Species	RDI (%)	Functional areas for research														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Black tiger prawn	100	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
2	Ornate lobster	40		■	■	■		■	■						■		
3	Blue swimmer crab	40		■	■	■							■	■	■		
4	Banana prawn	33		■	■			■	■				■				
5	Redclaw	33	■	■	■									■	■		

(1) biology/ecology, (2) genetics/selective breeding, (3) nutrition, (4) health/disease/biosecurity, (5) environmental requirement, (6) husbandry techniques, (7) farming systems, (8) water quality, (9) waste treatment, (10) animal welfare, (11) markets/marketing/logistics/supply chains, (12) product development, (13) economics, (14) environmental interactions, (15) law/policy/regulation. RDI is Research Demands Index calculated as the percentage of researched areas out of total 15 functional areas surveyed.

Table 58. Functional areas requiring substantial research effort by species overseas

No	Common name	RDI (%)	Functional areas for research														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Black tiger Prawn	93		■	■	■	■	■	■	■	■	■	■	■	■	■	■
2	Giant freshwater prawn	93		■	■	■	■	■	■	■	■	■	■	■	■	■	■
3	Whiteleg shrimp	93		■	■	■	■	■	■	■	■	■	■	■	■	■	■
4	Indian shrimp	47		■	■	■	■	■	■				■				
5	Scalloped spiny lobster	40	■	■	■	■		■	■								
6	Redclaw	33			■			■					■	■			■
7	Mantis shrimp	13		■	■												
8	SA mud crab	13		■	■												
9	Ornate lobster	7			■												

(1) biology/ecology, (2) genetics/selective breeding, (3) nutrition, (4) health/disease/biosecurity, (5) environmental requirement, (6) husbandry techniques, (7) farming systems, (8) water quality, (9) waste treatment, (10) animal welfare, (11) markets/marketing/logistics/supply chains, (12) product development, (13) economics, (14) environmental interactions, (15) law/policy/regulation. RCI is Research Demands Index calculated as the percentage of researched areas out of total 15 functional areas surveyed.

3.5. REMARKS

- Excluding the once farmed kuruma prawn seven out of the 12 audited species are commercially farmed in Australia. Overseas, this figure is even higher, i.e. 89% of the audited species. Thus, this finding may imply higher commercialization rate or potential for aquaculture of crustaceans compared with finfish. However, the aquaculture industry is currently dominated by just one species – the black tiger prawn. The other species, although have been farmed commercially, still have limited production. These species nonetheless have higher market demands, especially for export. Thus, RD&E should aim to boost production of species that have greater demand for export markets (e.g. redclaw and ornate spiny lobster) or domestic markets (e.g. redclaw, mud crab and soft-shelled blue swimmer crab) (see Part 6).

- Crustacean aquaculture is characterized for its high value products. Thus, it is easier to start farming even with very small production. Market development could naturally start from serving local demand. Once production is sufficiently large and consistent, the product could be marketed either nationally or internationally. This study also confirms the most preferred form of product is live animals for crustaceans. Preference for live animals appears much stronger overseas. Thus, research on harvesting, live transport, holding systems, quality assurance and provenance could be in great demand as Australia is a large country and export to premium markets is an attractive option for producers/traders. Adoption of existing technologies should be considered as live crustacean markets are much more popular overseas. Several species such as marrons, yabbies, redclaw, mud crab and blue swimmer with similar biology regarding holding and live transport could benefit from such studies. Our audits on how past researches support different stages of production of crustaceans also reveal huge gaps in harvest, processing and transport.
- This study reveals that major aquaculture species have attracted more research, i.e. black tiger prawn and redclaw in Australia; whitleg shrimp, black tiger prawn and giant freshwater prawn overseas. Thus, aquaculture industry needs to reach a certain scale to drive research interest or fund research activities. Development of new species for aquaculture have been popularly initiated by governmental agencies in partnership with investors or when the farming of existing species had some serious problems and producers were forced to change or diversify aquaculture species.
- Research on crustaceans started quite early in Australia, but aquaculture production has not increased at the pace observed in many other countries. This clearly imply that research alone can't create or boost commercial production. In terms of functional area, research on crustaceans in Australia have focused on husbandry techniques and, to a lesser extent, nutrition, genetics/selective breeding and farming systems. Important areas like economics, policy/regulation, waste treatment, animal welfare and environmental interactions attracted limited interest of scientist. Coincidentally, these are related to the identified barriers to further development of crustacean aquaculture. Research gaps on genetics (to support selective breeding program), nutrition, health and water quality management are also identified through this study for many species except black tiger prawn and ornate spiny lobster. Regarding production stages, more attention is required for nursery, larval rearing and broodstock maturation
- This study identifies insufficient supply of quality seed as the most common barrier to further development. Seed is absolutely the first input required for farming once the production site and farming system are available. Insufficient seed supply for stocking could be the result from lack of inputs (domesticated broodstock, feeds, conditioners) or low efficiencies of hatchery production. These challenges have been reported for a group consists of yabbies, redclaw and marrons via an FRDC snap-shot survey in 2017 (see Appendix 2). Further research on hatchery production is thus needed. Technology adoption may play an important role since crustacean aquaculture is generally more advanced overseas. A wide range of advanced technologies and quality-proven inputs for hatchery production of penaeid prawns and giant freshwater prawns should be seriously explored. As global production of redclaw is far higher than that in Australia, similar approach of screening suitable technologies/inputs should be applied for this species. Besides, insufficient supply of quality seed indicates the lack of centralized hatchery system to support small scale producers, who can't afford to operate their own hatcheries or domestication/breeding programs. This barrier can be removed through more development and extension rather than simply research. Investors

should be introduced to these opportunities and supported adequately to supply this growing industry with good broodstock and seeds.

- The other major barriers to crustacean aquaculture development in Australia include increasing risk of diseases, too small industry and unfavourable regulations (related to the import of crustaceans from overseas and licensing new farms or new production sites). Increasing risk of diseases is common if farming is intensified or the industry has reached a scale that is large enough for diseases to emerge and spread as seen in many other countries (Flegel *et al.* 2019). Removing this barrier is, however, highly feasible using the know how and preventive measures that have established overseas. Australia is even in a much better position thanks to its geographical separation from other continents and strict biosecurity regulations. However, balancing imports with growing local industries or granting more licenses/sites for aquaculture do require policy reform. Research on economics, supply chains and policies development are thus of prime importance and should have the priority in the near future.
- As for individual species, black tiger prawn should have the priority for further development. This is to exploit a substantial R&D capital for this species which have accumulated over many years. Furthermore, Australia is one of just a few countries that still produce black tiger prawn today. Many other countries have switched to farming the whiteleg shrimp. Technically, the top barrier for black tiger prawn farming in Australia is the lack of a national breeding program to supply specific-pathogen-free or ideally disease resistant broodstock to the producers. The root cause of this delay is that the prawn industry has remained too small in scale, making investment in long-term breeding program not cost-effective. One way to increase production and at the same time demand for postlarvae (to justify the cost of domestication/breeding program) is to consider extensive farming of black tiger prawn in Northern and/or Western Australia. Irvin *et al.* (2018) and CRCNA (2020) have identified massive area suitable for prawn farming there. Extensive farming of prawn is typical for low stocking densities (0.5 – 2.0 pcs/m^2) with no feeding nor energy required, thus almost no environmental impacts. It has been practised for many years in Southeast Asia and South America. Although productivity remains low, ranging from 200 – 500 kg/ha/year, this could be significantly enhanced up to 2,000 kg/ha/crop. Products, if well promoted, could be considered as organic and fetch for very high prices in premium export markets (US$ 200 – 300/kg). The other species that should be promoted for aquaculture include banana prawn, redclaw, ornate spiny lobser, Margaret River marron and mud crab. The farming of these species is either commercially viable or technically feasible. Better supply of quality seed for stocking, development of good diets and cost-effective recirculation aquaculture system (RAS) to satisfy current licensing requirements could result in instant increase of production. The results can be amplified if market research and promotion campaigns are conducted to encourage consumptions both domestically and in targeted markets such as China, Hong Kong, Taiwan, EU, Japan and North America.

PART 4: MOLLUSCS GROUP

4.1. AUDIT OF RESEARCH EFFORT

4.1.1. The audited species

Twelve species in Australia and four others overseas were audited by scientists for this study. All the audited species are marine. Australian and overseas species are all different. In Australia, species that have been farmed commercially by many producers include Sydney rock oyster and Pacific oyster (Table 58). Few producers are producing abalones, Native rock oyster and blaclip oyster. The flat oyster is produced by only one company. Production is relatively small for all species except Pacific oyster and pearl oyster. In Vietnam, Portuguese oyster, Suminoe oyster and venerid clam are farmed by many small-scale producers with annual production of 10,000 – 20,000 tonnes (Table 59).

Table 59. Audited mollusc species in Australia and their aquaculture status

*2018 production in tonnes (FAO 2020)

No.	Common name	Scientific name	Number of audits	Farming status by production (t) if known
1	Pearl oyster	*Pinctada maxima*	2	Yes
2	Sydney rock oyster	*Saccostrea glomerata*	2	Yes
3	Pacific oyster	*Crassostrea gigas*	1	2,976
4	Greenlip abalone	*Haliotis laevigata*	1	1,027
5	Blacklip abalone	*Haliotis rubra*	2	Yes, inc. above
6	Jade Tiger abalone	*Haliotis interspecies hybrid*	1	inc. above
7	Flat oyster	*Ostrea angasi*	1	Yes
8	Native rock oyster	*Saccostrea cuculatta*	1	Yes
9	Blacklip oyster	*Saccostrea echinata*	1	Yes
10	Doughboy scallop	*Chlamys asperrima*	1	No
11	Commercial scallop	*Pecten fumatus*	1	No
12	Sydney blood cockle	*Anadara trapezia*	1	No

Table 60. Audited mollusc species overseas and their aquaculture status

No.	Common name	Scientific name	Number of audits	In countries	Global production (tonnes)
1	Portuguese oyster	*Crassostrea angulata*	2	Vietnam	
2	Suminoe oyster	*Crassostrea arakensis*	1	Vietnam	
3	Bluff/dredge oyster	*Ostrea chilensis*	1	New Zealand	
4	Venerid clam	*Tapes dorsatus*	1	Vietnam	

4.1.2. Reasons for species selection

In Australia, aquaculture potential of the candidate species is the major reason for research (Figure 37). Research conducted in response to industry request account for 20% of the audited research. About 27% were assigned by employer or supervisor. Influence of funding agencies has been limited (7%) while none of the audited research was conducted based on recommendation of market studies. In contrast, 60% of the audited research overseas were derived from market studies. Further, funding agencies have had a strong influence on species selection. Interestingly, there have been strong connections between Australia and Vietnam on oyster research (O'Connor *et al.* 2019).

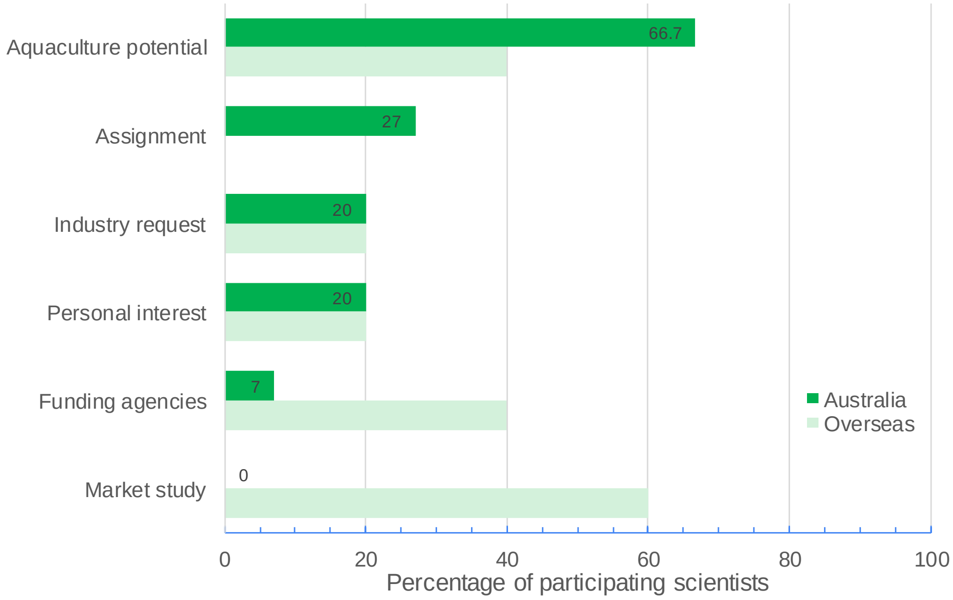


Figure 35. Reasons for species selection for research in Australia and overseas

4.1.3 Current market and consumer's preference

In Australia, 92% of the audited species are produced for domestic market. About 42% have access to export markets (Figure 38). Among these the silver-lipped pearl oyster is mainly for export. The percentage of audited species that could be marketed both domestically and internationally is 33% including abalones and Sydney rock oyster. This figure is 75% overseas, indicating stronger preference to species that have export potential.

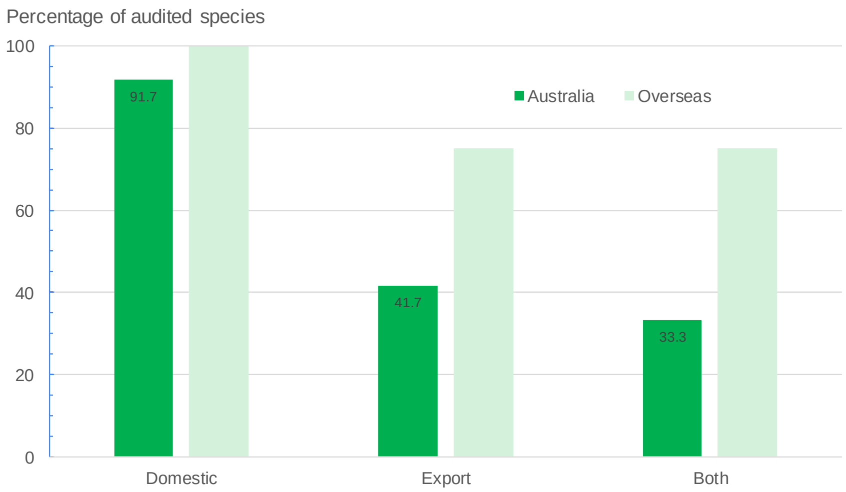


Figure 36. Current markets of the audited molluscs in Australia and overseas

Table 61. Current markets of the audited molluscs in Australia

No.	Species	Domestic market	Export market	Notes

1	Greenlip abalone			Few countries
2	Blacklip abalone			Few countries
3	Jade Tiger abalone			Few countries
4	Sydney rock oyster			Few countries
5	Sydney blood cockle			
6	Doughboy scallop			
7	Pacific oyster			
8	Flat oyster			
9	Silver-lipped pearl oyster			Globally
10	Native rock oyster			
11	Blacklip oyster			
12	Commercial scallop			

Table 62. Current markets of the audited molluscs overseas

No.	Species	Domestic market	Export market	Notes
1	Portuguese oyster			Few countries
2	Oyster			Few countries
3	Venerid clams			Few countries
4	Flat (Bluff/dredge) oyster			

Regarding consumer's preference, 85% of the audited species in Australia are preferred to be marketed live (Figure 39). The Doughboy scallop and silver-lipped pearl oyster do not belong to this group. Fresh/frozen products either as whole or meat are accepted for 39% of the audited species. Species that could be marketed frozen include abalones and scallops (Table #). Overseas, live or fresh products are preferred. However, frozen meat of the Portuguese oyster is accepted.

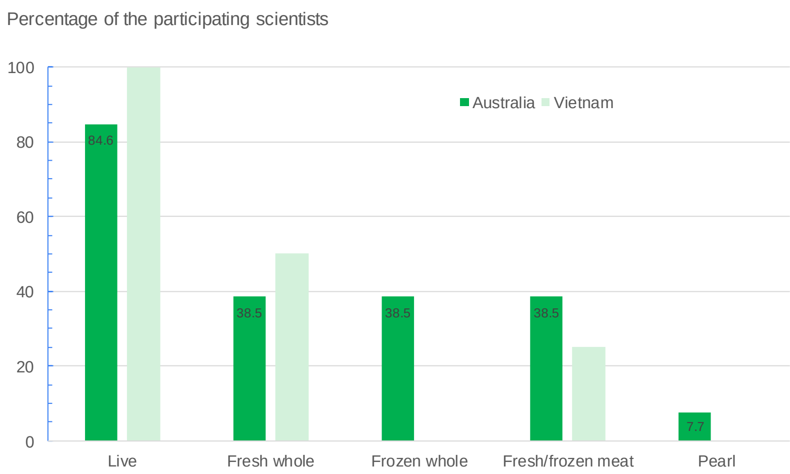


Figure 37. Preferred forms of mollusc products in Australia and overseas

Table 63. Preference diversity index (PDI) of audited edible species in Australia

No.	Species	PDI (%)	Preferred form of product			
			Live	Fresh whole	Frozen whole	Fresh/frozen meat
1	Greenlip abalone	75				
2	Blacklip abalone	75				
3	Jade Tiger abalone	75				
4	Commercial scallop	75				
5	Sydney blood cockle	50				
6	Doughboy scallop	50				
7	Flat oyster	50				
8	Sydney rock oyster	50				
9	Pacific oyster	25				
10	Native rock oyster	25				
11	Blacklip oyster	25				

Table 64. Preference diversity index (PDI) of audited edible species overseas

No.	Species	PDI (%)	Preferred form of product			
			Live	Fresh whole	Frozen whole	Fresh/frozen meat
1	Portuguese oyster	75				
2	Suminoe oyster	50				
3	Bluff/dredge oyster	25				
4	Venerid clam	25				

Preference diversity index (PDI – percentage of preferred forms over the four common forms) is 52.3% on average for the audited molluscs in Australia (Table 62). Three abalone species and commercial scallop are on top with an PDI of 75%. PDI is lowest at 25% for Pacific oyster, Native rock oyster and blacklip oyster. These species are all preferred live on the market. Among the overseas species, Portuguese oyster has the highest PDI of 75%.

4.1.4. Research history and time effort

In Australia, research on Sydney rock oyster started in 1982, earliest among the audited ones. Research effort, either individual or collective, is also highest for this species (Table 64). Research on flat oyster, commercial scallop, Doughboy scallop and Sydney blood cockle started early, but did not continue. Furthermore, research effort on these species are limited to only 4 – 6 years. The abalone group have received reasonable research effort, ranging from 20 – 26 years. Pacific oyster has been researched since 2004 with less effort compared with abalones, but its commercial production has been the highest among all the audited species. Blacklip oyster and Native rock oyster could be considered as new candidate species. Overseas, research on the audited molluscs started later in Vietnam and New Zealand compared with Australia. Thus, research effort is limited. Portuguese oyster outweighs the other species in terms of individual research effort of scientist (Table 65).

Table 65. Research history and effort on the audited molluscs in Australia

No	Species	n	Start year	Individual effort (years/scientist)	Total years of research
1	Sydney rock oyster	2	1984	26.5	53
2	Flat oyster	1	1988	6	6
3	Commercial scallop	1	1994	6	6
4	Doughboy scallop	1	1994	5	5
5	Sydney blood cockle	1	1994	4	4
6	Greenlip abalone	1	1995	20	20
7	Blacklip abalone	2	1995	13	26
8	Jade Tiger abalone	1	1995	20	20
9	Pacific oyster	1	2004	14	14
10	Silver-lipped pearl oyster	2	2009	5.5	11
11	Blacklip oyster	1	2016	2	2
12	Native rock oyster	1	2018	1	1

Table 66. Research history and effort on the audited molluscs overseas

No	Common name	n	Start year	Individual effort (years/scientist)	Total years of research
1	Portuguese oyster	2	2007	6	12
2	Suminoe oyster	1	2008	2	2
3	Bluff/dredge oyster	1	2015	3.5	3.5
4	Venerid clam	1	2018	2	2

4.1.5. Researched functional areas

In Australia, the audited research has focused on health/biosecurity/diseases (73%) and to a lesser extent nutrition and genetics/selective breeding (60%), farming systems and husbandry techniques (53%) (Figure 40). Other functional areas have attracted limited research effort, especially economics, product development and waste management. Overseas, husbandry technique has received the highest effort (80%). The other major functional areas for research include nutrition, farming systems and environmental requirement; all at 60%. Compared with Australia, more effort (40%) has been invested in research on biology/ecology and water quality. However, research effort has been none for nearly half of the surveyed areas.

As for individual species, research on Sydney rock oyster in Australia is the most comprehensive one. This species' RCI (Research Comprehensiveness Index) is 73% covering most production-related functional areas (Table 66). The next group with RCI of 60% include pearl oyster and Native rock oyster. Interesting, RCIs of species with good growth of commercial production like abalones and Pacific oyster are lower. RCI of Pacific oyster is only 13% focusing on genetics/breeding and health/biosecurity/diseases through a breeding program for disease resistance (Kube *et al.* 2017). As commercial production of Pacific oyster has been highest among all aquaculture mollusc species, this might be the best combination for research on mollusc that we should consider investing.

RCIs of the audited species overseas are lower than those in Australia and skew towards the production-related functional areas. Portuguese oyster has the highest of PCI of 53%, followed by Suminoe oyster (40%) (Table 67). That of bluff oyster and venerid clam is only 13% since these are considered as new species.

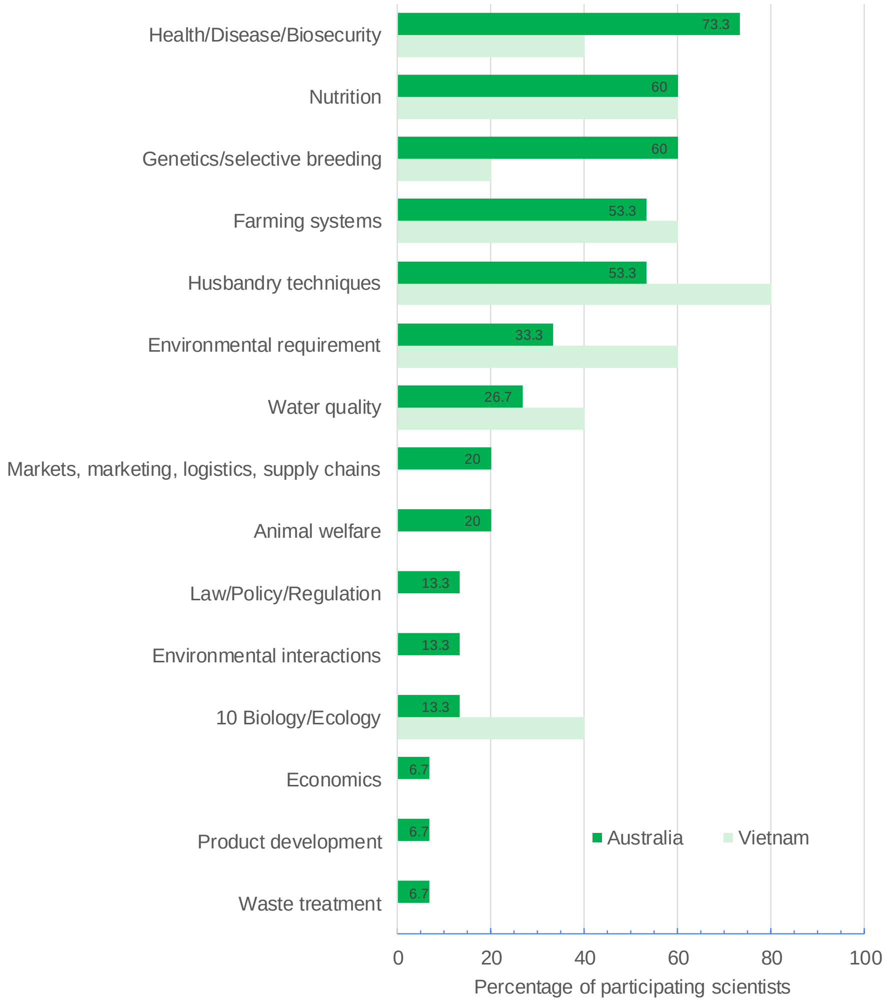


Figure 38. Functional areas targeted by mollusc research in Australia and Vietnam

Table 67. Researched functional areas by species in Australia

No	Common name	RCI (%)	Functional areas for research														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Sydney rock oyster	73	■	■	■	■	■	■	■	■			■			■	■
2	Pearl oyster	60		■	■	■	■	■	■		■	■		■			
3	Native rock oyster	60	■			■	■	■	■	■			■		■		■
4	Doughboy scallop	40		■	■	■	■	■	■								
5	Blacklip abalone	40		■	■	■					■	■		■			
6	Blacklip oyster	33		■	■			■	■	■							
7	Commercial scallop	33			■	■	■	■	■								
8	Greenlip abalone	27		■	■	■						■					
9	Jade Tiger abalone	27		■	■	■						■					
10	Flat oyster	27			■	■		■	■								
11	Sydney blood cockle	13						■	■								
12	Pacific oyster	13		■		■											

(1) biology/ecology, (2) genetics/selective breeding, (3) nutrition, (4) health/disease/biosecurity, (5) environmental requirement, (6) husbandry techniques, (7) farming systems, (8) water quality, (9) waste treatment, (10) animal welfare, (11) markets/marketing/logistics/supply chains, (12) product development, (13) economics, (14) environmental interactions, (15) law/policy/regulation. RCI is Research Comprehensiveness Index calculated as the percentage of researched areas out of total 15 functional areas surveyed.

Table 68. Researched functional areas by species overseas

No	Common name	RCI (%)	Functional areas for research														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Portuguese oyster	53	■	■	■	■	■	■	■	■							
2	Suminoe oyster	40	■		■		■	■	■	■							
3	Bluff/dredge oyster	13						■	■								
4	Venerid clam	13			■			■									

(1) biology/ecology, (2) genetics/selective breeding, (3) nutrition, (4) health/disease/biosecurity, (5) environmental requirement, (6) husbandry techniques, (7) farming systems, (8) water quality, (9) waste treatment, (10) animal welfare, (11) markets/marketing/logistics/supply chains, (12) product development, (13) economics, (14) environmental interactions, (15) law/policy/regulation. RCI is Research Comprehensiveness Index calculated as the percentage of researched areas out of total 15 functional areas surveyed.

4.1.6. Production stages targeted by research

Research on the audited species have targeted to support all different stages of production. Broodstock maturation and grow-out stages have been targeted by 80% of the participating scientists. Other stages that have received significant attention include broodstock domestication (67%) and larval rearing (60%). Fewer researches have targeted the three post-farming stages namely harvest, processing and transport (Figure 41). Overseas, grow-out stage has been targeted by 100% of the participating scientists. Broodstock maturation and larval rearing are the next most popular stages targeted by research (80%). None of the audited research effort has been invested in processing and transport stages.

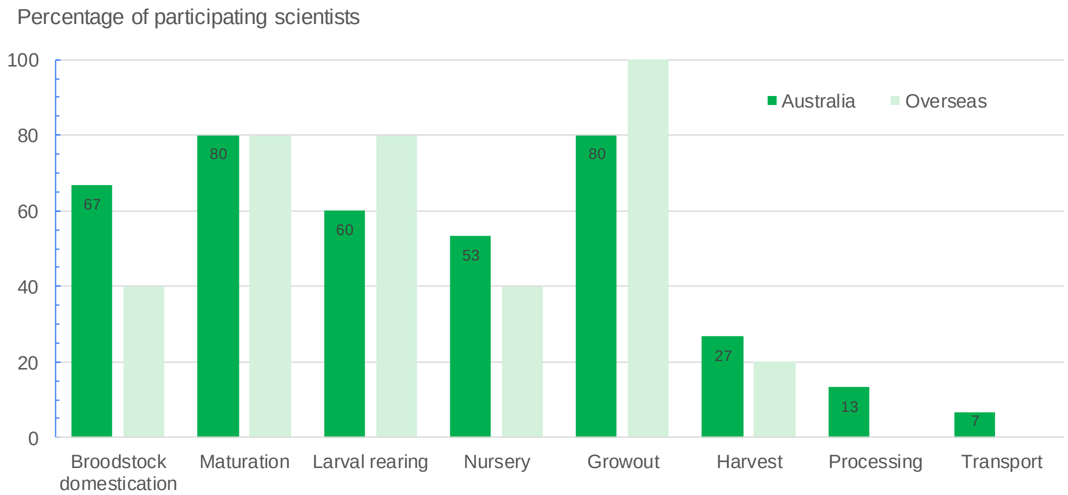


Figure 39. Production stages supported by the audited research in Australia and overseas

As for individual species in Australia, research on pearl oyster have targeted 75% of its production stages except processing and transport (Table 68). PSCI is 63% for a group include Doughboy scallop, blacklip abalone, Sydney rock oyster and blacklip oyster. Research that support the three post-farming stages have been limited for most of the audited species. It should be noted that research have not targeted larval rearing and nursery of three different abalone species, probably because there have been no major problems to these two production stages. PSCI for Pacific oyster is the smallest, i.e. 13%. Research for this species only targets broodstock domestication. Overseas, research on Portuguese oyster and venerid clam have targeted all farming stages from broodstock domestication to grow-out making PSCI of these two species 63% (Table 69). PSCIs of Suminoe oyster and bluff oyster are lower, ranging from 25 to 38%. Almost no research targeted the three post-farming stages: harvest, processing and transport.

Table 69. Production stages targeted by research on the audited molluscs in Australia

(B) broodstock domestication, (M) maturation, (L) larval rearing, (N) nursery, (G) grow-out, (H) harvest, (P) processing, (T) transport. PSCI (%): production-stage coverage index.

No	Species	PSCI (%)	Production stages							
			(B)	(M)	(L)	(N)	(G)	(H)	(P)	(T)
1	Pearl oyster	75								
2	Doughboy scallop	63								
3	Blacklip abalone	63								
4	Sydney rock oyster	63								
5	Blacklip oyster	63								
6	Sydney blood cockle	50								
7	Greenlip abalone	50								
8	Jade Tiger abalone	50								
9	Flat oyster	50								
10	Commercial scallop	50								
11	Native rock oyster	38								
12	Pacific oyster	13								

Table 70. Production stages targeted by research on the audited molluscs overseas

(B) broodstock domestication, (M) maturation, (L) larval rearing, (F) fingerling production, (G) grow-out, (H) harvest, (P) processing, (T) transport. PSCI (%): production-stage coverage index.

No	Species	PSCI (%)	Production stages							
			(B)	(M)	(L)	(F)	(G)	(H)	(P)	(T)
1	Portuguese oyster	63								
2	Venerid clam	63								
3	Suminoe oyster	38								
4	Bluff/dredge oyster	25								

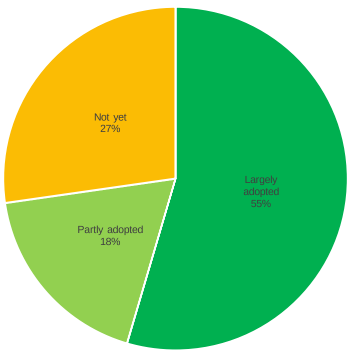


Figure 40. Adoption of mollusc research results by the industry

4.1.7. Industrial funding and adoption of research results

Industrial funding was available for research on 6/12 audited species including three abalone species, Pacific oyster, pearl oyster and Sydney rock oyster. Thanks to this linkage, research results have been largely adopted by the local industries for all these six species (Figure 42). Furthermore, research on Pacific oyster has been supported by FRDC. Research on flat oyster and blacklip oyster have not received industrial funding, but their results are partly adopted by the industry (Table 70). In Vietnam, research on Portuguese has been funded by international agencies. Results are largely adopted by the local industry. Funding from local industry was made to research on bluff oyster. Results are partly adopted.

Table 71. Industrial funding and adoption of research results

(×: no; ✓: partly; ✓✓✓: largely)

No.	Species	Industrial funding	Rate of adoption by industry
8	Pearl oyster	✓	✓✓✓
9	Sydney rock oyster	✓	✓✓✓
3	Pacific oyster	✓	✓✓✓
4	Greenlip abalone	✓	✓✓✓
5	Blacklip abalone	✓	✓✓✓
6	Jade Tiger abalone	✓	✓✓✓
7	Flat oyster	×	✓
10	Blacklip oyster	×	✓
2	Doughboy scallop	×	×
11	Commercial scallop	×	×
1	Sydney blood cockle	×	×

4.2. OPPORTUNITIES FOR FURTHER DEVELOPMENT

4.2.1. Evaluation of species potential

In Australia, Sydney rock oyster rank tops on the list with an absolute potential score of 300 (Table 71). This species is promising in all aspects, from market advantages to biological potential and enabling factors. Other species that have good potential across all the three aspects evaluated include the greenlip and Jade Tiger abalones (275), commercial scallop (258), flat oyster (238) and, to a lesser extent, blacklip oyster and blacklip abalone. Interestingly, the overall potential scores of Pacific oyster and pear oyster are much lower, i.e. 112 and 98, respectively using the assessed criteria of this study although these two species have had significant commercial aquaculture productions. As evaluated by the participating scientists, both Pacific oyster and pearl oyster have poorer biological potential compared with the other species. The participating scientists have elaborated that for pearl oyster reproduction in captivity, seed supply, diseases, growth rate, flesh yield and domestic market price are all unfavourable to further development of this species. There is no market advantage for Doughboy scallop, Sydney blood cockle and Native rock oyster. Poor biological potential of the last two species make their potential for commercial aquaculture highly slim. If market is developed for Doughboy scallop, aquaculture production of this species might grow. Overseas, Portuguese and Suminoe oysters both have high potential for commercial aquaculture production (Table 72). Their limitations merely rest with their biological potential (60/100). The potential of bluff oyster is slim, while that of venerid clam is almost none using the criteria assessed in this study.

As a group, the average potential of 12 audited molluscs in Australia is well above average for all three groups of criteria. Enabling factors group has the highest score of 77% higher than market advantage (55%) and biological potential (61%). Compared with the other countries participated to this study, the audited Australian molluscs have better biological potential but lower market advantage (Figure 43). This is understandable as species that are more difficult to breed/produce often have better market advantage, especially regarding price.

Table 72. Potential for aquaculture of the audited molluscs in Australia. Data are percentage of the criteria classified as favourable.

No.	Common name	*n*	Market potential	Biological potential	Enabling factors	Overall potential
1	Sydney rock oyster	*2*	100	100	100	300
2	Greenlip abalone	*1*	75	100	100	275
3	Jade Tiger abalone	*1*	75	100	100	275
4	Commercial scallop	*1*	75	100	83	258
5	Flat oyster	*1*	75	80	83	238
6	Blacklip oyster	*1*	50	80	83	213
7	Blacklip abalone	*2*	63	60	83	206
8	Doughboy scallop	*1*	0	80	83	163
9	Pacific oyster	*1*	25	20	67	112
10	Pearl oyster	*2*	63	10	25	98
11	Sydney blood cockle	*1*	0	20	67	87
12	Native rock oyster	*1*	0	0	67	67

Table 73. Potential for aquaculture of the audited crustaceans overseas. Data are percentage of the criteria classified as favourable.

No.	Common name	*n*	Market potential	Biological potential	Enabling factors	Overall potential
1	Portuguese oyster	*2*	100	60	100	260
2	Suminoe oyster	*1*	100	60	100	260
3	Bluff/dredge oyster	*1*	75	40	0	115
4	Venerid clam	*1*	50	0	33	83

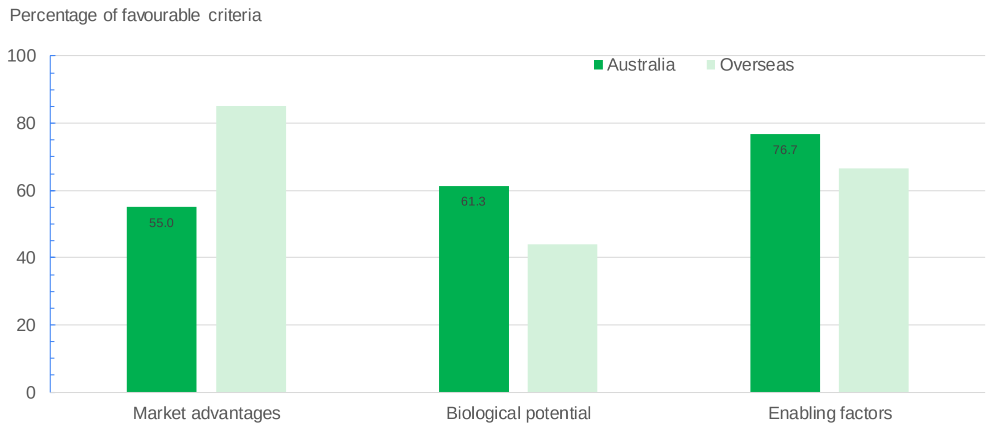


Figure 41. Potential for aquaculture of the audited mollusc species evaluated by the participating scientists in Australia and overseas

4.2.2. Possession of desirable attributes

Evaluation against eight desirable attributes shows that 83% of the audited molluscs in Australia are high-value species and easy to reproduce in captivity. In addition, they could be farmed using existing systems and technology, and have been traded regionally or globally (Figure 44). R&D investment is, however, quite limited. Furthermore, none of these species have short grow-out periods or low production costs. In contrast, 75% of the audited species overseas have estimated production cost lower than US$3/kg while 50% of them have grow-out period less than 12 months. All audited species can be fetched for premium prices and have been traded regionally or globally. R&D investment is much better compared with Australia.

As for individual species, pearl oyster and Sydney rock oyster rank top of the list with the highest Desirable Score Index (DSI) of 78% (Table 73). The next group that have a DSI of 63% include three abalone species and Native rock oyster. Interestingly, DSI of Pacific oyster is only 38%, equal to that of the two scallops and smaller than flat oyster. Sydney blood cockle and blacklip oyster do not have much potential given their low DSIs. More R&D support is clearly a need for most of the audited species. Overseas, DSI is high for Portuguese oyster (88%), Suminoe oyster (75%) and venerid clam (75%), implying better selection of aquaculture candidate (Table 74). Low production cost, good market prices and familiarity to consumers regionally or globally clearly make these species highly competitive. The potential of bluff oyster is far less than that of these species.

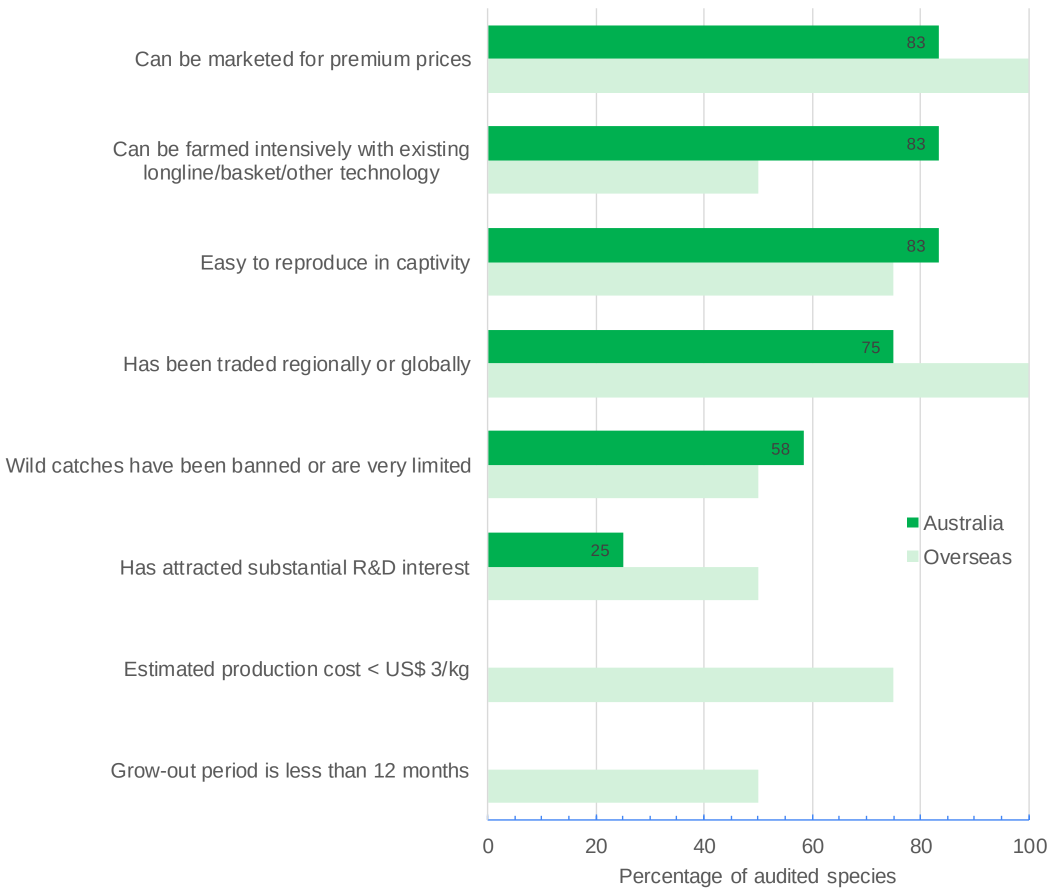


Figure 42. Possession of nine desirable attributes of the audited molluscs in Australia and overseas

Table 74. Possession of desirable attributes and desirable score index (DSI) by species in Australia

(Re) easy to reproduce in captivity, (Gr) grow-out period less than 12 months, (ES) can be farmed intensively using existing systems such as long line or basket, (MP) premium market prices, (R&D) has attracted substantial R&D interest, (Wi) wild catch is limited or banned, (PC) estimated production cost less than US$3/kg, (Tr) has been traded regionally or globally.

No	Species	DSI	Desirable attributes							
		(%)	Re	Gr	ES	MP	R&D	Wi	PC	Tr
1	Pearl oyster	75								
2	Sydney rock oyster	75								
3	Greenlip abalone	63								
4	Blacklip abalone	63								
5	Jade Tiger abalone	63								
6	Native rock oyster	63								
7	Flat oyster	50								
8	Pacific oyster	38								
9	Doughboy scallop	38								
10	Commercial scallop	38								
11	Sydney blood cockle	25								
12	Blacklip oyster	25								

Table 75. Possession of desirable attributes and desirable score index (DSI) by species overseas

(Re) easy to reproduce in captivity, (Gr) grow-out period less than 12 months, (ES) can be farmed intensively using existing systems such as long line or basket, (MP) premium market prices, (R&D) has attracted substantial R&D interest, (Wi) wild catch is limited or banned, (PC) estimated production cost less than US$3/kg, (Tr) has been traded regionally or globally.

No	Species	DSI	Desirable attributes							
		(%)	Re	Gr	ES	MP	R&D	Wi	PC	Tr
1	Portuguese oyster	88								
2	Suminoe oyster	75								
3	Venerid clams	75								
4	Bluff/dredge oyster	38								

Table 76. Technology readiness level for each production stage by species in Australia

No	Species	*n*	TRI	Technology readiness level							
			(%)	BMA	SPA	LAR	NUR	GRO	HAV	PRO	TRA
1	Pacific oyster	*1*	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
2	Greenlip abalone	*1*	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
3	Blacklip abalone	*2*	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
4	Jade Tiger abalone	*1*	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
5	Flat oyster	*1*	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
6	Sydney rock oyster	*2*	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
7	Commercial scallop	*1*	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
8	Blacklip oyster	*1*	2.8	3.0	3.0	2.0	2.0	3.0	3.0	3.0	3.0
9	Doughboy scallop	*1*	2.5	3.0	3.0	3.0	3.0	2.0	2.0	2.0	2.0
10	Sydney blood cockle	*1*	2.4	2.0	3.0	3.0	1.0	1.0	3.0	3.0	3.0
11	Pearl oyster	*2*	2.3	2.0	1.5	2.0	2.0	2.5	2.5	3.0	3.0
12	Native rock oyster	*1*	1.1	2.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Average		2.7	2.8	2.7	2.7	2.5	2.5	2.7	2.8	2.8

(BMA) broodstock maturation, (SPA) spawning, (LAR) larval rearing, (FIN) nursery, (GRO) grow-out, (HAV) harvest, (PRO) processing, (TRA) transportation. Technology readiness levels: 3.0 = commercially viable, 2.0 = technically feasible, 1.0 = experimental.

Table 77. Technology readiness level for each production stage by species overseas

No	Species	*n*	TRI (%)	Technology readiness							
				BMA	SPA	LAR	NUR	GRO	HAV	PRO	TRA
1	Portuguese oyster	*2*	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
2	Suminoe oyster	*1*	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
3	Venerid clams	*1*	2.8	2.0	3.0	3.0	3.0	3.0	3.0	2.0	3.0
4	Bluff/dredge oyster	*1*		NA	2.0	2.0	NA	NA	NA	3.0	3.0
	Average			2.7	2.8	2.8	3.0	3.0	3.0	2.8	3.0

(BMA) broodstock maturation, (SPA) spawning, (LAR) larval rearing, (NUR) nursery, (GRO) grow-out, (HAV) harvest, (PRO) processing, (TRA) transportation. Technology readiness levels: 3.0 = commercially viable, 2.0 = technically feasible, 1.0 = experimental.

4.2.3. Technology readiness

In Australia, the farming of seven species including Pacific oyster, three abalone species, Sydney rock oyster, flat oyster and commercial scallop are considered commercially viable with a Technology Readiness Index (TRI) of 3.0 for all production stages (Table 75). Blacklip oyster has a high TRI of 2.8, but its commercial aquaculture production is less ready for development given that larval rearing and nursery stages are just technically feasible. Doughboy scallop is ready for commercial grow-out trials. The hatchery stages of pearl oyster appear to require more improvement. More R&D are in need for Sydney blood cockle and especially Native rock lobster. Overseas, except for bluff oyster in New Zealand, three species in Vietnam all have high TRIs, i.e. 2.8 – 3.0 indicating their readiness for further expansion in aquaculture production (Table 76).

4.2.3. Potential to adopt existing technologies

In Australia, 10/15 participating scientists provided information about the potential for adopting existing technologies. Species that received no evaluation include pearl oyster, flat oyster and commercial scallop. Adoption of existing technologies is possible for all the surveyed stages. High potential is suggested for broodstock domestication (90%), larval rearing (80%), broodstock maturation (70%) and grow-out (60%) (Figure 45). Other stages such as nursery, harvest, processing and transport have smaller potential for technology adoption. Interestingly, the trend is different overseas. Except for broodstock domestication stage, potential for technology adoption remains low for all other farming stages, but 100% for harvest, processing and transport stages. This observation may suggest significant difference in biology of the audited species.

In terms of species, the abalone group have the highest potential for adoption of existing technologies index (PAETI) of 75% (Table 77). Broodstock maturation and nursery are the two production stages where technology adoption is not possible. PAETI is 63% for Doughboy scallop, Native rock oyster, Sydney rock oyster and blacklip oyster. Native rock oyster appears to require different grow-out technologies as adoption of existing technologies is zero for its grow-out stage. PAETI of Sydney blook cockle and Pacific oyster is low, ranging from 13 to 25%, suggesting more research on these two species. Overseas, adoption of existing technologies is possible to all the surveyed stages of Portuguese oyster (Table 78). This species appears as a good choice with an absolute PAETI. Thus, its commercial production has full potential to grow. PAETI of Suminoe oyster and venerid clam are smaller. Technology adoption is restricted mainly to harvest, processing and transport.

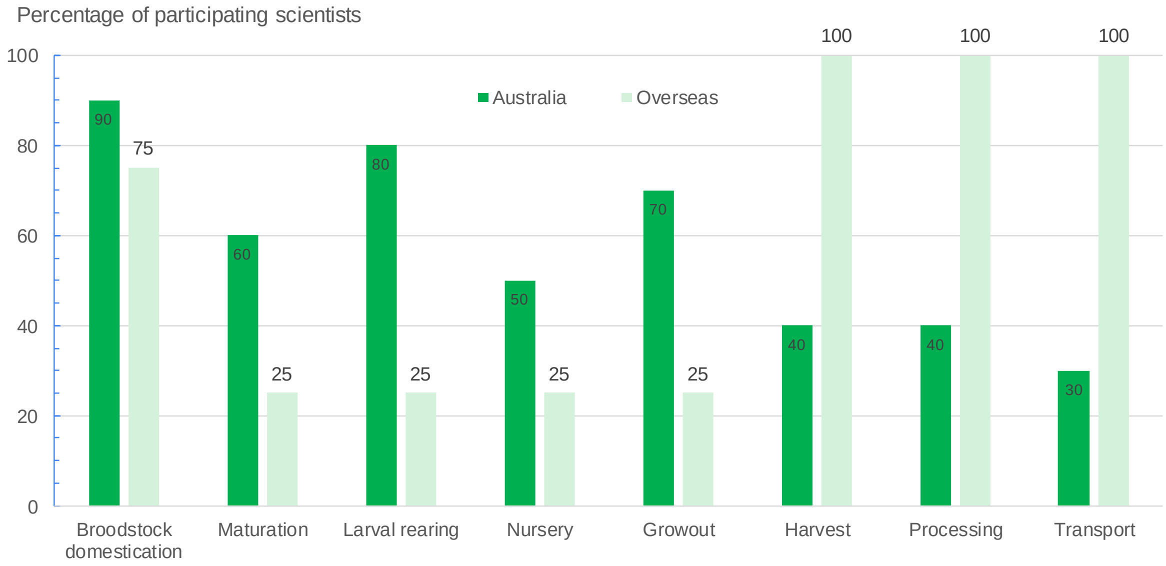


Figure 43. Potential for adoption of existing technologies across different production stages of the audited molluscs in Australia and overseas

Table 78. Potential for adoption of existing technologies in different production stages of the audited molluscs in Australia

(B) broodstock domestication, (M) maturation, (L) larval rearing, (N) nursery, (G) grow-out, (H) harvest, (P) processing, (T) transport. PAETI (%): potential for adoption of existing technologies index

No	Species	PAETI (%)	Production stages (B)	(M)	(L)	(N)	(G)	(H)	(P)	(T)
1	Greenlip abalone	75	■		■		■	■	■	■
2	Blacklip abalone	75	■		■		■	■	■	■
3	Jade Tiger abalone	75	■		■		■	■	■	■
4	Doughboy scallop	63	■	■	■	■	■			
5	Native rock oyster	63	■	■	■	■		■		
6	Sydney rock oyster	63	■	■	■	■	■			
7	Blacklip oyster	63	■	■	■	■	■			
8	Sydney blood cockle	25		■	■					
9	Pacific oyster	13	■							

Table 79. Potential for adoption of existing technologies in different production stages of the audited molluscs overseas

(B) broodstock domestication, (M) maturation, (L) larval rearing, (N) nursery, (G) grow-out, (H) harvest, (P) processing, (T) transport. PAET (%): potential for adoption of existing technologies index

No	Species	PAETI (%)	Production stages (B)	(M)	(L)	(N)	(G)	(H)	(P)	(T)
1	Portuguese oyster	100	■	■	■	■	■	■	■	■
2	Suminoe oyster	50	■					■	■	■
3	Venerid clams	38						■	■	■

4.3. BARRIERS TO FURTHER DEVELOPMENT

4.3.1. Identified barriers

In Australia, the most significant barrier for crustacean aquaculture is insufficient supply of quality seed identified by 67% of the participating scientists (Figure 46). Increasing incidence of infectious diseases is the next major barrier at a smaller magnitude (40%). The other barriers that require some attention include limited funding for R&D, lack of public interest, too small industry, low profit and unfavourable regulation. In contrast, market demand, grow-out performance, investment, infrastructure, downstream capacity, availability of skilled labour, etc. are not the major barriers to mollusc aquaculture in Australia.

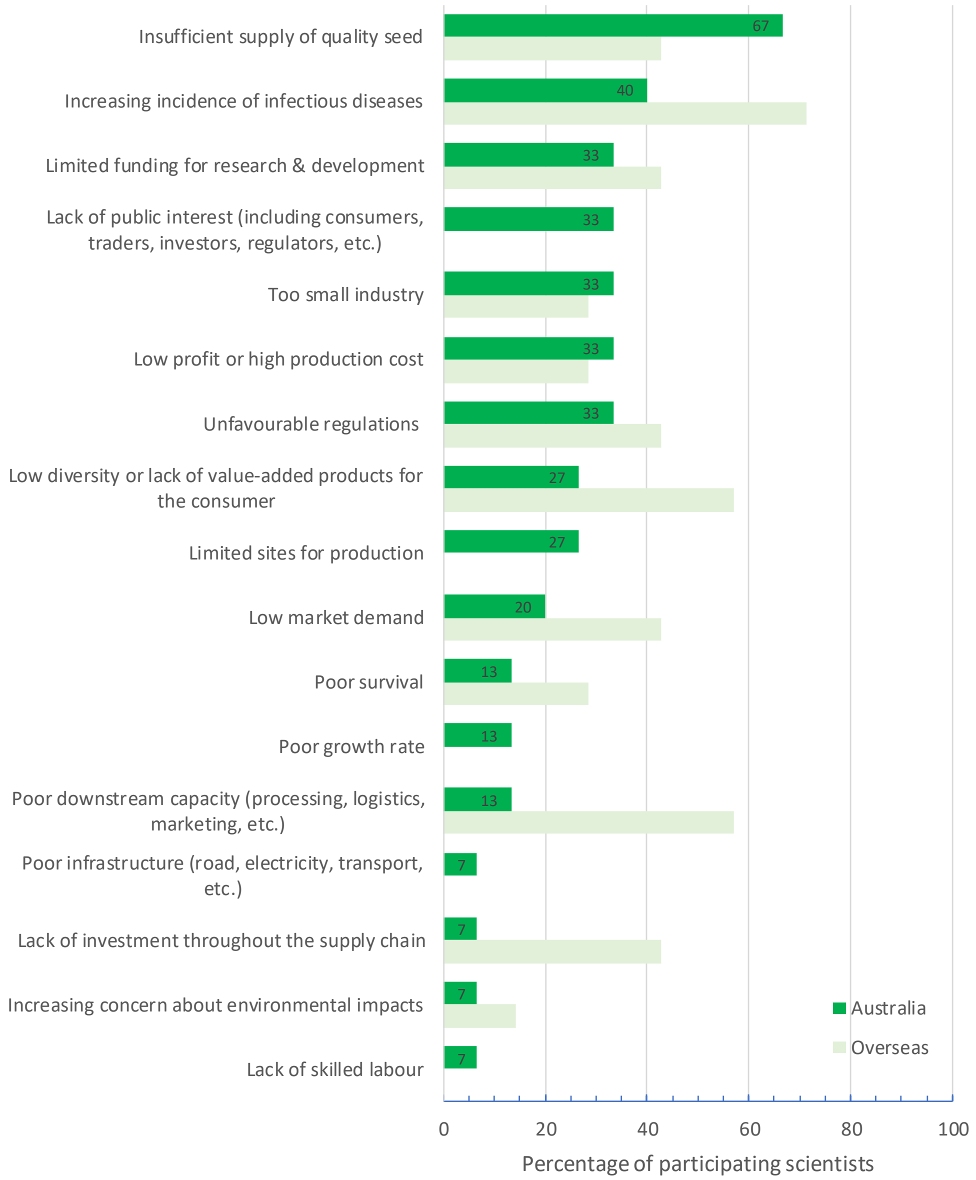


Figure 44. Identified barriers to development of mollusc aquaculture in Australia and overseas

Overseas, the number of barriers to further development is fewer than that for Australia. Five barriers are not reported for any of the audited species including limited sites for production, lack of skilled labour, poor growth rate, lack of public interest and poor infrastructure. Identified by more than 83% of the participating scientists the most significant barrier is increasing incidence of infectious diseases. This probably results in another barrier - poor survival in grow-out (33%), which is much more prominent compared with Australia. The next two major ones, recognized by 67% of the participating scientists, include poor downstream capacity and low diversity or lack of value-added products for the consumer. Though less significant compared with Australia, insufficient supply of quality seed remains a major barrier at the same magnitude (50%) of unfavourable regulations and lack of investment throughout the supply chain. Limited funding for R&D, too small industry and low profit are also reported as barriers at similar level to what reported for Australia. Poor growth rate of the audited species, poor infrastructure, lack of skilled labour and increasing concern about environmental impacts are not barriers for further development.

As for individual species in Australia, Native rock oyster has the highest Barriers Index (BI) of 64.7%, making further development of this species' aquaculture highly challenging (Table 79). Native rock oyster shares the most common barriers with several other audited species in Australia such as insufficient supply of quality seed, increasing incidence of infectious diseases, too small industry, low profit and lack of funding for R&D. Poor survival in grow-out phase is another critical barrier for Native rock lobster. In contrast, the number of barriers for two scallop species and blacklip oyster is much fewer. Their BIs range from 11.8 to 17.6%. However, these barriers are quite critical or common too (insufficient supply of quality seed, low profit or low market demand).

Pearl oyster has the second highest BI (47.2%), two folds higher than that of a group including three abalone species and Pacific oyster which is like pearl oyster have had relatively significant commercial aquaculture production. The barriers that make pearl oyster different from that group include the lack of skilled labour, poor survival in grow-out phase and increasing concern of environmental impacts not to mention limited sites for production. BIs of Sydney blood cockle, Sydney rock oyster and flat oyster range from 29.4 to 35.3%. Interestingly, the barriers for further development of this group are all around unfavourable regulations and insufficient supply of quality seed, and to a lesser extent, low market demand, low profit, limited site for production. It should be noted that lack of funding for R&D is identified as barrier for further development of Native rock oyster, pearl oyster and three abalone species.

Overseas, Portuguese oyster and Suminoe oyster have the highest BIs among the six audited species (Table 80). The barriers for further development of these two species are very similar including unfavourable regulations, low market demand, low profit, increasing incidence of infectious diseases, insufficient supply of seed, low diversity or lack of value-added products, poor downstream capacity and lack of investment throughout the supply chain. Portuguese oyster has an extra one (poor survival in grow-out phase), which directly hampers production growth. Despite sharing a BI of 29.4% the barriers that blood cockle's aquaculture currently has are more removable compared with venerid clam. The latter species' aquaculture is currently hampered by two more critical barriers: infectious disease and poor survival in grow-out phase. BIs of bluff oyster and pearl oyster is low (17.8%), suggesting good opportunities for further development. Interesting, the situation for pearl oyster aquaculture in French Polynesia share two barriers with Australia, i.e. increasing concern of environmental impacts and lack of funding for R&D but is different regarding market demand. Its aquaculture development is, however, challenging compared with Australia.

Table 80. Barriers to aquaculture development of the audited mollusc species in Australia

No	Common name	n	BI (%)	Barriers to development																
				1	2	3	4	5	6	7	9	10	11	12	13	14	15	16	17	18
1	Natal rock oyster	1	65			1			1	1	1		1		1	1	1	1	1	1
2	Silver-lipped pearl oyster	2	47				1	1	1	1	1			1				1		1
3	Sydney blood cockle	1	35	1	1	1	1			1									1	
4	Sydney rock oyster	2	30	1		1	1		2	1										
5	Flat oyster	1	30	1	1				1	1							1			
6	Blacklip abalone	2	24								1	2					1	1		
7	Greenlip abalone	1	24								1	1					1	1		
8	Jade Tiger abalone	1	24								1	1					1	1		
9	Pacific oyster	1	24				1		1	1			1							
10	Doughboy Scallop	1	18		1	1				1										
11	Black-lip rock oyster	1	12	1						1										
12	Commercial Scallop	1	12			1				1										
	Percentage of audited species (%)			33	25	42	33	8	42	75	42	25	17	8	8	8	42	42	17	17

n: number of audits;

BI (%): barriers index, i.e. percentage of the number of identified barriers over 18 pre-defined ones;

(1): Unfavourable regulations; (2) Low market demand; (3) Low profit or high production cost;

(4) Limited sites for production; (5) Lack of skilled labour; (6) Increasing threat of infectious diseases;

(7) Insufficient supply of quality seed; (9) Too small industry;

(10) Low diversity or lack of value-added products; (11) Poor downstream capacity; (12) Increasing concern over environmental impacts;

(13) Lack of investment throughout the supply chain; (14) Poor infrastructure; (15) Lack of public interest;

(16) Limited funding for R&D; (17) Poor growth in grow-out; (18) Poor survival in grow-out;

Table 81. Barriers to aquaculture development of the audited molluscs overseas

No	Common name	n	BI (%)	Barriers to development																
				1	2	3	4	5	6	7	9	10	11	12	13	14	15	16	17	18
1	Portuguese oyster	2	52.9	■	■	■			■	■		■	■		■					■
2	Suminoe oyster	1	47.1	■	■	■			■	■		■	■		■					
3	Blood cockle*	1	29.4								■	■	■		■			■		
4	Venerid clam	1	29.4						■			■	■					■		■
5	Bluff/flat oyster	1	17.6	■					■		■									
6	Pearl oyster*	1	17.6		■									■				■		
	Percentage of audited species (%)			50	50	33			67	33	33	67	67	17	50			50		33

** added from late contributions only for reference purpose about barriers to further development*

n: number of audits; BI (%): barriers index, i.e. percentage of the number of identified barriers over 18 pre-defined ones;

(1): Unfavourable regulations; (2) Low market demand; (3) Low profit or high production cost;

(4) Limited sites for production; (5) Lack of skilled labour; (6) Increasing threat of infectious diseases;

(7) Insufficient supply of quality seed; (9) Too small industry;

(10) Low diversity or lack of value-added products; (11) Poor downstream capacity; (12) Increasing concern over environmental impacts;

(13) Lack of investment throughout the supply chain; (14) Poor infrastructure; (15) Lack of public interest;

(16) Limited funding for R&D; (17) Poor growth in grow-out; (18) Poor survival in grow-out;

4.3.2. Availability of required inputs for commercial production

The availability of required inputs for farming rated as “highly assessible” reveal some constraints to increasing commercial aquaculture production of the audited molluscs in Australia (Figure 47). Water conditioners and substances to control diseases are not highly accessible. Limited availability appears across a wide range of inputs that are highly essential to farming such as seeds, production site, broodstock, finance, labour and technical report. Feeds, processing facilities and transport to markets are all available at high rate. Overseas, inputs for farming are generally more available compared with Australia. However, there are some constraints with processing facilities and domesticated broodstock (Figure 47).

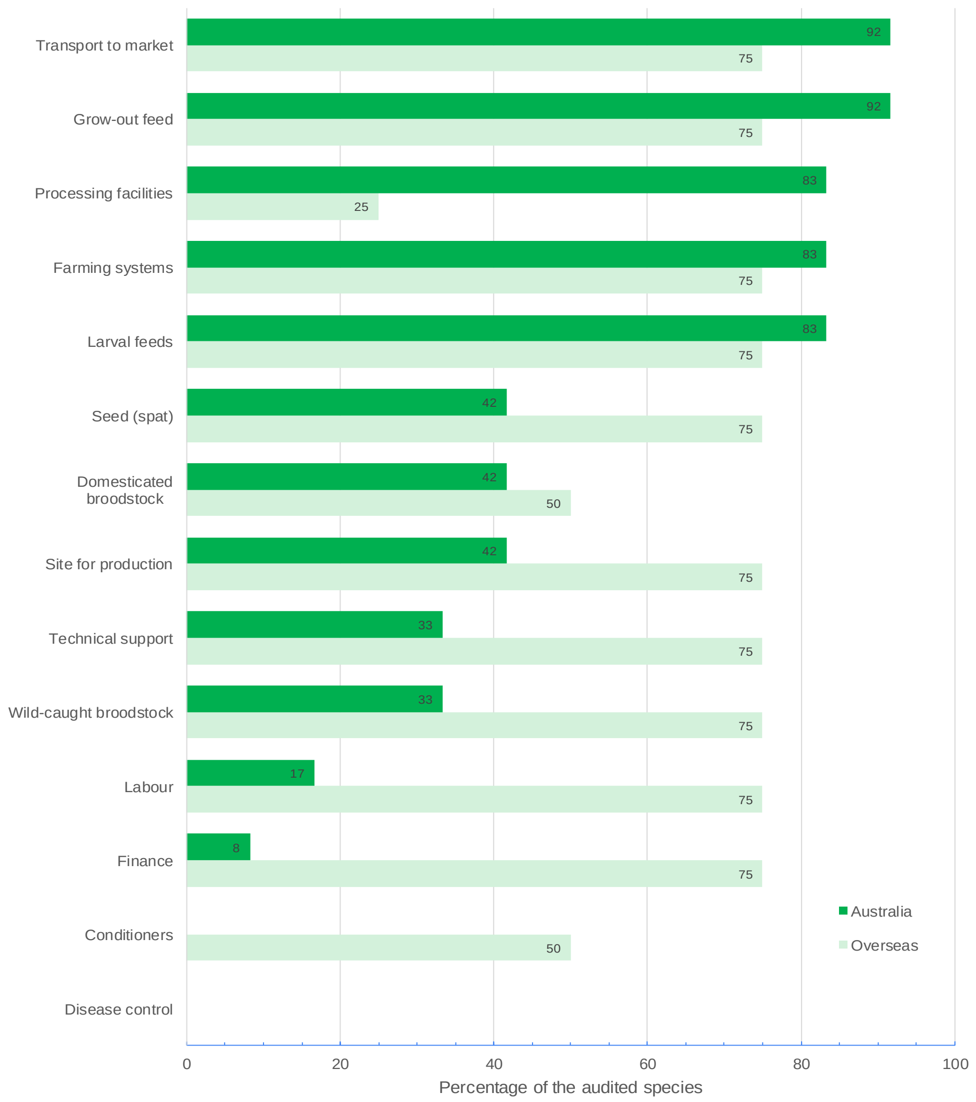


Figure 45. Required inputs that are highly assessible for commercial aquaculture production of the audited mollusc in Australia and overseas

As for individual species, Sydney rock oyster has the highest HAI (Table 81). This means the farming of Sydney rock oyster has the best conditions to grow in production, especially if the current limitations (i.e. limited availability of inputs for disease control and water quality management) are resolved. Abalones are the next species that their aquaculture can access to all the key inputs for farming. Pearl oyster and Pacific oyster have the same HAI, but broodstock and seed availability are more limited for pearl oyster. Aquaculture of blacklip oyster, scallops, Sydney blood cockle and rock oyster still need more inputs available to increase in production. These current constraints may help identify research that could help create the required inputs. Overseas, bluff oyster is the only species that still have a lot of constraints to commercial aquaculture production (Table 82).

Table 82. Availability of required inputs for farming of finfish species in Australia

a: available, ha: highly accessible, AI(%): availability index, HAI(%): high accessibility index; (1) site for production, (2) wild-caught broodstock, (3) domesticated broodstock, (4) seeds, (5) larval feeds, (6) grow-out feeds, (7) drugs/chemicals for disease control, (8) conditioners for water quality management, (9) farming systems & equipment, (10) processing facilities, (11) transport to markets, (12) labour, (13) finance, (14) technical support

No	Audited species	HAI (%)	AI (%)	Required inputs for farming													
				1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Sydney rock oyster	79	7	ha	ha	ha	ha	ha	ha			ha	ha	ha	ha	a	ha
2	Abalones*	64	29	ha	a	ha	ha	ha	ha	a		ha	ha	ha	a	a	ha
3	Pearl oyster	50	50	a	ha	a	a	a	ha	a	a	ha	ha	ha	ha	ha	a
4	Pacific oyster	50	36	a	a	ha	ha	ha	ha			ha	ha	ha	a	a	a
5	Blacklip oyster	43	29	a	ha	a		ha	ha			ha	ha	ha	a		a
6	Flat oyster	36	50	a	a	a	a	ha	ha			ha	ha	ha	a	a	a
7	Commercial scallop	36	36	a	a			ha	ha			ha	ha	ha	a	a	a
8	Sydney blood cockle	36	29	a	ha			ha	ha			a	ha	ha	a		a
9	Doughboy scallop	29	36	a	a			ha	ha			ha	a	ha	a		a
10	Rock oyster	14	50	ha	ha	a						a	a	a	a	a	a

**Abalones include green-lipped, black-lipped and hybrid species*

Table 83. Availability of required inputs for farming of finfish species overseas

a: available, ha: highly accessible, AI(%): availability index, HAI(%): highly accessibility index; (1) site for production, (2) wild-caught broodstock, (3) domesticated broodstock, (4) seeds, (5) larval feeds, (6) grow-out feeds, (7) drugs/chemicals for disease control, (8) conditioners for water quality management, (9) farming systems & equipment, (10) processing facilities, (11) transport to markets, (12) labour, (13) finance, (14) technical support

No	Audited species	HAI (%)	AI (%)	Required inputs for farming													
				1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Portuguese oyster	86	14	ha	ha	ha	ha	ha	ha	a	ha	ha	a	ha	ha	ha	ha
2	Suminoe oyster	86	14	ha	ha	ha	ha	ha	ha	a	ha	ha	a	ha	ha	ha	ha
3	Venerid clam	64	36	ha	ha	a	ha	ha	ha	a	a	ha	a	a	ha	ha	ha
4	Bluff/dredge oyster	14	14	a								a	ha	ha			

4.4. FUTURE RESEARCH

4.4.1. Research intention

In Australia all the participating scientists express their intention to continue research on mollusc species (Figure 48). Of these 53% strongly confirm research intention while the rest indicate some possibilities. Funding from FRDC is requested by 60% of the participating scientists. About 67% would like to seek for industrial partners. Scientists who researched on pearl oyster, Pacific oyster, abalones, Sydney rock oyster, blacklip oyster and Native rock oyster suggest more research on these species with funding from FRDC. Overseas, although 100% of the participating scientists indicate their intention for further research, the level of certainty is lower than that in Australia (i.e. only 28.6% say yes). It is understandable as the percentage of scientists that request funding for research is higher. Furthermore, the need for industrial partner is more profound, expressing by 85.7% of the participating scientists. The species that are recommended for further research include Portuguese oyster, Suminoe oyster and blood cockle.

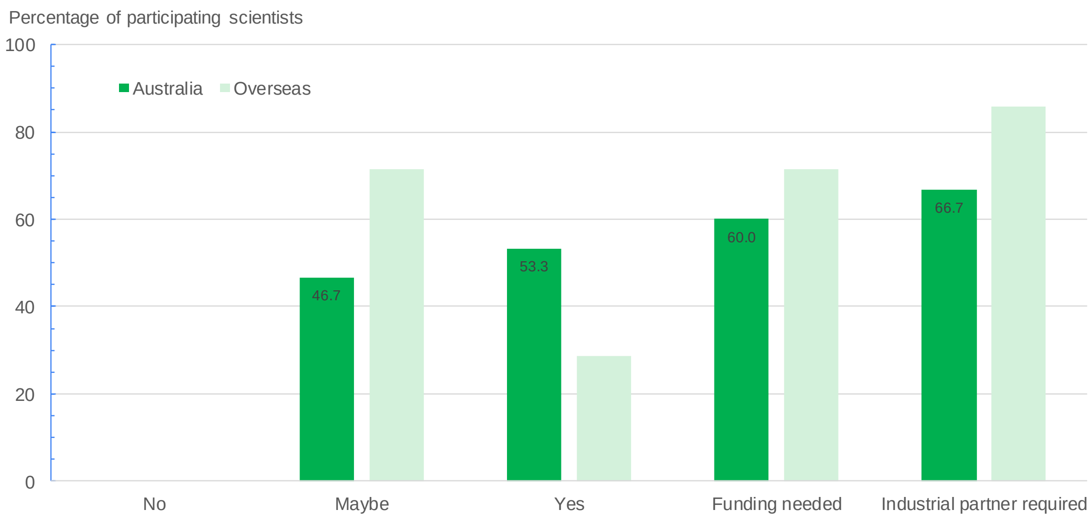


Figure 46. Intention for future research on mollusc species and requests for support

Table 84. Future intention, request for funding and industrial partnership for research on the audited molluscs in Australia

No.	Common name	*n*	Further research	Request for FRDC funding	Request for industrial partner
1	Pacific oyster	*1*	Yes	Yes	No
2	Silver-lipped pearl oyster	*1*	Yes	Yes	Yes
3	Native rock oyster	*1*	Yes	Yes	Yes
4	Sydney rock oyster	*1*	Yes	Yes	Yes
5	Blacklip oyster	*1*	Yes	Yes	Yes
6	Blacklip abalone	*2*	Yes, Maybe	½	No
7	Flat oyster	*1*	Maybe	Yes	Yes
8	Sydney blood cockle	*1*	Maybe	No	Yes
9	Doughboy scallop	*1*	Maybe	No	Yes
10	Greenlip abalone	*1*	Maybe	No	No
11	Jade Tiger abalone	*1*	Maybe	No	No
12	Commercial scallop	*1*	Maybe	No	Yes

Table 85. Future intention, request for funding and industrial partnership for research on the audited molluscs overseas

No.	Common name	*n*	Further research	Request for funding	Request for industrial partner
1	Portuguese oyster	*2*	Yes	½	Yes
2	Oyster	*1*	Yes	Yes	Yes
3	Flat (Bluff/dredge) oyster	*1*	Maybe	No	Yes
4	Venerid clams	*1*	Maybe	Yes	Yes
5	Pearl oyster	*1*	Maybe	Yes	Yes
6	Blood cockle	*1*	Yes	Yes	

4.4.2. Functional areas that still require substantial effort

In Australia, research on genetics/selective breeding is recommended for 80% of the audited species. Health/biosecurity/diseases (67%) and farming system (60%) are the next two functional areas that receive high rate of recommendation (Figure #). The other functional areas that have received reasonable attention (33 -40%) include market/marketing/logistics/supply chain, nutrition, husbandry techniques and product development. Similar recommendations are recorded for Vietnam. Research on genetics/selective breeding and health/biosecurity/diseases are recommended for 80% of the audited species. Interestingly, much stronger emphasis (60%) are recommended for economics, market-related issues, product development, environmental interactions and law/policy/regulation compared with Australia.

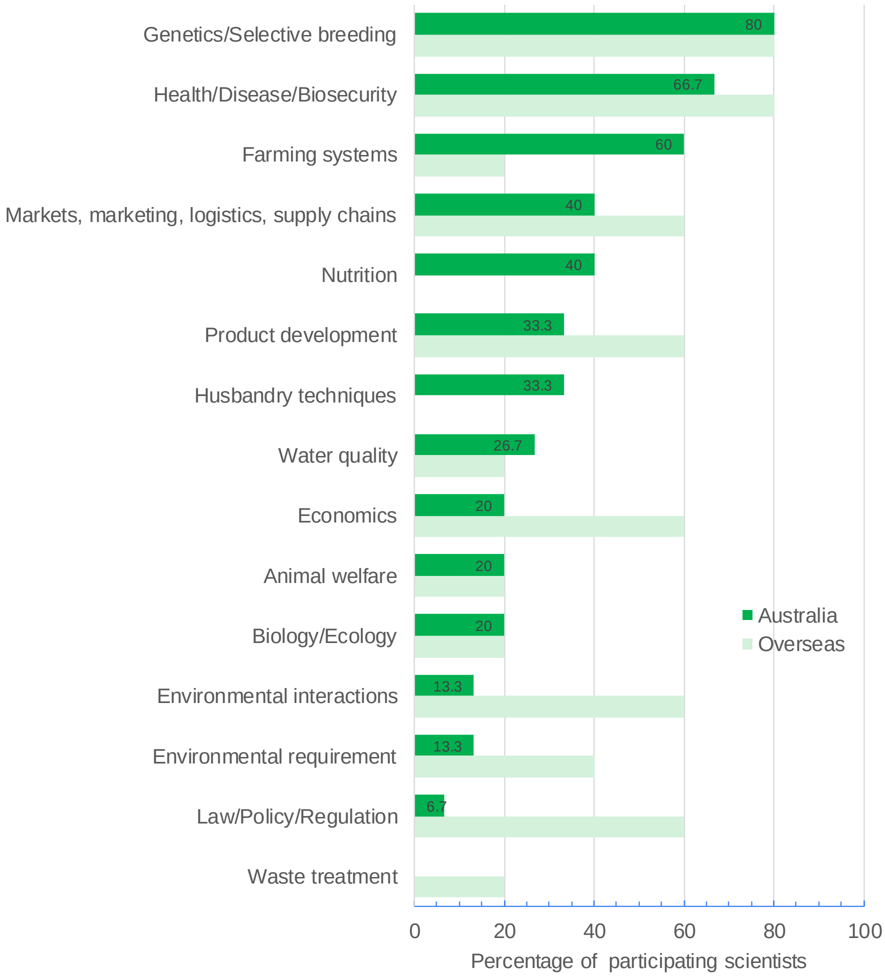


Figure 47. Functional areas that require substantial research effort to develop mollusc aquaculture in Australia and overseas

Substantial research effort is recommended for 11/12 and 3/4 species audited in Australia and overseas, respectively by the participating scientists. Flat oyster is the Australian species that has no recommendation for further research. Strong focuses include genetics/selective breeding, health/biosecurity/diseases and farming techniques for 11 Australian species (Table 85). Research Demand Index (RDI) is highest at 60% for Sydney blood cockle and Sydney rock oyster. Animal welfare and product development are recommended for all the three abalone species. For Pacific oyster continued effort is recommended for genetics/selective breeding and health. Overseas, venerid clam has the highest RDI of 87%, significantly higher than that for Portuguese oyster or Suminoe oyster (Table 86).

Table 86. Functional areas requiring substantial research effort by species in Australia

No	Species	RDI (%)	Functional areas for research														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Blood cockle	60		■	■	■	■	■	■				■	■	■		
2	Sydney rock oyster	60	■	■		■	■	■	■	■			■			■	
3	Native rock oyster	53	■	■		■		■	■				■		■		■
4	Blacklip oyster	47		■	■	■		■	■	■			■				
5	Greenlip abalone	40		■	■	■			■			■		■			
6	Blacklip abalone	40		■	■	■			■			■		■			
7	Jade Tiger abalone	40		■	■	■			■			■		■			
8	Pearl oyster	33	■	■		■			■	■							
9	Doughboy scallop	27		■									■	■	■		
10	Pacific oyster	13		■		■											
11	Commercial scallop	7		■													

(1) biology/ecology, (2) genetics/selective breeding, (3) nutrition, (4) health/disease/biosecurity, (5) environmental requirement, (6) husbandry techniques, (7) farming systems, (8) water quality, (9) waste treatment, (10) animal welfare, (11) markets/marketing/logistics/supply chains, (12) product development, (13) economics, (14) environmental interactions, (15) law/policy/regulation. RDI is Research Demands Index calculated as the percentage of researched areas out of total 15 functional areas surveyed.

Table 87. Functional areas requiring substantial research effort by species overseas

No	Common name	RDI (%)	Functional areas for research														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Venerid clam	87	■	■		■	■		■	■	■	■	■	■	■	■	■
2	Portuguese oyster	53		■		■	■						■	■	■	■	■
3	Suminoe oyster	47		■		■							■	■	■	■	■

(1) biology/ecology, (2) genetics/selective breeding, (3) nutrition, (4) health/disease/biosecurity, (5) environmental requirement, (6) husbandry techniques, (7) farming systems, (8) water quality, (9) waste treatment, (10) animal welfare, (11) markets/marketing/logistics/supply chains, (12) product development, (13) economics, (14) environmental interactions, (15) law/policy/regulation. RCI is Research Demands Index calculated as the percentage of researched areas out of total 15 functional areas surveyed.

4.5. REMARKS

- Mollusc aquaculture has great potential where water bodies are free from pollutants and red tides thanks to their low-input nature. If hatchery and farming technologies are well established, mollusc aquaculture could be low in production cost, but relatively high in value of end products; and in a long run more sustainable since it could rely on natural environment especially for feeding. The audits show that mollusc candidates for aquaculture in Australia are highly diverse. Commercial aquaculture production is already established for pearl oyster, Sydney rock oyster, Pacific oyster and abalones. Research on other species have been conducted to explore their potential for aquaculture. In general, mollusc researches are advanced in Australia. It is interesting that none of the audited researches were prompted from the results of market studies. Our visits to different fish markets show a wide range of Australian wild-caught molluscs at prices lower than that for the most popular aquaculture species mentioned above. As none of the audited mollusc species in this study grow fast (i.e. grow-out period is less than 12 months) or low production cost, farming new species must be highly challenging or less attractive to investors due to potentially low profitability. Thus, it is wise to focus RD&E effort to increase production efficiencies of the existing industries. This strategy is critical to strengthen the competitiveness of Australian mollusc products in international markets as currently 41% of the audited species could be exported. For new species or industry priorities should be given to those that could be produced in large volume at low cost, preferably using existing technologies established in Australia and overseas. Pipi, blood cockles and hard clams should be considered for Northern and Western Australia. Our observations show market prices are good for these species. What important next is a proper market research to assess demands for this group of species, not only in Australia but potential international markets as well. Hatchery and farming technologies are available for these species. Adaptive research and commercial trials would help quickly establish farming protocols. Massive farming areas are available in Northern Australia (Irvin *et al.* 2017; CRCNA 2020). The reputation of Australian agriculture products and pristine environment will help export these species to Asia where consumption of high-quality seafoods is growing faster than supply or European countries which have been sourcing aquaculture mollusc species from Asia with increasing concerns of quality.

- Past research effort on mollusc species had focused on health, nutrition, genetics/breeding and, to a lesser extent, farming systems and husbandry techniques. These observations are in line with both the challenges for health management in an open farming environment that the industries have encountered for many years and advancement of breeding programs. Successful breeding programs have been implemented for abalone, Pacific oyster and recently pearl oyster (Elliott *et al.* 2010, Kube *et al.* 2018; Flower 2020). A similar breeding program should be established for Sydney rock oyster. This species is high ranked among the audited species in many different aspects, indicating great potential for further development. Within the scope of this study, research coverage is far more advanced in Australia than overseas. This helps explain why Australian mollusc aquaculture has developed well and has a lot of potential to grow in the future. As for production stages, past research had commonly supported broodstock maturation, grow-out, broodstock domestication and larval rearing. These are all essential to grow commercial aquaculture production. Thus, what have kept commercial aquaculture of molluscs from growth are likely more non-technical factors. Furthermore, as live products are preferred by consumers for all the 12 audited species, more research on harvesting, processing and transport are in need, especially if export markets are targeted.
- As already reported for the audited crustacean species, the most two common barriers to further development of mollusc aquaculture are insufficient supply of quality seed and increasing disease incidences. It should be noted that these barriers are existing for important commercial species such as pearl oyster and Pacific oyster. High production cost (due to high labour cost and slow growth rate of the selected species) will make the farming of these species in Australia less competitive compared with other countries in the global market. Insufficient supply of quality seed does have severe effects of scaling up commercial aquaculture. This barrier has been identified via this study for finfish, crustaceans and now molluscs. Further research to improve hatchery production at commercial scale will help remove this barrier. As diseases have become continuing threat, breeding programs for disease resistance or general robustness would be helpful. A combination of genetics research and industry-based selective breeding program for disease resistance and growth appears helpful to industry development given the demonstrated success of breeding program for Pacific oyster (Kube *et al.* 2018). Research on zonal management to control or manage disease outbreaks are also highly important.
- Our further examinations reveal that limited availability of required inputs for farming is another challenge, especially for new species. Low availability of key inputs like drugs/chemicals to control diseases, conditioners for water quality management, broodstock and seed should be addressed via a combination of research and supports for start-up companies (in terms of

policies and technically). As for research, evaluation of suitability or application protocol development of available drugs/chemicals and conditioners overseas could help speeded up time to market for these inputs. Also limited availability of skilled labour indicate the need for training while finance and technical support may require policy reforms to be improved.

- Compared with finfish and crustacean groups, molluscs have higher potential for production increase and less barriers to overcome. R&D are in need for many species including those more established in terms of aquaculture production either as volume or value. As Australia has been quite advanced in research, further investment in R&D will help maintain our leading role, which eventually secure the competitiveness of our products in international markets and to offer more high-quality products at affordable prices for domestic consumption. Species that should be supported by R&D include Sydney rock oyster, Pacific oyster, pearl oyster and abalones. The results of this study suggest that R&D priority should be given to Sydney rock oyster. This species appears to be a very good candidate from both market and technical perspectives. Research on new species such as blood cockle, pipi, hard clams or scallops should aim at hatchery production using the know-how and technologies that are already established for more established species or through adoptions of overseas technologies. The available seeds from research could be then used to examine low-input farming models such as extensive, ranching or restocking programs. Doughboy and commercial scallops are quite challenging as wild-caught products are still available at low prices and likely higher preference of consumers.

PART 5: OTHER SPECIES

5.1. AUDIT OF RESEARCH EFFORT

5.1.1. The audited species and current aquaculture status

Four other species were audited by Australian scientist including the green halophilic alga, torch coral, purple sea urchin and tropical sea cucumbers (Table 82). This group of species are highly diverse in terms of product utilization. Torch coral *Euphyllia glabrescens* is an ornamental species. Commercial production is small scale and currently produced by few producers or farms in Australia. The green halophilic alga *Dunaliella salina* has been commercially cultivated in Australia since the 1980s to produce carotenoid β-carotene for pharmaceutical and nutraceutical applications. Australia has two production plants which are the largest commercial microalgae production plants globally (Borowitzka 2013). Dried D. salina for use in animal feed is also produced. Commercial farming of tropical sea cucumbers has not started yet. Sea cucumbers are merely harvested from wild stocks by licensed fishermen. Demand for Australian sea urchin roe has rapidly increased in recent years. Aquaculture of sea urchin at this stage relies on the collection of wild urchins from urchin barrens for roe enhancement. This practice helps control explosion of wild sea urchin population. Marketable roe can be achieved after 12 weeks of onshore aquaculture roe enhancement.

Table 88. Other species audited in Australia and overseas

No	Common name	Scientific name	Markets	Preferred products
1	Green alga	*Dunaliella salina*	Domestic, Export	Extracted beta-carotene, dried algae
2	Purple sea urchin	*Heliocidaris erythrogramma*	Domestic	Roe
3	Tropical sea cucumbers	*Holothuria scabra*	Export (limited)	Fresh, dried and frozen whole
4	Torch coral	*Euphyllia glabrescens*	Domestic, Export (limited)	Live
5	Diatom	*Thalassiosira weissflogii*	Domestic	Live, Extracted substances
6	Copepods	*Calanus spp., Acartia tonsa, Pseudodiaptomus annandalei*	Domestic	Live, frozen whole
7	Japanese palolo	*Tylorrhynchus heterochaetus*	Domestic, Export (limited)	Live, fresh/frozen whole

Overseas, diatom, copepods and Japanese palolo were audited by scientists in Taiwan and Vietnam. The centric diatom *Thalassiosira weissflogii* and copepods are used for larviculture of aquaculture species. Thus, they are considered as inputs for aquaculture rather than food-fish species. The Japanese palolo is a delicacy in Vietnam. This high-value species has been farmed in several northern provinces of Vietnam. Good prices and export potential have encouraged producers to invest in farming. Current aquaculture production of Japanese palolo is estimated at around 300 tonnes/year in Vietnam.

5.1.2. Research history and effort

Research on green algae by Northern Territory Department of Primary Industries & Fisheries dated back to 1988, earliest among all the audited species and lasted for 5 years till 1993. Research results could support stock culture, mass culture and harvest of green alga. Research on sea cucumber started long before those on purple sea urchin and torch coral. Three ASCRC projects on population genetics, propagation and sea ranching, and broodstock conditioning of tropical sea cucumbers were conducted with good collaboration with Tasmanian Seafoods P/L, Flinders University, University of the Sunshine Coast, DAC and ACIAR. Research on purple sea urchin started in 2016, prompted by the potential of this species for aquaculture, personal interest and assignment of employer. Research on torch coral just started in 2018 in response to industry request. Market demand for this species has been high. Its “gold” phenotype is considerably more valuable than any other. Overseas, research on other species overseas started between 2012 and 2018. Research effort in terms of duration is quite limited in generally, indicating either these species are new, or their farming is still at early stages.

Table 89. Research start time and duration

No	Species	Start year of research	Research duration (years/scientist)
1	Green alga	1988	5
2	Purple sea urchin	2016	2
3	Tropical sea cucumbers	2008	3
4	Torch coral	2018	1
5	Diatom	2012	7
6	Copepods	2015	4
7	Japanese palolo	2015	3

5.1.3. Research areas: targeted functional areas and production stages

Among the 15 surveyed functional areas, husbandry techniques attracted more research, followed by health and environmental requirements. As for individual species research on purple sea urchin has the highest Research Comprehensive Index (RCI), covering 7/15 functional areas (Table 88). These areas are all supportive to farming, but more R&D are needed to fill up the current gaps in order to facilitate commercial aquaculture. Green alga and tropical sea cucumbers rank next with an RCI of 36%. Interestingly, markets/marketing/logistics/supply chains and product development were among the five functional areas that had been researched for green alga, indicating its aquaculture must have been established. The targeted functional areas for research on tropical sea cucumbers are helpful to establish hatchery and grow-out productions. Torch coral has a lower RCI of 21%. Research on this species focused on husbandry techniques, farming systems and water quality for torch coral. Overseas, RCI of diatom is highest at 93%. The other two species especially Japanese palolo have much lower RCIs.

Table 90. Functional areas researched by Australian and overseas scientists

No	Common name	RCI (%)	Functional areas for research														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Purple sea urchin	50	■		■	■	■	■				■				■	
2	Green alga	36				■	■	■					■	■			
3	Tropical sea cucumber	36	■	■	■	■		■									
4	Torch coral	21						■	■	■							
5	Diatom	93	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
6	Copepods	36			■		■	■		■						■	
7	Japanese palolo	14						■						■			

(1) biology/ecology, (2) genetics/selective breeding, (3) nutrition, (4) health/disease/biosecurity, (5) environmental requirement, (6) husbandry techniques, (7) farming systems, (8) water quality, (9) waste treatment, (10) animal welfare, (11) markets/marketing/logistics/supply chains, (12) product development, (13) economics, (14) environmental interactions, (15) law/policy/regulation. RCI is Research Comprehensiveness Index calculated as the percentage of researched areas out of total 15 functional areas surveyed.

Regarding production stages, broodstock domestication and grow-out are the focuses of research on all the audited species. The other important stages for research are broodstock maturation, larval rearing and harvest. There are still big gaps for research that can support nursery, harvest, processing, transport and hatchery phase. Research on harvest was conducted only for green alga and purple sea urchin. Torch coral and tropical sea cucumbers have the highest PSCI (50%). There are still many gaps in research for purple sea urchin to make its aquaculture possible. Similarly, research is in need for nursery and grow-out of tropical sea cucumbers. Overseas, Japanese palolo has the highest PSCI (75%). Research on husbandry techniques for Japanese palolo supports all farming production stages, making this species' aquaculture viable. That of diatom is 63%, significantly higher than PSCI of copepods.

Table 91. Production stages targeted by research

(B) broodstock domestication, (M) maturation, (L) larval rearing, (N) nursery, (G) grow-out, (H) harvest, (P) processing, (T) transport. PSCI (%): production stage coverage index.

No	Species	PSCI	Production stages							
		(%)	(B)	(M)	(L)	(N)	(G)	(H)	(P)	(T)
1	Torch Coral	50								
2	Tropical sea cucumber	50								
3	Green alga	38								
4	Purple sea urchin	38								
5	Japanese palolo	75								
6	Diatom	63								
7	Copepods	25								

No funding for R&D from the industry or adoption of research results was reported for the four audited species in Australia. That is understandable for tropical sea cucumbers, purple sea urchin and torch coral, whose aquaculture is still under exploration. For green alga it is believed that cultivation technologies have been established in house by commercial companies and are commercially confidential. Results of research on Japanese palolo have been adopted largely by the local aquaculture industry in Vietnam. Similar to what reported in Australia, there has been no funding from the industry for research on Japanese palolo.

5.3. OPPORTUNITIES FOR FURTHER DEVELOPMENT

5.3.1. Evaluation of aquaculture potential

Market potential are above average for all the four audited species and very high for torch coral and tropical sea cucumbers. However, biological potential of purple sea urchin and torch coral are much higher than that of tropical sea cucumbers. Enabling factors appear unfavourable to all the audited species, ranging from 17 to 33%. This implies that aquaculture development for these species is still highly challenging. Overall, the potential for commercial aquaculture of torch coral is highest, followed by tropical sea cucumbers and purple sea urchin. Green alga has the lowest overall potential. Overseas, Japanese palolo stands out from the other two species with an overall potential score of 227, higher than that of torch coral in Australia.

Table 92. Potential for aquaculture of the audited crustaceans in Australia. Data are percentage of the criteria classified as favourable

No.	Common name	*n*	Market potential	Biological potential	Enabling factors	Overall potential
1	Torch coral	*1*	100	80	33	213
2	Tropical sea cucumbers	*1*	100	40	33	173
3	Purple sea urchin	*1*	50	80	33	163
4	Green alga	*1*	75	20	17	112
5	Japanese palolo	*1*	100	60	67	227
6	Copepods	*1*	50	20	83	153
7	Diatom	*1*	50	40	50	140

5.3.2. Possession of desirable attributes

Evaluation based on nine desirable attributes reveal that DSI (desirable score index) is the same for purple sea urchin, torch coral and tropical sea cucumbers. There are few differences between tropical sea cucumbers and the other two species. Tropical sea cucumbers have slow growth rate but are easy to reproduce in captivity. Thus, it may be easier to produce juveniles for commercial farming. In contrast, torch coral and purple sea urchin grow fast but captive reproduction is not easy. Furthermore, the exploitation of wild stocks of tropical sea cucumbers is restricted in Australia while heavily depleted in many other countries. This helps create demand for farmed sea cucumbers. However, low production cost is likely not possible for all these species. Overseas, DSI of three audited species is 44%. Interestingly, copepods and Japanese palolo have the same desirable attributes.

Table 93. Possession of desirable attributes and desirable score index (DSI) by species

(Re) easy to reproduce in captivity, (Gr) grow-out period less than 12 months, (SC) can be farmed intensively in sea cages, (MP) premium market prices, (R&D) has attracted substantial R&D interest, (Pt) grow well on plant-protein-based diet, (Wi) wild catch is limited or banned, (PC) estimated production cost less than US$3/kg, (Tr) has been traded regionally or globally.

No	Species	DSI	Desirable attributes								
		(%)	Re	Gr	SC	MP	R&D	Pt	Wi	PC	Tr
1	Purple sea urchin	55.6									
2	Torch coral	55.6									
3	Tropical sea cucumber	55.6									
4	Green alga	44.4									
5	Diatom	44.4									
6	Copepods	44.4									
7	Japanese palolo	44.4									

5.2.3. Technology readiness

Assessment of technology readiness show that farming of green alga is commercially viable as already reported by Borowitzka (2013). Torch coral still have some challenges with spawning in captivity. Thus, this species may be less ready for aquaculture than tropical sea cucumbers. Farming of purple sea urchin for roe production is commercially viable if wild animals are collected for a period of roe enhancement. However, hatchery technology needs to be established for purple sea urchin via research on broodstock maturation, spawning, larval rearing and nursery. These will help turn sea urchin into real aquaculture species and make its farming sustainable. Overseas, production of diatom and Japanese palolo are both technically feasible. Copepod production still requires substantial research in all production stages.

Table 94. Technology readiness level for each production stage by species in Australia

No	Common name	n	TRI (%)	Technology readiness level							
				BMA	SPA	LAR	NUR	GRO	HAV	PRO	TRA
1	Green alga	*1*	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
2	Torch coral	*1*	2.6	3.0	1.0	3.0	3.0	3.0	3.0	3.0	2.0
3	Tropical sea cucumber	*1*	2.5	3.0	3.0	2.0	2.0	3.0	2.0	3.0	2.0
4	Purple sea urchin	*1*	1.5	1.0	1.0			3.0	3.0	2.0	2.0
5	Diatom	*1*	2.2	3.0		2.0		3.0	2.0	1.0	2.0
6	Japanese palolo	*1*	2.0	2.0	2.0	2.0	2.0	3.0	3.0	1.0	1.0
7	Copepods	*1*	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

(BMA) broodstock maturation, (SPA) spawning, (LAR) larval rearing, (NUR) nursery, (GRO) grow-out, (HAV) harvest, (PRO) processing, (TRA) transportation. Technology readiness levels: 3.0 = commercially viable, 2.0 = technically feasible, 1.0 = experimental.

5.2.4. Potential for adoption of existing technologies

Torch coral and tropical sea cucumbers are believed to benefit from adoption of existing technologies. For torch coral technology adoption is possible for processing and transport. Existing grow-out technologies can be adopted for tropical sea cucumbers. Overseas, Japanese palolo has the highest PSCI (63%). Technology adoption is possible for hatchery production, nursery and grow-out. This advantage will help accelerate the development of Japanese palolo aquaculture. PSCIs copepods and diatom are much lower.

Table 95. Production stages that could benefit from adopting existing technologies

(B) broodstock domestication, (M) maturation, (L) larval rearing, (N) nursery, (G) grow-out, (H) harvest, (P) processing, (T) transport. PSCI (%): production stage coverage index.

No	Species	PSCI (%)	Production stages							
			(B)	(M)	(L)	(N)	(G)	(H)	(P)	(T)
1	Torch coral	25								
2	Tropical sea cucumber	13								
3	Japanese palolo	63								
4	Copepods	25								
5	Diatom	13								

5.3. BARRIERS TO FURTHER DEVELOPMENT

Barrier Index (BI) is relatively low for the audited species. None of the surveyed barriers are reported for the green alga. Unfavourable regulations, insufficient supply of quality seed, lack of funding for R&D and lack of investment are the major barriers to further development of the three remaining species. As for individual species, both tropical sea cucumbers and torch coral have insufficient supply of quality seeds as a barrier. More specifically, as reported through this study there are still several technical challenges for tropical sea cucumbers including reproduction control in captivity, weaning/settlement, knowledge of and access to nutritional requirements, tolerance to high rearing densities, size at maturation/ability to control maturation, feed conversion during grow-out/nutritional requirements.

Table 96. Barriers to aquaculture development of other species audited in Australia and overseas

No	Species	BI (%)	Barriers 1	5	7	9	10	11	13	16	17	18
1	Purple sea urchin	22.2	■			■			■	■		
2	Tropical sea cucumber	16.7	■		■							■
3	Torch coral	16.7			■				■	■		
4	Diatom	27.8		■			■	■	■		■	
5	Japanese palolo	27.8				■	■	■	■	■		
6	Copepods	5.6								■		

n: number of audits; BI (%): barriers index, i.e. percentage of the number of identified barriers over 18 pre-defined ones; (1): Unfavourable regulations; (5) Lack of skilled labour; (7) Insufficient supply of quality seed; (9) Too small industry; (10) Low diversity or lack of value-added products; (11) Poor downstream capacity; (13) Lack of investment throughout the supply chain; (16) Limited funding for R&D; (17) Poor growth in grow-out; (18) Poor survival in grow-out.

5.4. FUTURE RESEARCH

Research on purple sea urchin is recommended extensively across 15 functional areas with stronger emphasis on health, environmental requirements, husbandry, market and product development. RDI of purple sea urchin is significantly higher than that for tropical sea cucumbers and torch coral. Across the three species recommendations for research are more on biology/ecology, genetics/breeding and nutrition. Specific recommendation for future research on sea cucumber include (i) expand investigation of population structures of Australian tropical sea cucumbers, (ii) larval settlement cues, (iii) juvenile weaning and aquaculture diet development, and (iv) continue initial research on endogenous factors controlling maturation and spawning. For torch coral, it is expected that research could help produce multiple spawning to maximize production.

Table 97. Functional areas requiring substantial research effort

No	Species	RDI (%)	Functional areas for research 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Purple sea urchin	71	■			■			■	■	■		■	■	■	■	■
2	Sea cucumbers	29	■	■	■			■									
3	Torch coral	14		■	■												
5	Diatom	43		■						■	■		■	■			■
6	Copepods	36			■		■	■		■						■	

(1) biology/ecology, (2) genetics/selective breeding, (3) nutrition, (4) health/disease/biosecurity, (5) environmental requirement, (6) husbandry techniques, (7) farming systems, (8) water quality, (9) waste treatment, (10) animal welfare, (11) markets/marketing/logistics/supply chains, (12) product development, (13) economics, (14) environmental interactions, (15) law/policy/regulation. RDI is Research Demands Index calculated as the percentage of researched areas out of total 15 functional areas surveyed.

5.5. REMARKS

- Three out of the four audited species can be considered as new species for aquaculture in Australia. Commercial production of the halophilic green alga is well established. Intentions to expand its commercial production to new geographical locations, e.g. Northern Australia should be examined technically and economically with the existing industry in order to capitalize established technologies and more importantly market intelligence. The most interesting about this group is meeting demands of global niche markets for non-traditional aquaculture. Instead of producing food fish, aquaculture of these species aims to supply food delicacy, pharmaceuticals, functional food ingredients or ornamental. Global R&D capital of tropical sea cucumbers, sea urchin and green alga are considered substantial. Further R&D investment, if wisely selected, could significantly assist commercial aquaculture production.

More importantly, it is likely that Australia should promote "non-traditional aquaculture" for several reasons. To name just two, first we can't compete at large scales with other countries if producing the same species due to high production cost and limited production sites. Second, as the overall development context does not favour aquaculture development (i.e. unfavourable regulations and slowly growing demand for seafoods), it would be wise to target aquaculture species with small production volume but very high values. With a great diversity of aquatic fauna and flora Australia can offer far beyond few identified species in this study. Examples of species of high value and great demand include sea horses, horseshoe crabs, puffer fish, krill, marine sponges, etc.

- Both sea cucumber and purple sea urchin are promising candidates for commercial aquaculture especially when integrated with the farming of existing species such as Atlantic salmon, barramundi or black tiger prawn. Integrated farming can make the most of the existing farming systems and increase the overall carrying capacity of the environment. More importantly, these by-products can generate significant income for the producer. As these species are all sedentary, sea ranching or extensive aquaculture are also options to consider. For all these purposes or options investment in centralized hatchery production is critical and could be effectively supported by adaptive or applied research. Recent advances of research on aquaculture of sea urchins (Williamson 2015; Dvoretsky & Dvoretsky 2020) and tropical sea cucumbers (ACIAR 2012; Han *et al.* 2016) can back up hatchery start-ups or breeding programs. Apart from supplying local industries, there have been indications that juveniles of Australian sea urchins could be exported to other countries for aquaculture purpose.
- The barriers to further development for this group of species echo what have been identified for the audited finfish, crustaceans and molluscs. Unfavourable regulations, insufficient supply of quality seed, lack of funding for R&D and lack of investment are the common barriers to aquaculture development in Australia. The lack of quality seed could be removed effectively through stronger focus of RD&E on hatchery production. Adaptive or applied research in partnership with investors or existing aquaculture producers should be encouraged to minimize R&D investment and lag time for industry development. The other barriers can be addressed by more economics and policies research with a clear aim to inform policy makers and the public about the benefits that non-traditional aquaculture could sustainably provide.

PART 6: AUDITS BY AQUACULTURE PRODUCERS

6.1. THE AUDITED SPECIES

Only mud crab (*Scylla serrata*) and ornate spiny lobster (*Panulirus ornatus*) were audited for Australia (Table). Audit results are presented in the next section. The lack of participation of aquaculture producers in this study made our intended comparison with evaluations by scientists impossible. Overseas, aquaculture producers from Colombia, Mexico, Zambia, Egypt and Vietnam audited 9 different species. Whiteleg shrimp (*Penaeus vannamei*) dominates with 7 audit attempts, followed by barramundi (*Lates calcarifer*) with 3 audit attempts. The audited species overseas include black tiger prawn (*Penaeus monodon*), cobia (*Rachycentron canadum*) and barramundi, which are currently farmed in Australia. Snubnose pompano (*Trachinotus blochii*) and a similar species – permit (*Trachinotus falcatus*) are also audited. Except Nile perch all the other audited species are currently farmed and marketed in many different countries. Global production of tilapia, whiteleg shrimp and Tra catfish have reached million tonnes (FAO 2020). Audit results of overseas species are also presented as reference for Australian aquaculture producers and scientists.

Table 98. Species audited by aquaculture producers in Australia and overseas

No.	Common name	Scientific name	Number of audits	Farming status	
				Australia	Globally
1	Mud crab	*Scylla serrata*	1	✗	✓
2	Ornate spiny lobster	*Panulirus ornatus*	1	✗	✓
3	Whiteleg shrimp	*Penaeus vannamei*	7	✗	✓
4	Black tiger prawn	*Penaeus monodon*	1	✓	✓
5	Barramundi	*Lates calcarifer*	3	✓	✓
6	Cobia	*Rachycentron canadum*	1	✓	✓
7	Snubnose pompano	*Trachinotus blochii*	1	✗	✓
8	Permit	*Trachinotus falcatus*	1	✗	✓
9	Nile perch	*Lates niloticus*	1	✗	✓
10	Tra catfish	*Pangasianodon hypophthalmus*	1	✗	✓
11	Tilapia	*Oreochromis niloticus*	1	✗	✓

6.2. AUDITS BY AUSTRALIAN AQUACULTURE PRODUCERS

6.2.1. Mud crab

- Mud crab (*Scylla serrata*) is native to Australia and is widely distributed in the Indo-Pacific. This species fetches high prices in domestic market. Its potential for export is high as mud crab are highly sought in many international markets. Like many other crustacean mud crabs must be sold live as preferred by consumers.
- The participating producer reported that planning for mud crab aquaculture was conducted in 2015. The producer's interest in mud crab was prompted by many reasons such as high market demand, profitability, possibility of using existing farming systems, availability of suitable sites for production, availability of required technologies and inputs, existing permit, available supports and established market. Furthermore, the producer believed mud crab aquaculture could enhance the livelihood support of Aboriginal communities. The plan was to produce broodstock and crablets. The company has no R&D unit. Technologies are developed in house with 50% adopted from overseas and 80% from other species. The producer claimed his aquaculture business cover all production stages from broodstock maturation to grow-out

and transport. Furthermore, it was proficient in broodstock management and grow-out. Due to excessive regulations this production plan for mud crab was abandoned. The producer was not aware of any similar attempts to farm mud crab in Australia.

Table 99. Key audit results for mud crab (*Scylla serrata*) and ornate spiny lobster (*Panulirus ornatus*) by Australian producers

Parameters	Mud crab	Ornate spiny lobster
Suitability Index (%)	53.3 (8/15)	53.3 (8/15)
Availability of inputs for farming (%)	92.9 (13/14)	42.9 (6/14)
Farming level	Experimental	Technically feasible
Desirable Index (%)	55.5 (5/9)	44.4 (4/9)
Barrier Index (%)	22.2 (4/18)	11.1 (2/18)
Research Demand Index (%)	46.7 (7/15)	26.7 (4/15)

- As evaluated by the producer mud crab has a favourable score for aquaculture of 53.3 % with 8/15 criteria rated favourable, i.e. easy to reproduce in captivity, good understanding of nutritional requirement, good growth rate, potential of technology adoption, access to production site and market price, export potential. Furthermore, this species possesses 5/9 desirable attributes (namely easy reproduction in captivity, premium market price, substantial R&D investment, wild catch is limited due to strict regulations and global trading history). However, the current level of mud crab farming in Australia is believed still at experimental stage. All the required inputs for mud crab aquaculture are available except domesticated broodstock. However, none of the inputs are considered as highly accessible. The producer predicted that globally market demand and prices for mud crab will increase in the next 5 – 10 years. Also, production and productivity will be improved as farming area is expanding. Production cost, disease risk and technological innovation remain the same as for 2018.
- Four barriers to commercial aquaculture of mud crab in Australia are identified by the producer. These include (i) unfavourable regulations, (ii) limited sites for production, (iii) insufficient supply of quality seed and (iv) increasing risk of diseases. The first barrier, as mentioned above, was the one that made this company give up its plan to produce mud crab. To diversity its aquaculture business this company is evaluating alternatives such as finfish and the ornamental Pacific cleaner shrimps (*Lysmata* sp.).
- The producer is still interested in farming mud crab. Regarding further research on mud crab 7/15 functional areas are recommended including genetics/selective breeding, health, nutrition, farming systems, markets, environmental interactions and policy/regulation.

6.2.2. Ornate spiny lobster

- Like mud crab the ornate spiny lobster *Panulirus ornatus* is native to Australia but widely distributed in tropical waters of the Indo-West Pacific. In Australia spiny lobsters are harvested from the wild and exported live or frozen to several countries. However, consumers prefer live lobsters.

- Planning for commercial production of ornate spiny lobster started in 2018. High market demand, profitability and competitive strength were the three drivers of this production plan. The potential competitive strength is the most important driver as this company would be the world first one to produce both puerulii and marketable-size ornate spiny lobsters. The company's aquaculture business covers most of the production stages including broodstock maturation and spawning, larval rearing, harvest, processing and transport. Production stages that require improvement are broodstock domestication/selective breeding, nursery and grow-out. Thus, perulii are the initial products the company wants to produce. The company has its own R&D unit. Know-how of hatchery production was provided by a research institution. It is estimated that technology adoption is 10% from overseas and 0% from other species.
- As evaluated by the producer the ornate spiny lobster has a favourable score of 53.3%, similar to mud crab with 8/15 criteria rated favourable, i.e. availability of broodstock, reproduction control, less risk of diseases, good survival and growth rate, good domestic market prices, export potential and market sale. Competition with similar products is considered unfavourable. This species has 4/9 desirable attributes (premium price, substantial R&D investment, restricted wild harvest and global trading history). The current level of ornate spiny lobster aquaculture varies with production stages. Grow-out is technically feasible. Harvest, processing and transport are all commercially viable. No evaluation was made by the producer for broodstock maturation, spawning, larval rearing and nursery. As for farming inputs, there are concerns of limited availability of grow-out feeds, farming systems and equipment, technical support and sites for production. The producer predicted that globally market demand, market price, production and technological innovation will all increase in the next 5 – 10 years. Slight increment of productivity, production cost and farming area should be expected. However, risk of diseases remains as for 2018.
- Two barriers (unfavourable regulations and limited sites for production) are identified for commercial aquaculture production of ornate spiny lobster in Australia. They echo exactly what haven reported for mud crab. However, the company plans to strengthen its business viability increasing production via R&D partnership, call for investment, improvement of productivity, reduction of production cost, adoption of technological innovations, increasing production sites and vertical integration.
- For further research on ornate spiny lobster the producer recommended four functional areas: genetics/selective breeding, nutrition, husbandry techniques and farming systems. Regarding the need to diversify its aquaculture business the producer is assessing a few candidates such as short spined sea urchin (*Heliocidaris erythrogramma*) and algae/seaweeds group.

6.3. AUDITS BY OVERSEAS AQUACULTURE PRODUCERS

6.3.1. Suitability for commercial aquaculture

The nine audited species overseas are considered suitable for commercial aquaculture thanks to many favourable characteristics (Figure 50). However, there some limitations regarding tolerance to diseases, tolerance to high rearing densities and survival in grow-out phase. When evaluated separately the group that consists of species currently farmed (black tiger prawn, barramundi, cobia) or considered for farming (snubnose pompano and permit) in Australia have some advantages such as possibility to adopt existing technologies, flesh yield, market scale and domestic market prices; but are less favourable regarding tolerance to diseases and tolerance to high rearing densities.

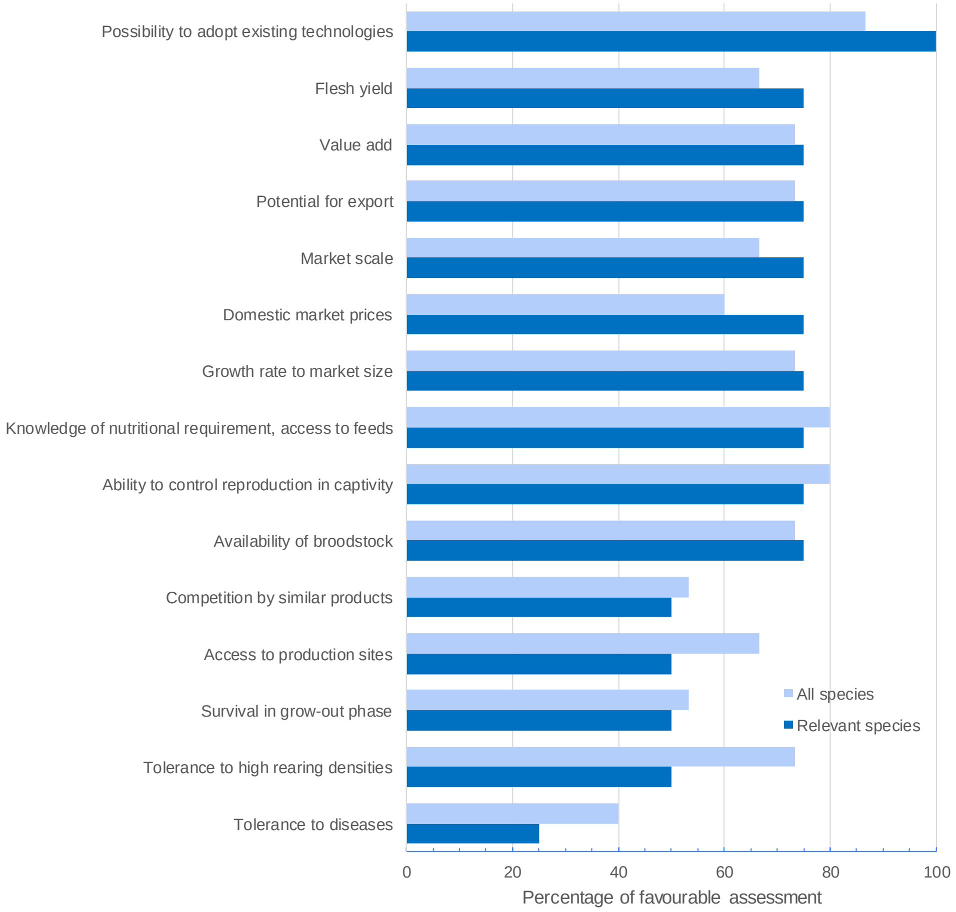


Figure 48. Characteristics of the audited species overseas by the participating producers

The suitability for commercial aquaculture is highest for snubnose pompano *Trachinotus blochii* and its cousin – permit *T. falcatus* and is lowest for barramundi among the nine audited species (Figure 51). Black tiger prawn is considered far less suitable than whiteleg shrimp. This evaluation is sound as whiteleg shrimp has been accounted for more than 80% of global shrimp production reaching 5.0 million tonnes in 2018 (FAO 2020). Cobia suitability for commercial aquaculture is rated as high as that for tilapia, Nile perch or Tra catfish. However, it is still a potential since cobia aquaculture production has been marginal compared with 6.5 million tonnes of tilapia or 1.2 million tonnes of Tra catfish produced annually (FAO 2020). Overall, the audited species overseas have an average SI (Suitability Index = % of favourable evaluation out of 15 characteristics) of 72.7%. Further evaluation using 9 desirable attributes results in an average DI (Desirable Index, see Part 2) of 73.3% for the audited species overseas.

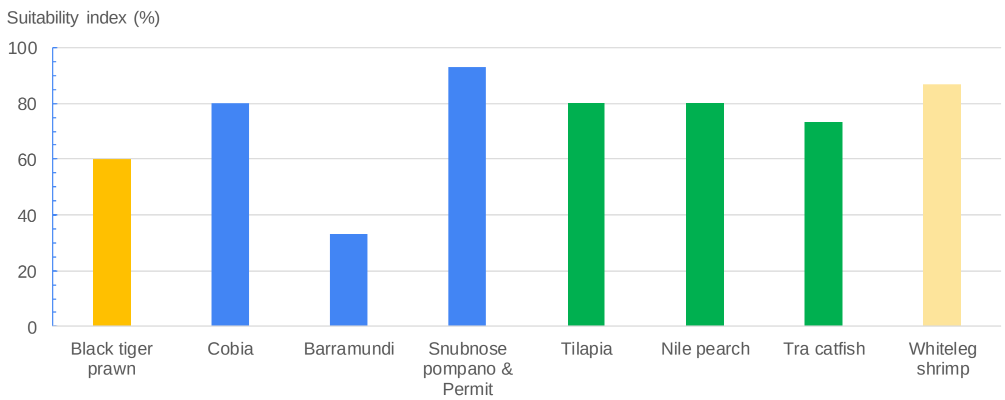


Figure 49. Suitability for commercial aquaculture of the audited species as evaluated by overseas aquaculture producers (%)

6.3.2. Selection of species for commercial production

The most common reasons for species selection are high market demand and expected profitability (Figure 52). What important next include the possibility to farm using existing systems/technologies and then availability of production sites. The availability of technical/financial supports or technologies/inputs for farming is considered by more than 60% of the participating aquaculture producers. It is apparent that commercial production is only possible if market demand is high and key inputs for farming are available.

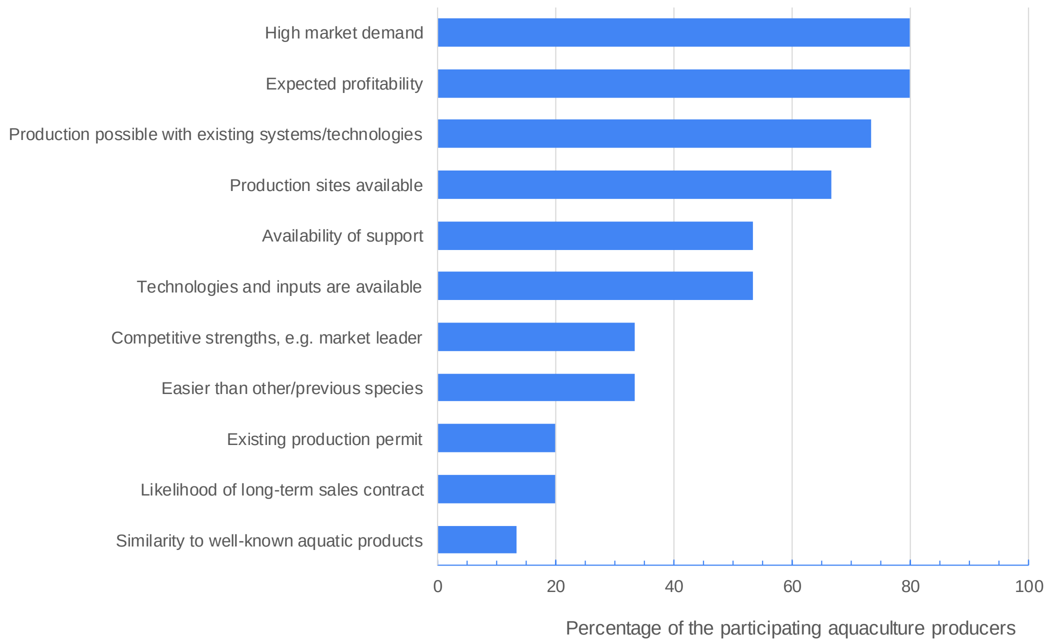


Figure 50. Reasons for species selection for commercial aquaculture production

6.3.3. Technology development and adoption

Nearly 87% of the participating producers claim that they have developed their production technologies in-house. The other 13% who produce tilapia and whiteleg shrimp obtained production technologies from research institutions. About 67% of the participating producers reported they learned production technologies from other producers while 93% relied on supports of researchers or research institutions. On average 57.7% of the current technologies used for commercial production of the nine audited species are adopted from what have been developed for other species or for other countries.

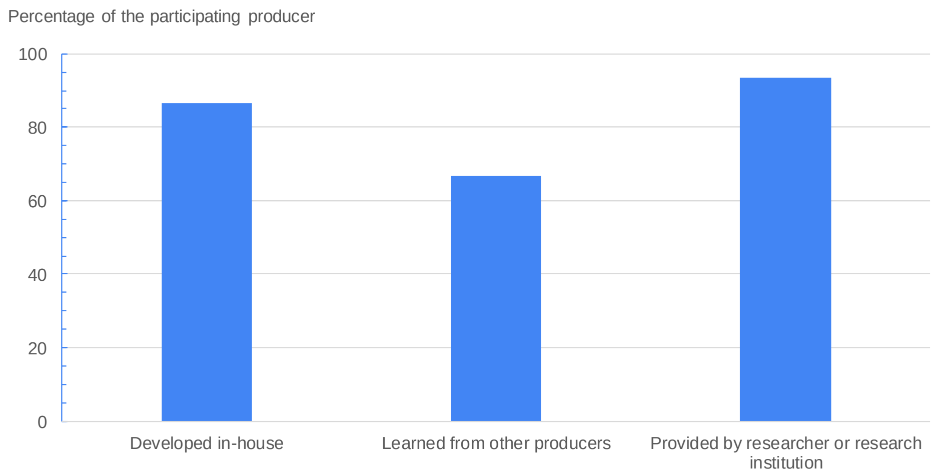


Figure 51. Sources of information for production technology development reported by the participating aquaculture producers

6.3.4. Needs for further improvement

Across different production stages broodstock domestication has the highest demand for improvement. Furthermore, demand for improvement in the hatchery phase is higher than the rest. Transport and grow-out have the lowest demands. These observations emphasize the need to further improve hatchery technologies. In combination with advances in broodstock domestication and/or selective breeding, it could result in significant improvement of seed supply and quality.

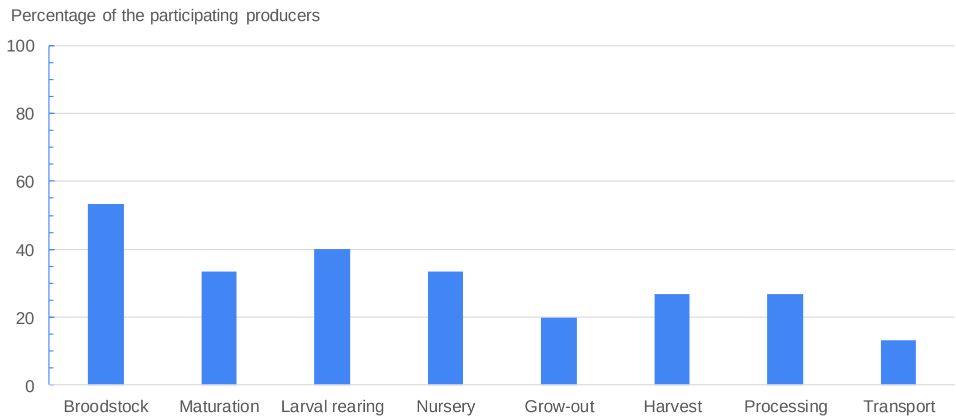


Figure 52. Improvement needs for different production stages

6.3.5. Barriers

Increasing threat of infectious diseases is the top barrier for the audited species, whose commercial aquaculture production are already significant except Nile perch. The next two major barriers are lack of investment and increasing concern of environmental impacts. These are identified for more than 40% of the audited species. Limited funding for R&D, poor infrastructure, heavy reliance on fish meal, insufficient supply of quality seed, low profit and unfavourable regulations are considered barriers to further development of 33% of the audited species. None of the participating producers refer limited sites for production or two small industry as barriers, which are in contrast with what reported for Australian species.

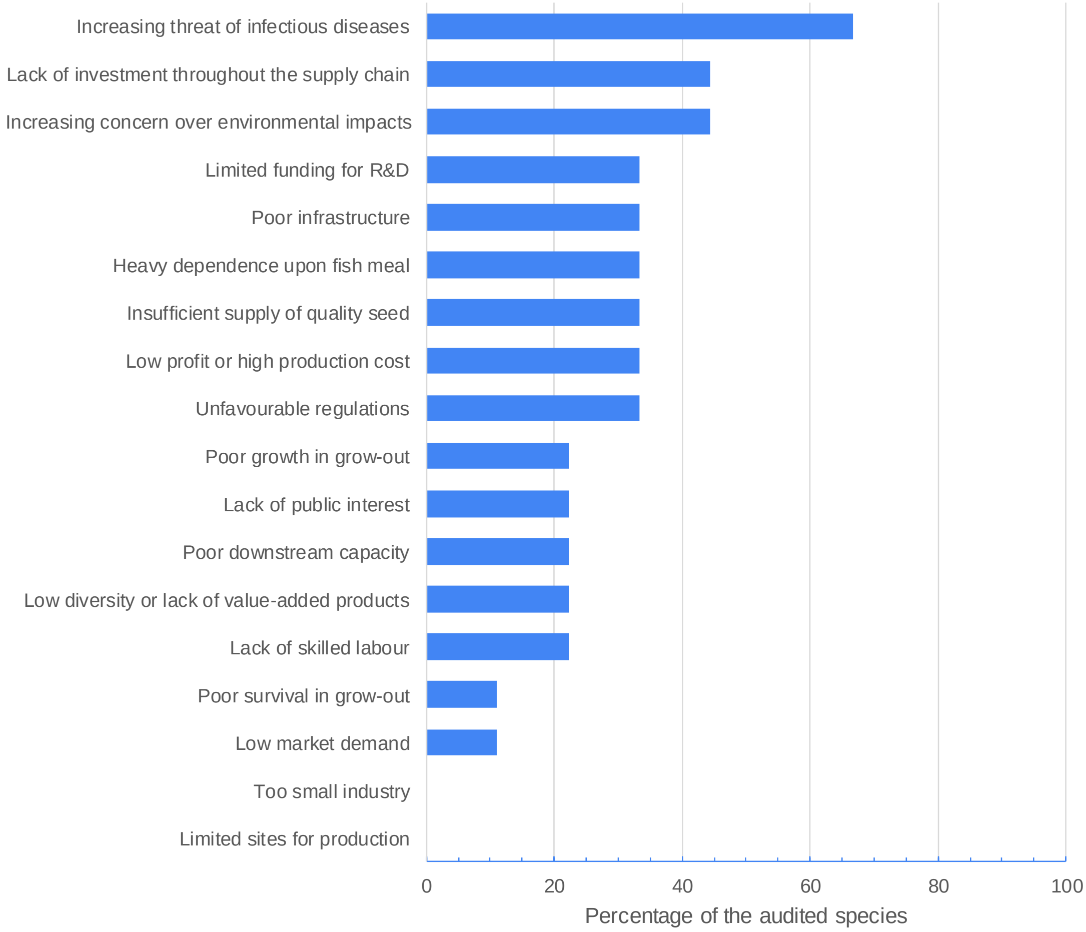


Figure 53. Identified barriers for the audited species

As for individual species barramundi has many more barriers than the other audited species (Figure). Barriers such as limited production site, poor growth rate, insufficient supply of quality seed, too small industry and lack of public interest are not applicable to barramundi. However, low market demand, diseases and poor survival during grow-out period are the barriers to commercial aquaculture of barramundi. It is the only species among the 9 audited species overseas has low market demand as the barrier to further development. In contrast, snubnose pompano and permit has no barriers to further development, suggesting their great potentials for commercial aquaculture where farming is favourable. BI of cobia is less than half of barramundi's, but double that of tilapia. Among the three species with significant global productions whiteleg shrimp aquaculture has more barriers to further development compared with tilapia and Tra catfish. BI of black tiger prawn is just half of whiteleg shrimps, suggesting higher potential for increasing production.

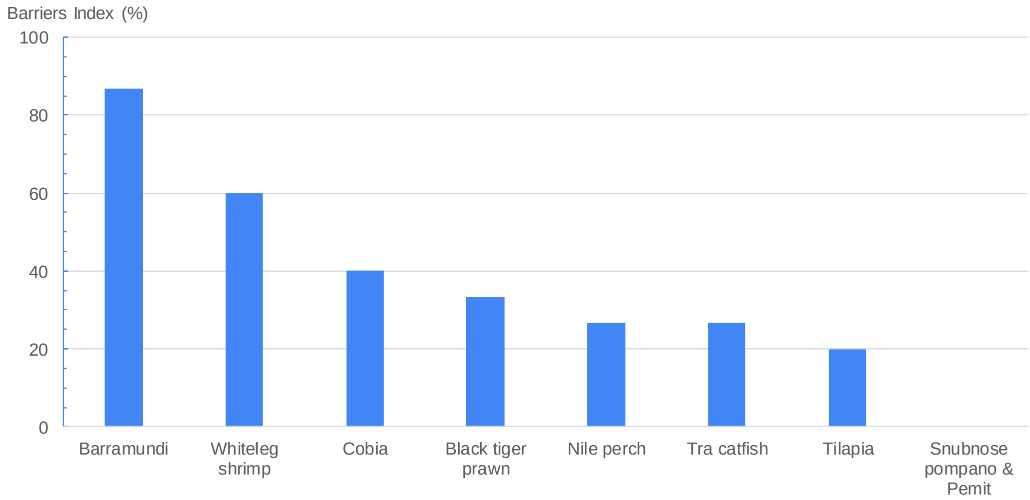


Figure 54. Barrier Index (% of the identified barriers out of 18 surveyed ones) of the audited species

6.3.6. Production outlook

The future of aquaculture of the audited species is promising. Generally, demands, market price, production, farming area, technological innovation and productivity are all predicted to increase (Figure 57). Demand is expected to significantly increase for tilapia, Nile perch, black tiger prawn, snubnose pompano and permit while slightly increase for the other species such as whiteleg shrimp, cobia and barramundi. Significant increase of market price is predicted only for tilapia and black tiger prawn. However, there are some challenges regarding significant increase of production cost (for cobia, whiteleg shrimp and tilapia) or significant problems of diseases (for cobia, whiteleg shrimp, Tra catfish). Interestingly, a reduction of production cost is expected for snubnose pompano and permit while less diseases is expected for tilapia. Overall, it appears that overseas black tiger, snubnose pompano and permit have better of opportunities for production increase compared with barramundi and cobia.

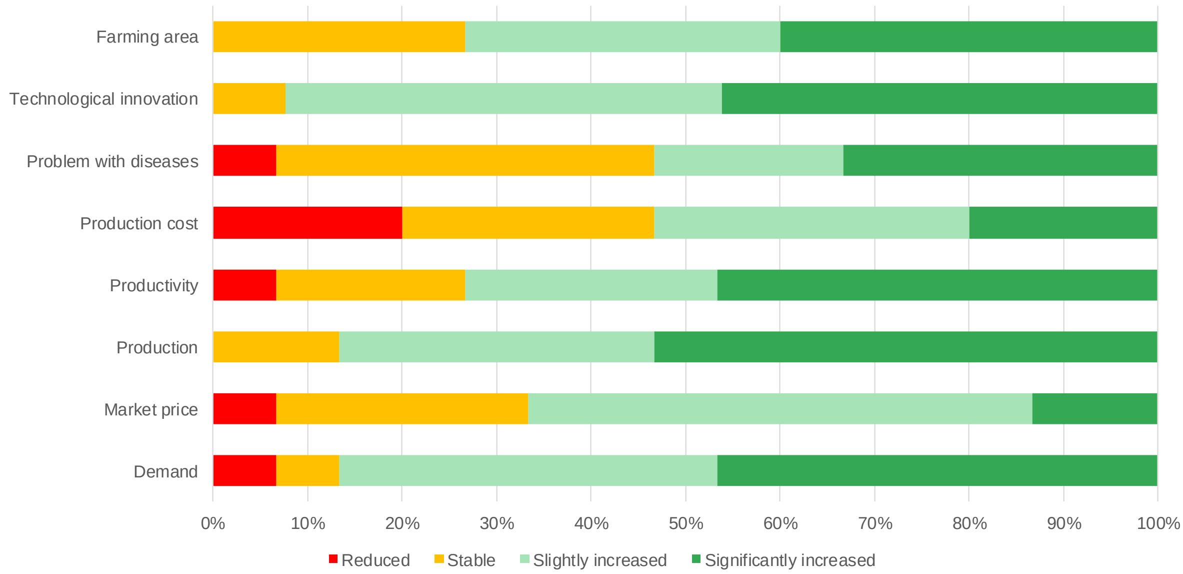


Figure 55. Aquaculture development outlook for the audited species

6.3.6. Research needs

Producers of the nine audited species recommend more research across 15 different functional areas. Significant focuses are placed on farming systems and health (67%). The other areas that have high demands for research include husbandry techniques, genetics/selective breeding and, to a lesser extent, nutrition, waste treatment and environmental requirement. As for individual species, RDI (Research Demand Index) is highest for whiteleg shrimp and lowest for snubnose pompano and permit. For whiteleg shrimp no research is recommended regarding biology/ecology, markets, production development and policy/regulations. Nutrition and husbandry techniques (more on feeding management) are recommended for snubnose pompano and permit. The importance of feeding management for better profitability is emphasized as the participating producer, who has worked for years on different species, believe that we can't apply salmon feeding or feeding to 80% satiation in large scale farming of tropical marine finfish. Better understanding is needed about feeding requirement in relation to fish size, feed composition, water temperature, etc. Barramundi has higher research demand than cobia. Replacing trash fish with formulated diet for feeding cobia has the priority. For both species, genetics/selective breeding, health and market are the functional areas requiring more research. Research on farming systems is recommended for all the three audited freshwater fishes.

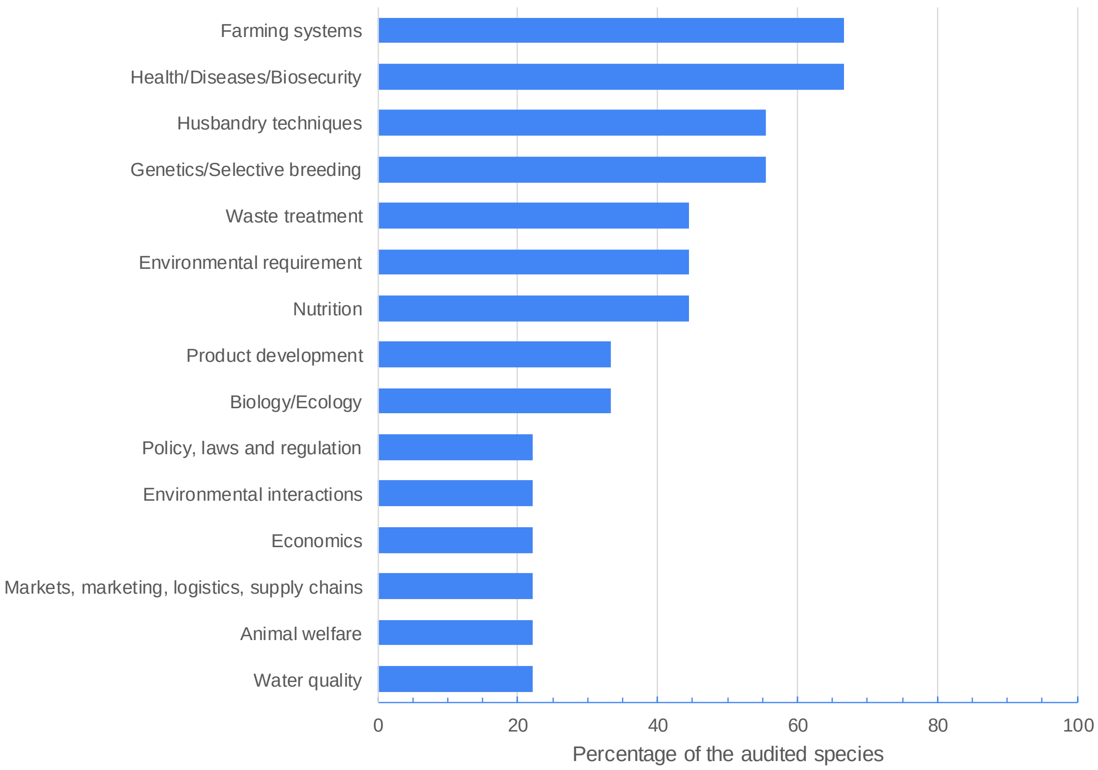


Figure 56. Functional areas that require more research to support commercial aquaculture production of the audited species

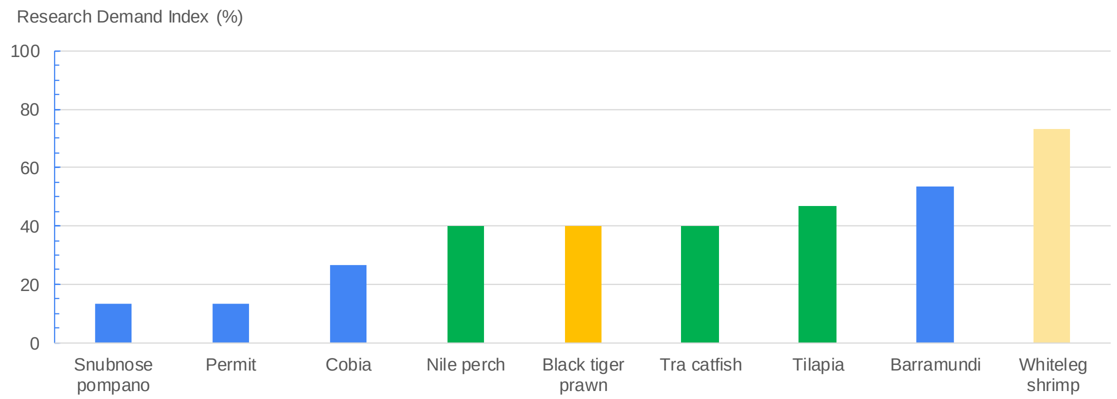


Figure 57. Research demand index for the audited species (calculated as percentage of functional areas that require more research out of the 15 surveyed functional areas)

6.4. REMARKS

- Farming of ornate spiny lobster and mud crab are expected to grow in Australia. They both have low BIs and above-average potential. Between the two species ornate spiny lobster appears a better choice thanks to its premium market price, export demand, substantial R&D capital, possibility to farm either in sea cages or RAS and more importantly the availability of hatchery-produced perulii in Australia. As for now Australia is the most successful country in developing hatchery technologies for tropical spiny lobsters. This unique competitive strength will help Australia to dominate the supply of farmed lobsters in the future, especially in markets where consumers care about the sustainability of aquaculture.
- Except Nile perch all the audited species overseas have had established commercial aquaculture productions. Although the development contexts are different among countries, evaluation of species suitability for commercial aquaculture could be used as reference for Australian aquaculture development. Clearly, high demand, good market prices, availability of technologies and inputs, and good profit have driven decision of producers. Often species that are harder to farm have higher demand, market prices and thus better profit for producers. Thus, they could be selected for aquaculture despite some biological constraints such as slow growth, higher susceptibility to diseases or reliance on animal protein, e.g. fish meal. Aquaculture of species that have too many constraints may grow initially but is unlikely to thrive in long terms.
- The barriers reported for the audited species overseas are likely those for Australian aquaculture in the future. As aquaculture production reaches a certain level, diseases can quickly become the top threat. This is considered the top barrier to further development of aquaculture. Another issue to be aware of is reduced profitability due to competition and market saturation. A good example is Tra catfish. Low value and small profit margin of Tra catfish aquaculture do not encourage investment in farming and in R&D. Although commercial aquaculture production of Tra catfish has exceeded one million tonnes since 2012, farming technologies remain far less advanced compared with the other major aquaculture species. This emphasizes the need for R&D for significant improvement of production efficiencies, which consequently enhances profitability. Generally, research is

needed for aquaculture development regardless of the state of development or production scale. Each development stage has its own challenges that need to be addressed properly.

- 7/15 audit attempts by aquaculture producers overseas are from Vietnam. This country is one of the major aquaculture producers globally. The availability of key inputs (labour, feeds, sites and seed) and good market demand appear to grow aquaculture production. Seed supply is traditionally considered the prerequisite for aquaculture development both to start or to upscale. The availability of seed allows more producers to trial new species using existing system and their own experience. Farming system and feeds for one species could be used, though not optimal, for another to start with. Thus, if market demand is high, seed supply can help start new aquaculture business. This should be used as reference for aquaculture development in Australia.
- In-house technology is important. Technology development is easier when producers learn from each other apart from assistance of scientists or research organizations. It seems that aquaculture producers overseas are closely linked with peers and research organizations. Most of the audited species overseas already have significant aquaculture productions. However, demands for research is high (higher than new species) in order to improve broodstock domestication, selective breeding and hatchery production. Furthermore, coping with increasing diseases and low profit is common for established aquaculture industries. These should be the focuses for aquaculture R&D in Australia to support future growth of the industry. Know-how and innovative inputs could also be marketed overseas to create good income for the country.
- Research demand as suggested by the participating producers is higher for barramundi than black tiger prawn and cobia. Snubnose pompano and permit appear to have a lot of potential for commercial aquaculture development. Their aquaculture has no barriers while required technologies for different production stages have been established. Research demand for these two species is around nutrition and feeding management. If snubnose pompano and permit are considered for aquaculture in Australia, their potential for commercial aquaculture could be magnified by the established strengths of Australia in research on nutrition, genetics and selective breeding.

PART 7: FURTHER INSIGHTS OF AQUACULTURE DEVELOPMENT & NEW AQUACULTURE SPECIES

SUMMARIZED FROM INTERVIEWS AND MARKET VISITS

7.1. MARKET DEMANDS AND CONSUMER'S PREFERENCE

Our visits to different fish markets in Hobart, Sydney, Melbourne and Brisbane showed limited availability of aquaculture products. The most popular aquaculture species include Atlantic salmon, tiger prawn and banana prawn, Pacific oyster and to a lesser extent yellowtail kingfish, Murray cod, silver perch and redclaw. Many new species for aquaculture are still abundantly supplied by the fisheries or by imports. Furthermore, Australian wild-caught products are available at prices that are low enough to discourage aquaculture investors. The key learnings from seafood traders or fish mongers are summarized below.

- **Australian do not eat seafood; we eat meat**. Prawns and salmon are farmed, but the price is going up or not reducing as seafood traders expected. Market can only grow if products are more affordable. Families thus stick to chicken with a price range of 4.0 – 10.0/kg. Asian communities in Australia, however, do consume seafood. This trend is growing but needs to be captured by introducing the right species.
- **It takes time, continual effort and funding to grow markets**. Marketing campaign is a must and usually costly. Farmed Atlantic salmon has had good prices and well received by consumers. But that is the result of 10 – 20 years of marketing. Initially, the price was not as high as now. Similar effort should be made if one would like to successfully introduce other farmed species.
- **From market point of view the formula for success of a specific aquaculture species include three essential elements**
    + **Affordable price** helps grow the market as price decides consumption. Many Australian aquaculture farmers would like to sell their products at the prices for farmed Atlantic salmon. This is not possible as it is hard to a similar species to Atlantic salmon or it will require substantial investment to achieve good preference of consumers. Desirable farm-gate price for whole white-flesh fishes should be around $10 – 13/kg. With a fillet yield of 40 – 50% this price range already make fillet's price $25/kg or higher. Market price will be then higher than $30/kg after adding an overall minimum 30 – 40% profit for the processor, whole seller and retailer. A good example is Murray cod. With a fillet yield of 45% now its fillet price is $45/kg. Adding 30% profit for the restaurant/hotel businesses makes Murray cod a luxury food item, thus limiting consumption. If farm-gate price of Murray cod is $12/kg, seafood traders can sell whatever production produced. Generally, it is hard to find a species that we can farm to compete with the cheap, imported *Pangasius* catfish or, if still abundant, similar wild-caught species.
    + **High fillet yield** is another important requirement for aquaculture species as fillet is more convenient for cooking. Aquaculture developers should estimate fillet yield of candidate species and use it for initial evaluation. Fillet yield must be 40% at minimum or ideally 50 – 60%. Generally, for fish mongers or seafood traders, 30% fillet yield guarantees break-even while 40% allows some profit. Flathead is an iconic species of Australia. However,

flathead fillet is expensive because of its low fillet yield, i.e. 18 – 30% depend upon fish sizes.

+ **Product flexibility**: it will be an advantage if a species could be marketed as either whole fish (plate size or larger) or fillet. This will allow producers more options with production planning for optimal profit and changing market demand, e.g. farming plate-size or filletable fish. Good examples include snapper, flounder and barramundi. As whole barramundi price is $11/kg for plate-size fish and $16/kg for filletable (3 – 4 kg) fish, producing larger fish is certainly more profitable but plate-size fish is also marketable when needed.

- **Other important considerations for a candidate species**

  + **Competitiveness** with similar products on the market: when considering new species aquaculture producers or investors should first estimate production cost to determine farm-gate price; then use the general factors provided below to work out if the new species is competitive to similar products on the market.
    - Wholesale price ($/kg) = 1.2*(farm-gate price + transportation cost)
    - Retail price ($/kg) = 1.3*wholesale price
    - Consumer prices at restaurant = 1.4* retail price
  + **Transportation cost** is often $1.0/kg from farm to markets given that the amount to deliver is large enough, e.g. a 600-kg pallet. Double this cost if the species is produced in Northern Australia. Generally, the smaller the amount, the more expensive transportation cost per unit of product. In some cases, transportation cost may forbid marketing.
  + **Freshness**: supply to markets in big cities must be fast enough to ensure freshness and synchronize with demand. Thursday usually takes up to 70 - 80% of the weekly demand since restaurants/hotels stockpile for use during the weekend. The other days are just to top up. When products are produced far away from the target markets, good logistics is important to support aquaculture business. There has been a case that one species produced in Western Australia can't compete for price and freshness with the same species imported from Sri Lanka due to different logistics.

- **Several species of good demand are recommended for aquaculture by seafood traders. They are classified into three groups**:

Group	Species	Notes
Very high demand	+ Red snapper + Mud crab and + Blue swimmer crab + Spiny rock lobster	Softshell crab is currently in good demand. The products are fresh-frozen. Great demand for fresh softshell crabs does require predictable production and delivery must be fast and effective enough to ensure premium quality.
High demand	+ Ocean trout + Blue eye trevalla	Blue eye trevalla is high quality, good taste fish but not as popular as tuna, salmon, scallop for the sashimi market. Fillet price is $40 – 60/kg. The fish could be up to 20 – 30 kg in size and available for 9 months a year.

		Large fish of 4 – 5 kg or more have been found with eggs.
Growing demand	+ Yellow belly flounder + Yellowtail King fish + Sea urchin + Live prawns	Plate-sized is preferred for yellow belly flounder. Fillet of yellowtail King fish for sashimi darkens quickly due to high fat content, thus not attractive to buyers/consumers.

7.2. EXPERT OPINION ON AQUACULTURE DEVELOPMENT

In this session we summarize the insights obtained from different face-to-face discussions with producers, industry developers, government agencies, consultants and scientists about aquaculture development in Australia with special focus on new species, new industries. All these participating experts have engaged significantly from different aspects in the development of Australian aquaculture through their careers. Many have international experience.

7.2.1. Great potential for aquaculture in Australia

All the participating experts agree that aquaculture has a great potential to grow in Australia thanks to several advantages such as reputation of agriculture product quality, increasing demand for seafood, export potential, favourable environment, diverse climates, species diversity, technology advances, strong R&D capability and good management of biosecurity. Literately, this general potential has been well documented and discussed at different national events. With regards to suitable farming area and species diversity Australia ranks among the top countries globally for aquaculture potential (Gentry *et al.* 2017). FRDC, NAC and large Australian companies had predicted that finfish aquaculture production could reach 100,000 tonnes by 2015 (FRDC 2008). Recently, CSIRO estimated more than one million hectares suitable for aquaculture in Western and Northern Australia (Irvin *et al.* 2018; CRCNA 2020).

7.2.2. Challenges equal to potential

Aquaculture development has been, however, not as fast as predicted due to several challenges including regulation, limited production sites, high cost, social license, scale of the current industries and commercial competitiveness.

- **Regulation**: The current regulations in Australia do not encourage the industry to experiment, thus limiting a large amount of innovations. This is very different compared with other top aquaculture producers globally. Approval processes in Australia are lengthy and costly. Generally, it is difficult to get new aquaculture licenses or approval for a new production site. The only exemption would be if the investors/producers adopt recirculating aquaculture system (RAS) for production. Observations show that political will is of prime importance to aquaculture development. This changes temporarily and geographically. Higher motivation and thus better chance are seen for less-developed states or territories, i.e. WA, NT, QLD and TAS.
- **Limited production sites** due to environmental concerns and low social license. Aquaculture production can increase by expansion of farming areas and/or productivity. The first option has been limited in Australia forcing the industry towards the second option, which does take time and significant investments in terms of R&D or infrastructures. Despite high market demand and being the most developed industry in Australia, salmon companies have been struggling to scale up their businesses due to limited production sites. Offshore farming

requires substantial investment and more R&D. RAS could be an option for smolt production, but technical feasibility and commercial viability must be assessed.

- **High production cost**: Australia is a large country with major domestic markets and input suppliers far away from aquaculture production areas. This immediately results in higher logistics costs and more challenges for the supply chain regarding processing, preservation and transport of products. In addition, labour cost in Australia is higher than other countries, resulting in higher production or processing costs and a long-term need for automation. The latter depends on the scale of operation. Because of the general high production cost, aquaculture in Australia appears only viable if targeting high-value species in the early stages of development.
- **Small-scale industry** is another challenge. First, compared with other countries and except Atlantic salmon, aquaculture of other species in Australia is still relatively small in terms of production. Thus, it is more expensive to produce essential inputs for aquaculture or not attractive to invest in their productions. Thus, the industry must either accept local inputs at higher costs and/or relying on imports which is often not cheaper. Second, small-scale industry makes investment in research and infrastructures all less cost-effective, especially if the target industry spreads out over different geographic locations. A typical example is the development of breeding program. It is known that selective breeding program requires both long-term financial commitment and strong scientific supports. While aquaculture of salmon, oyster and abalone in Australia have benefited greatly from well-designed and funded breeding programs, other major or potential species have been struggling for one simply because the industry can't afford such an investment.
- **Conflict between trade and growing national aquaculture production**: Importing seafoods is an attractive option for traders since the imported products are generally cheaper and could be sourced year-around. Furthermore, high value of the Australian dollar favours importing. Strong competition of similar imported products does limit the consumption of Australian higher-priced aquaculture products. As having been observed in Europe and other continents, it is almost impossible for Australian farmers to farm a species that could compete with the $6 - 8/kg *Pangasius* fillet imported from Asia. Truth in labelling has grown recently but at a slow rate while the supply industry is actively lobbying against it. Australian people tend to support Australian products. However, continuous effort at national level to promote aquaculture product must be made if we would like to increase aquaculture production. Importing seafoods can compromise biosecurity of the local aquaculture industry. The Australian barramundi and prawn farmer associations have kept pressing the importance of biosecurity or alternatively stringent policy on the import of high-risked products from other countries as source of diseases. The recent occurrence of white spot disease in Queensland is a devastating example to the prawn industry of Australia.
- **Social license for aquaculture has not been high enough**. Unplanned or improper development of aquaculture can result in environmental impacts. This has been seen in developing countries where economic growth or food security was considered as a short-term priority. Australia has had its reputation for environmental protection. Thus, it is understandable that public support to aquaculture is not high due to concerns over environmental impacts. Low social license retards aquaculture development for both existing and new aquaculture industries. One participating expert recommends that "We need to work within our own sphere of influence as a truthful advocate for the operation and products of Australia aquaculture with the aim of maintaining social licence for our industry".

- **Existing gap between research and application**: This makes industry adoption more challenging especially for new species as research usually are at small scale, more fundamental and fragmented (due to funding availability and specific capability of the research provider). The outcomes of research on functional areas for example molecular biology, nutritional requirement, endocrinology or genetics of aquaculture species if was not prompted by a specific problem of the industry will have to go through another stage to identify and test potential applications. In many cases the information is made available through publications. Adoption or application is up to the potential user. For new species it is much harder as the industry simply is not there yet to adopt research outcomes. With an existing industry if one would like to introduce new technologies or practice semi-commercial trials need to be organized as it is too risky for the industry to apply straight on its production systems. Small-scaled research facilities of universities or research institutions often fail to support this type of research leaving the opportunity unexplored until the target industry must count on it to solve an emerging problem. Furthermore, many R&D providers including universities have been struggling to find enough funding for research. Thus, the research topic may not be the first choice of scientists or funding is large and long-term enough to make it sufficient for application. Breakthrough innovations are, therefore, hard to find. This current gap must be well addressed for further development of commercial aquaculture in Australia.

7.2.3. An absolute need to understand market needs

Market study is considered key to development. Scientists and research organizations should be aware of this need since its importance is repeatedly emphasized by aquaculture producers, aquaculture developers and seafood traders. Market demand must be surveyed and analysed to develop R&D strategies or decide if research on new species is well justified. Very often new species with no or limited market demand failed to thrive regardless of research outcomes. A wise approach that help determine or prioritise species is to identify "supply gaps" before estimating market size and product price.

Aquaculture research is too often production centred. Furthermore, they may not have insufficient consideration of the economics, potential market and price point. Logically, one should target species that could fill the supply gap of known products in the market. This could be done via a survey of people working in the wholesale market or fish selling businesses. Questions to consider include

+ What products are difficult to source?
+ Where are the market opportunities?
+ How much value or tonnage is required for supply?
+ For those products what is the wholesale price point?
+ What are the preferred product forms for each product, e.g. fillets or whole fish?
+ What is the intended market, restaurant, retailer?
+ What would be the point of difference to other products in the same category?

The obtained result will help identify if the supply of a certain product, often wild-caught or imported more than farmed, is short. Then, one could start to explore if farming of that species is possible or what farmed species that have similar qualities that could substitute the gap. Generally, Australian prefer locally produced and/or good-for-health species. In addition, consumers are willing to pay higher prices for Australian products.

Furthermore, the aquaculture industry is the immediate market for R&D providers. It requires in-depth understandings to effectively serve. R&D providers should be informed of the industries' needs and plans or actively seek for such information. It has been observed that larger sectors are response better than smaller ones. Thus, the role of National Aquaculture Council and producers associations is considered essential regarding the collection of feedback from the industries.

7.2.4. Both current and new species are important

Generally, helping existing aquaculture industries to grow should be considered first simply because species that already has an established market have better chances to grow in production. The exploration of new species is good if that help either supply niche markets or address identified constraint(s) of the current species. Aquaculture producers agree that there is plenty of room for more than one new white fleshed fish. There are already dominant ones such as Atlantic salmon and barramundi, but other species would also be attractive especially those are easy to reproduce in captivity and can grow fast to filletable sizes. Further development then depends on scalability and severity of problems associated with the learning curve such as disease, feed development and quality control.

In addition, it would be helpful if the new species' aquaculture could benefit from technologies or farming systems that have been developed for current species. The Murray cod industry in NSW has increased production rapidly in recent years thanks to good demand both domestically and internationally. However, this development is believed also as a result of Murray cod farmers adopting technologies once established for silver perch. Another important note is that there has been a clear trend of focusing on high-value species in Australia. For aquaculture development we should favour species that can produce in large volume at low costs using low-protein diet. Globally, people need more cheap fish fillet no matter white or not.

7.2.5. Challenges for new species

Industry uptake is considered the biggest barrier for new species. Aquaculture producers usually prefer no change. They are not interested in alternative or additional species if their current species is working. Furthermore, the initial performance of a new species could easily be undermined because of the lack of knowledge and experience of the farmer. Thus, bad perception can be created and, once established, it is very hard to shake off. For new species the supply chain is not fully developed. Poor connections between production stages could result in detrimental effect on the viability of the involved businesses. Recent development of tropical grouper farming in Australia has witnessed that commercial hatcheries struggled to survive initially and ended up giving fingerlings for free to develop local industry. Also, it is difficult in the beginning since investors generally want an exclusive agreement with R&D providers. That is helpful for one or a group of investors but won't create an industry of many producers. The supply of inputs for farming of new species is also problematic if some modifications of existing inputs or new products are required.

7.2.6. How to develop new species

It is a consensus that we can learn from the success of Atlantic salmon industry to develop new industry. There are few lessons to learn including

- Atlantic salmon is a very special species, appealing to every market. The fish can be eaten in many different forms: whole, steak, fillet, smoked or raw. Its flesh appearance is highly attractive to consumers. Salmon holds so much fat with a great health profile for humans. High fat content of Atlantic salmon prevents the fish from being overcook unlike white flesh fish.
- Hatchery and grow-out technologies were all available at the start of the industry. Salmon was first introduced in 1963/64. Hatchery technologies established in 1973 well before actual farming started in Tasmania in 1985. Central hatchery to supply fingerlings was organized and supported by the government, helping multiple producers focus on grow-out.

- Atlantic salmon is a global aquaculture species thus has attracted profound interest of scientists and R&D providers. It is estimated that more than 50% R&D needs of the salmon industry in Australia have been addressed by global R&D effort.
- Technological advances have been continually developed for salmon in all aspects of farming. These helps reduce production cost significantly. Thus, market prices of Atlantic salmon remain stable although input costs have increased significantly. In contrast, market prices of other popular terrestrial meats like chicken, beef or pork keep raising.
- Solidarization of the local industry. Used to be 25 small companies that did not unify for planning and development. Few big companies bought those and since then have become more effective.
- Demand of domestic market has been strong and grown much faster than that of the industry.

7.2.7. Recommended species for consideration

- Sydney rock oyster: great aquaculture candidate thanks to its high value on local markets and large areas available for farming near Sydney. What needed now is long-term support for a breeding program to improve grow-out performance and quality of product.
- Seaweeds: select species that can assimilate nutrients from aquaculture systems, e.g. salmon cages using the concept of integrated farming or circular economy. In addition, the selected species should have real market values and permit for cultivation is obtainable.
- Abalone for both export and domestic markets to maximize the impacts of on-going breeding programs. Campaigns to promote abalone consumption in Australia should be conducted.
- Giant freshwater prawn *Macrobrachium spp.*: high-value species and native to Australia. As hatchery and grow-out technologies are well established, farming could start straight away. Supply is currently limited in Australia. Farmed products could target local markets first.
- Sea urchin: fresh roe of sea urchins fetches very high prices ($200 – 300/kg) in both domestic and export markets. Now sea urchins are collected from the wild. However, seed production has been trialled successfully in Australia and fattening or grow-out protocols have been research in other countries.
- Sea cucumbers: another high-value group of species which are detritovores. They could be farmed underneath finfish sea cages to harvest settleable organic matters, thus keeping the environment healthy. Overseas, sea cucumber aquaculture has been trialled successfully in coast shrimp ponds. Seed production is highly achievable thanks to established technologies.
- Finfish: barramundi, yellowtail King fish, cobia, pomfret, diamond mullet, whiting and snubnose pompano are recommended for marine/brackish waters. Among these barramundi and yellowtail King fish are the favourable species. For freshwater areas Murray cod, silver perch and silver cobbler are recommended.

7.2.8. Other recommendations for aquaculture development

- Research on Atlantic salmon should focus on cost-effective technologies for offshore farming, thermal tolerance and breeding program for high temperature tolerance. These will help increase commercial aquaculture production to meet both domestic and export demands.

- Research on barramundi should focus on selective breeding, fingerling production, biosecurity at both farm and industry levels, utilization of fish wastes from processing and opportunities for integrated farming with other species.
- Development of smart devices for farming, i.e. for monitoring and optimizing feeding, aeration and health status.
- More research on nutrition and feeding protocol for carnivorous species (usually high-value and favoured by producers) to reduce feed cost.
- Mitigating risks and reducing losses should be considered as needs for R&D. New opportunities could be new species or new product(s) from existing species.
- Where the natural environment favours the farming of a particular species that is considered important to regional economy, a pragmatic approach should be taken for best endeavours towards:
    a) Planned development of aquaculture industries appropriate for the region
    b) Harmonized framework for risk assessment and environmental approvals
    c) Simplified regulations and an adaptive approach to their application
    d) Government funding of nationally valuable R&D would not be undertaken in the absence of government underwriting. A key test for government underwriting is the "public good" component of the knowledge generated; characterized by "non-rivalry" and "non-excludability", i.e. it can be freely used by a number of users simultaneously for the overall benefit of society (eg FRDC public good funding).

Discussion

1. AUDIT OF RESEARCH EFFORT

Our study audited research effort on 44 different aquaculture species in Australia, covering both consolidated species (with significant commercial production or revenue) and new candidate species. The results reveal more insights about research effort on aquaculture species, which are helpful to understand why commercial production of few species have been more significant than many others and how supportive the audited research are.

Research interest has been spread equally among the three groups of species (finfish, crustaceans and molluscs) audited in this study. There are more new species in the finfish group compared with crustaceans and molluscs groups. Generally, the consolidated species have attracted more research interest reflected by higher collective effort of scientists, Research Comprehensive Index (RCI) and Production-stage Research Coverage Index (PRCI). This is understandable as research on these species have a greater and more immediate impacts. Moreover, funding for R&D from industry partners are more available to research on the consolidated species as found in this study. RCI is highest for Atlantic salmon (53%) among the 15 audited finfish species, back tiger prawn (100%) among the 12 audited crustacean species and Sydney rock oyster (73%) and pearl oyster (60%) among the 13 audited mollusc species. For many species research has been fragmented, reflected by low RCIs and PRCIs. This is inevitable since funding for R&D has been identified as one of the barriers to increasing commercial aquaculture production in Australia. Comparisons among the three groups of species show that research has been more comprehensive for mollusc species (Table 99). Furthermore, there are more variations of research comprehensiveness in the crustacean group than in the finfish group.

Table 100. Research focus and comprehensiveness of three audited groups of species

Parameters	Finfish	Crustaceans	Molluscs
Research Comprehensive Index (%)	31.1 ± 15.9 (7 ÷ 53)	33.9 ± 27.0 (13 ÷ 100)	37.2 ± 18.7 (13 ÷ 73)
Production-stage Research Coverage Index (%)	46.6 ± 23.2 (13 ÷ 100)	45.6 ± 27.0 (13 ÷ 88)	52.3 ± 15.8 (13 ÷ 75)

Across all the three groups of audited species, the top five functional areas that have been covered by research include genetics/breeding, nutrition, health, husbandry and farming systems (Figure 60). Less research in nutrition, husbandry and farming systems have been conducted for the audited finfish compared with the audited crustacean and mollusc species. Functional areas that have not attracted much research interest are waste management, law/policy/regulation. Research have targeted different production stages of the audited species (Figure 61). Stronger focuses are seen for grow-out, broodstock domestication and larval rearing stages than the other. Limitations in larval rearing and nursery for finfish and crustaceans may explain why commercial aquaculture production of those species has not increased much. Furthermore, there have been less research that support harvest, processing and transport. Research on molluscs appear to be more helpful and more evenly spread across the production stages.

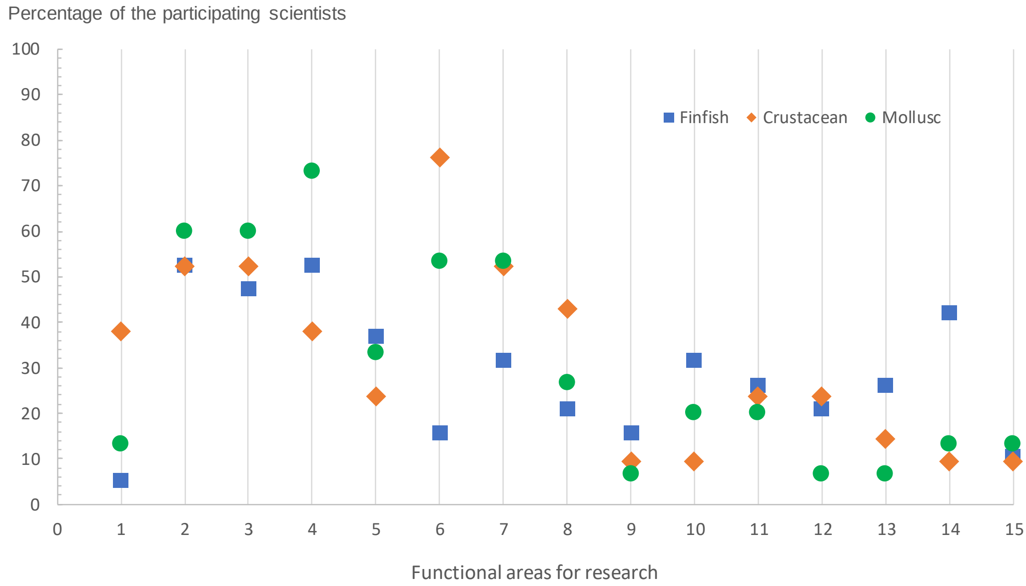


Figure 58. Function areas researched for the audited finfish, crustacean and mollusc species in Australia

(1) biology/ecology, (2) genetics/selective breeding, (3) nutrition, (4) health/disease/biosecurity, (5) environmental requirement, (6) husbandry techniques, (7) farming systems, (8) water quality, (9) waste treatment, (10) animal welfare, (11) markets/marketing/logistics/supply chains, (12) product development, (13) economics, (14) environmental interactions, (15) law/policy/regulation.

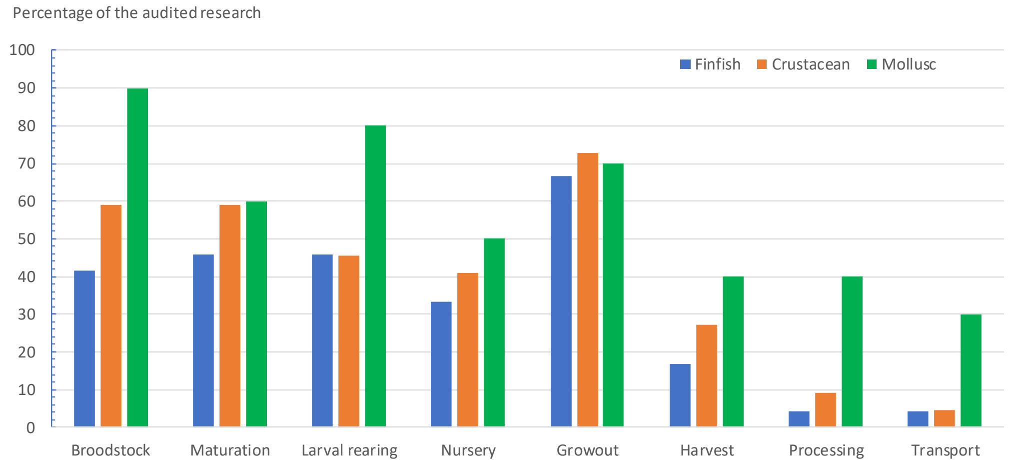


Figure 59. The level of support of past research for different production stages

Research demand, as suggested by the participating scientists and aquaculture producers, varies greatly among species. Generally, RDI is high for the consolidated species and very new ones but is likely different in nature or depth. For new species, one needs to do more research to understand them and to explore their potential for aquaculture. High research demand for the consolidated species is more about improving production efficiencies and addressing challenges that tend to emerge once the economies of scale is achieved such as increasing diseases, insufficient supply of quality seed, domestication of broodstock or selective breeding for better performance, waste management, product development, low profit, etc. In this study, species that have the highest RDIs include black tiger prawn and Atlantic salmon in Australia or tilapia and whiteleg shrimp overseas. It does take time to create an aquaculture industry of significant production or revenue, i.e. 30 – 50 years as seen for the major aquaculture species globally. Thus, unless technologies and inputs for farming are adopted from different existing aquaculture species, research demand for new species will remain high for many years to come.

A quick review by FRDC in 2017 showed that more than 90 species have been researched in Australia, either to explore their potentials or to assist with commercial production. However, only Atlantic salmon, tuna, pearl oyster, edible oyster and prawns have had significant commercial production either in tonnage or revenue (Chapman 2020). Commercial aquaculture of many other species is still very small in scale. This is common as 70% of global aquaculture production in 2016 were from only 20 species or 5 – 6% of nearly 400 species for aquaculture (FAO 2019). It has been known that diversification can enhance the resilience of aquaculture production. Globally, there has been a strong political will through policies development to promote species diversification in aquaculture (FAO 2011, cited by Metian et al. 2019). Australia is a big country with different climates. Diversification of aquaculture species thus helps supply local demands and contribute to economic growth. However, diversification requires more thoughts and plans in Australia for few reasons. First diversification does require relaxation of regulations to accommodate new development needs (Pingali & Rosegrant 1995), which is unlikely in Australia even for the already-consolidated aquaculture species. Second, seafood consumption has not grown fast enough in Australia (ABARES 2020). This together with increasing pressure from cheap imported products have retarded aquaculture production growth through expanding the current industries or new investment (Chapman 2020). R&D focus on the consolidated species can result in rapid innovation and improvement of production efficiency. The advantage of focused development has been well demonstrated for Atlantic salmon, tilapia and whiteleg shrimp (*Penaeus vannamei*) (Metian et al. 2019). Third, funding for R&D which is usually far less than research demands will be spread thinly over a wide range of species. Lack of focused investment or insufficient resources for research is unlikely to result in breakthrough innovations in short terms.

2. BARRIERS TO FURTHER DEVELOPMENT

Barriers to entry in Australian aquaculture industry are high and increasing as observed in 2016 – 2020 (Chapman 2020). In fact, difficult entry is considered as a strength for aquaculture business as it limits internal competition. Through our study, insufficient supply of quality seed is identified as the biggest barrier to further development of commercial aquaculture in Australia. This barrier was reported in all the audited groups and for many species regardless of their current farming status. Similar result has been reported by Davis *et al.* (2018) when evaluating the potential of 17 finfish species for aquaculture in the US. It has been known that seed quality decides up to 40 – 45% of the success of farming. The larger the scale of farming, the more important seed quality is as producers can't afford breaking supply contracts or huge opportunity cost. The availability of seed for stocking is highly essential to small scale producers who do not have their own hatcheries yet or to investors who would like to conduct grow-out trials. More importantly, seed availability allows research to be implemented in different functional areas such as nutrition, health, husbandry or simply seed quality improvement. The success of Atlantic salmon and trout farming in Australia is believed as the result of a good centralized system that supply fish fingerlings for many different producers, at least in the early stages of development. This hatchery system was then further supported by breeding programs that has enhanced growth rate, survival and resistance to diseases. None other aquaculture species in Australia has had such a support. Large companies still struggle with producing their own seeds while investment in breeding program is not cost-effective in many cases due to the lack of the economies of scale.

Increasing risk of infectious diseases, unfavourable regulations and too small industry are the other major barriers. Species with significant commercial production tend to have more problem with diseases. In Australia, Atlantic salmon, pearl oyster, edible oyster and penaeid prawns are reportedly more vulnerable to disease risks. Overseas, the participating scientists and aquaculture producers rank increasing risk of infectious diseases as the top barrier. As the aquaculture industry in Australia is still very small compared with that overseas, this barrier will become more and more significant in the future. Thus, it must be well addressed before creating huge damages to the industry.

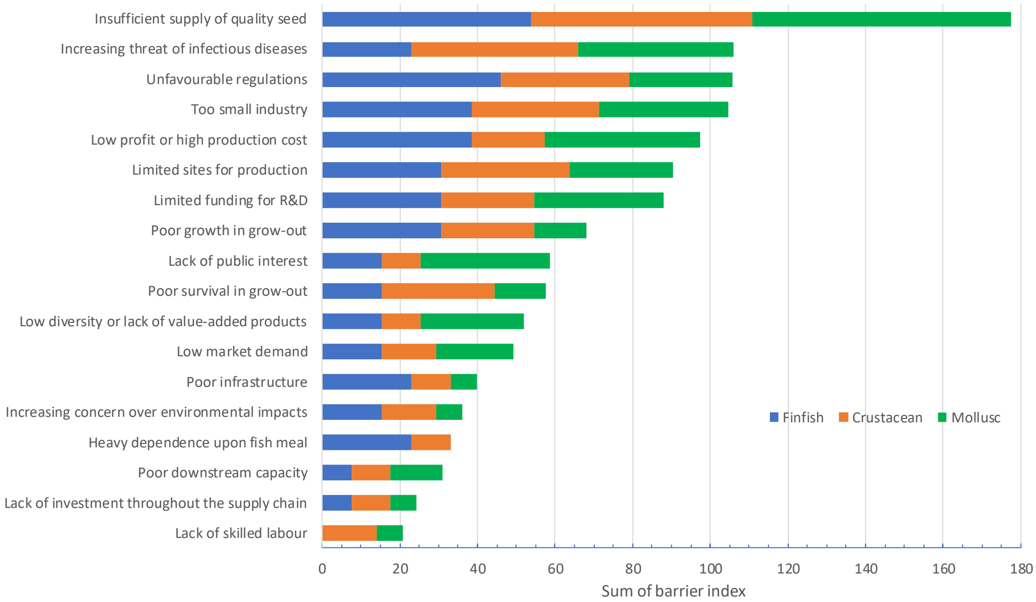


Figure 60. Barriers to further development of commercial aquaculture of the audited species

Unfavourable regulations have been commonly identified as a significant barrier to aquaculture development in Australia by different stakeholders. Chapman (2020) illustrates the aquaculture industry of Australia with heavy regulation as a negative impact. Numerous licences and approvals must be obtained to start farming or expand business to new production sites. Furthermore, these licences are different among the states and territories, making the application for them more costly and time consuming. In fact, limited sites for production ranks 6th among the 18 barriers surveyed in this study. As Australia ranks top globally about aquaculture potential (Gentry *et al.* 2017), it is likely that very limited production sites for aquaculture have been the result of unfavourable regulations and low social license. Without production site and reliable supply of quality seed there is no way that aquaculture could start, not to mention of growing.

Too small industry is another major barrier. Typically, small industries are less competitive and often suffer from high production cost. Nearly 60% of revenue of the Australian aquaculture industry are contributed by more than 1,000 small businesses (Chapman 2020). Most industry operators are sole proprietors or having a workforce of less than 20 staff. They can't compete with larger operators or with imports of similar products at lower prices because they do not have the economies of scale required to reduce production cost or invest in advanced technologies. The estimated start-up costs are substantial, e.g. $100,000 - $780,000 for producers in Queensland who would like to farm barramundi, prawn, finfish or redclaw. As a result, low profit or high production cost is identified as the 5th barrier to commercial aquaculture in Australia. For producers or investors who start with new species it is even harder. As reported by aquaculture producers overseas, farming new species is possible if existing farming systems can be used in addition to high demand and good profitability. This study also reveals that a large proportion of the audited species do not have good accessibility to the required inputs for farming. These observations altogether may help explain why commercial aquaculture production has remained small or negligible for many species.

Limited funding for R&D ranks 7th, relatively high among the 18 barriers surveyed by this study. Research is instrumental in technology development and improvement. The results of this study show that industry development has influenced research directions more strongly than the other way around. Lack of investment in RD&E by new investors have left scientists and research institutions with seeking for funding from the current industries which are often not interested in alternative species if their business is doing well or from governmental agencies. Our review of aquaculture-related final project reports on FRDC website show only 10 projects so far has been funded to support aquaculture production. Aquaculture of target species like striped trumpeter and native oyster are not successful yet while that of Sydney rock oyster and yellowtail king fish still require substantial research effort as recommended by the research teams. Limited funding for RD&E will not allow research providers to create breakthrough innovations or it takes much longer time to do it. If funding can't increase, we should prioritise R&D investment and pay more attention on technology adoption. The results of this study show that the potential for adopting existing technologies and inputs either for other species or countries is high. Also, the participating producers share that a significant proportion of their in-house technologies are from other producers and other countries. For species that are farmed both in Australia and other countries, the existing global R&D capital should be exploited more effectively. Given how difficult to establish new aquaculture business in Australia, the available funding for R&D should be used to strengthen the farming of consolidated species (i.e. Atlantic salmon, trout, prawns, oysters, abalones and tuna). New species is exceptional and only considered if could be incorporated into the existing aquaculture businesses via integrated farming or for bioremediation purpose but must be marketable with reasonably good profit. Also, there should be more funding for research that directly address the identified barriers such as improvement of hatchery production or policy development to support aquaculture business.

Barrier Index (BI) is highly variable across the 39 audited species that were evaluated by the participating scientists, ranging from 6 to 73%. Interestingly, the top five species ranked by BI value include, in order, black tiger prawn, barramundi, Native rock oyster, Atlantic salmon and yellowtail king fish. Except Native rock oyster, all the other four species are consolidated or more consolidated in terms of commercial aquaculture production. Similar assessment was made for barramundi by aquaculture producers overseas. According to them barramundi has the highest BI among the 9 audited species overseas. Thus, increasing barramundi production is not only challenging for Australia. On the other hand, BI of black tiger prawn is only less than half of it in Australia. This somehow indicates that technological barriers could be well addressed through technology transfer or adoption. At the other end of the scale, species with the lowest BI include Australian snapper, black bream, yabbies, Southern bluefin tuna and sand whiting. Black bream and Australian snapper both have poor growth rate. It should be noted that a significant number of aquaculture species in Australia do not have fast growth rate or high survival in aquaculture systems. Yabbies production has remained marginal while aquaculture of sand whiting has not started yet. As BI is more indicative rather than a real measure of how high the identified barriers are, it appears that barriers to increasing aquaculture production can exist for every species regardless of how consolidated the industry is. Barriers are only different in type or scale among species, location and level of industry maturity. Species that are still under development or with small production may not encounter some of the barriers that more consolidated species have.

3. OPPORTUNITIES AND FUTURE DIRECTIONS

This study has collected insights about the potential for aquaculture of 44 species in Australia and 54 species overseas as references. As a large country with growing population and diverse climates, Australia have a great chance to develop sustainable aquaculture. Diversification of aquaculture species sounds logical to capitalize suitable environments, better supply local communities and reduce logistics cost. The information we have collected would be helpful for screening candidate species, especially those have been researched or farmed in other countries covered by this study. Covid19 pandemic has opened more opportunities for more affordable species which could be produced locally using local inputs for farming since many supply chains have been heavily damaged, either too costly or not possible to operate (Samsing et al. 2020). As agreed by the participating scientists and aquaculture producers in this study, selection of candidate species for commercial aquaculture is highly important and should start with assessing market potential, availability of required technologies and inputs for farming, biological constraints, estimated profitability and compatibility to the current regulations. According to Paquotte *et al.* (1996), the best options for success in aquaculture are both (i) fast-growing species at low production costs; and (ii) products acceptable to consumers. We can use these lenses to identify potential species for aquaculture in Australia.

As discussed above species with growing market demand and/or has obtained the economies of scale in Australia should be given the priority for development and investment, including funding for RD&E. Species like Atlantic salmon, prawns, oysters, tuna, barramundi, yellowtail king fish are also farmed in different countries. Focused development for this species will help make the most out of the existing global knowledge and technologies, thus saving costs. Research innovations, if created in Australia, could be commercialized for greater income with producers in other countries apart from assisting the local industry. Furthermore, it takes time to develop an industry and much more time without favourable regulations. The demand for seafood in Australia is increasing but at a low pace because of small population, abundance of meats especially low-price chicken, good supplies of wild-caught products, increasing competition of cheap imported products, etc. We believe that aquaculture production can only increase significantly when demand for aquaculture products become much stronger as public interest will strongly influence political will, which would result in more relaxing or favourable regulations. In the near future a new species should only be considered if demand is confirmed by market studies and its farming is complimentary to the existing industry or target niche markets. Like many other industries, aquaculture business is profit driven. Thus, research that helps improve profitability tend to be supported. However, the potential impact must be significant enough to attract industry investment. Usually, small or medium companies use their financial resource to expand production rather than invest in R&D. Australia should aim to develop a small, growing aquaculture industry with high value and great production efficiencies. Export markets should be targeted for premium prices which help maximize profit. Recent market studies show increasing demand for imported quality seafood in several growing economies; of these the biggest is China. This option is highly suitable for less consolidated species but with high demand for export.

Non-traditional aquaculture should be considered for native species. This include extensive farming where land and water are available, e.g. Northern and Western Australia as identified by IRVIN ET AL (2018) and CRCNA (2020). Species for consideration should include prawns, mud crab, blood cockle, redclaw and marrons. Sea ranching or restocking is a good option for sea cucumber and sea urchin. These options are highly sustainable and help significantly reduce production cost. Great preference of consumers for wild-caught seafoods would help these types of low-input aquaculture to grow. Farming pharmaceuticals (green alga, sea cucumber, sea horse, puffer fish or the similar) should be encouraged as these generate high revenue from smaller production area and thus minimal environmental impacts. Also, greater emphasis on developing and supplying innovative technologies and inputs for global aquaculture.

This study shows great demand for research on genetics and selective breeding both in Australia and overseas. Combine with the need to supply more quality seed for industry growth it makes sense to suggest the creation of more centralized hatcheries in different states or production areas. These hatcheries should be multiple-species ones and ideally supported by national breeding programs. Genetics research and applied breeding have been the strengths of Australian agriculture and aquaculture. Apart from supplying the local industries, we can supply other major producers globally genetics improved seed for stocking. The whiteleg shrimp broodstock business in Hawaii is a good example. This small industry produces around 5 - 6 tonnes of prawn broodstock annually mainly for exports but generate a revenue of A$ 57 – 60 million. Australia is far away from the main aquaculture production area in Asia and has great biosecurity system and stringent regulations. Thus, the risk of our aquaculture stocks being infected by pathogens is small. With a great diversity of aquaculture species and climates and advanced knowledge in selective breeding we can diversify the aquaculture business into supplying quality seed for global aquaculture. International investors who would like to buy these products or can help market them should be invited to secure markets and reduce financial investment of Australian investors.

Conclusion

1. This study has audited past research effort on 44 aquaculture species for Australia and 54 species overseas. Results show that species with consolidated commercial aquaculture production have received more research supports. Researches on potential species or less consolidated are still fragmented, thus requiring more investment in RD&E. The focuses of past research on the audited species include five functional areas: genetics/breeding, nutrition, health, husbandry and farming systems. Regarding production stages, grow-out, broodstock domestication and larval rearing have attracted more research. Research demand is high for both consolidated and potential species. The participating scientists indicated stronger interest in finfish and requested more funding for research as well as opportunities to partner with the industry.

2. Insufficient supply of quality seed is identified as the top barrier to increasing commercial aquaculture production in Australia. Information collected from scientists and aquaculture producers through this study confirm the existence of this barrier, which is applicable to many species including those in the top 10 aquaculture species globally. The other major barriers are increasing risk of infectious diseases, unfavourable regulations and too small industry. Increasing risk of infectious diseases could become the top barrier quickly once the industry reaches its economies of scale in the future as reported by the participating scientists and aquaculture producers overseas. Technically, poor growth in grow-out of a large proportion of audited species is currently a barrier indicating species selection should be re-evaluated and, at the same time, the potential assistance of selective breeding program. Lack of production sites as the result of unfavourable regulations, low profit or high production cost due to too small industry and high costs, limited funding for R&D and lack of public interest are the other significant barriers to consider when developing aquaculture. Low accessibility to required inputs is an addition reason for lack of development of new species' aquaculture. These barriers and other constraints should be addressed in order to improve the competitiveness of the Australian aquaculture industry.

3. This study reveals a great potential for aquaculture development in Australia in the long term especially if premium export markets are targeted and low-input farming models are established for carefully selected species in the less developed states, e.g. Northern Australia and Western Australia. As seafood demand in Australia still needs more time to raise substantially, it is recommended that RD&E in the next 10 years should focus on improving production efficiencies for aquaculture of the more consolidated species (Atlantic salmon, oysters, black tiger prawn, bluefin tuna and barramundi) or those with good demand for export markets and farming technologies/inputs are available (e.g. abalones, lobsters, marrons, redclaw, sea cucumbers). Hatchery production and national breeding programs should be the focuses of RD&E, preferably with investment in infrastructure and initial operation cost from Federal or state governments to boost seed supply for domestic and even international producers. New species should only be considered if having unique advantages compared with the existing species or complimentary to the current aquaculture industry through integrated farming. Screening for new species should start with market potential assessment and availability of technologies/inputs to ensure profit for investor and producers.

4. Through this study a lot of insights are provided by scientists and aquaculture producers overseas about research effort, aquaculture development and species selection. These valuable references should be considered for the development of the Australian aquaculture industry since what have happened in more developed aquaculture countries could one day happen in Australia. Apparently, the more consolidated aquaculture species in Australia are also the major aquaculture species or highly recommended globally. For new species research and development overseas could be more advanced in some aspects of aquaculture compared with Australia, especially around application/adoption of research results in commercial production. Therefore, gathering information of new development including market intelligence and technology adoption should be conducted in parallel with research in the coming years for the benefits of the Australian aquaculture industry.

5. Our overall recommendation for aquaculture RD&E in Australia is that we should aim to develop an aquaculture industry with high production efficiencies supplying both domestic and international markets with selected high-value species. Low-input aquaculture models and sea ranching should be considered together with cost-effective RAS to reduce production cost, produce higher quality products and more importantly to meet the requirements of environmental regulations and public license. As we can work on many major aquaculture species, Australia should invest significantly in R&D to supply the world with not only quality products but also advanced aquaculture technologies and innovative inputs for farming and non-traditional aquaculture products such as pharmaceuticals and functional food ingredients. Globalization of sustainable aquaculture in Australia including attracting large, responsible international investors is considered key for future development of the Australian industry.

Implications

This study has attempted to provide more useful information about species selection and aquaculture development in Australia and overseas. Its implications to end users are referred below:

- Management: policy makers, governors, research management agencies and research sponsors could use our findings on barriers to further development, research achievements and research needs, availability level of technologies and inputs for farming both in Australia and overseas to develop strategies, prioritise RD&E activities and mobilize the required resources for aquaculture development.
- Industry and new investors: can use our audit results of the potential and constraints of a wide range of aquaculture species, R&D progress, barriers to development, availability of technologies and input for farming, the importance of technology adoption, potential competition with similar import products or advantages in export markets etc. to develop production strategies and plans or select an alternative species or farming/business models.
- Consumers: the findings of this study could help improve public awareness of the mandate of aquaculture in supplying good foods for human consumption and a wide range of products that aquaculture could offer. Better understandings of the current barriers that make aquaculture less competitive than it should be are expected to encourage more supports of Australian consumers to Australian produces. Significant difference in regulations between Australia and other countries could explain overseas consumers why Australian aquaculture products deserve premium prices to compensate the opportunity cost the country has invested in environmental protection and natural resources.
- Scientists: to have an overview about R&D progress, technology development and current barriers to further development of the audited species. These will help orient research effort to match with future needs and industry interests.

Recommendations

1. Organize national workshop to discuss the findings with the aquaculture industries, producer associations, state governments and relevant agencies, FRDC, NAC, research institutions, scientists, seafood buyers and investors and formulate solutions/actions that could help direct RD&E effort and investment from the government and private sectors to assist the creation of a competitive aquaculture industry for Australia.
2. Establish working groups to explore options and develop prioritised RD&E plans to (i) significantly increase production efficiencies of selected species (e.g. those with growing demand in domestic and/or export markets), (ii) establish more centralized hatcheries and breeding programs to ensure consistent supply of quality seed in short terms and genetically-improved seed in long terms, and (iii) support more research on aquaculture economics, supply chains, policy analysis and adoption of advanced technologies that could help meet environmental requirement and public license.
3. Work with state governments to identify aquaculture opportunities related to what mentioned in (2), develop supporting policies for R&D start-ups and call for investment. Investors with established technical capabilities or existing access to markets should be targeted.
4. Publish selected findings of this study in the forms of scientific manuscript, magazine articles or short updates to the industry in order to create better impacts. Explore the possibility to commission annual reviews of market demand, research advances and implications, technology development, industry performance, new opportunities for key aquaculture species in Australia. This will help facilitate the globalization of Australian aquaculture and consequently industry growth.

Further development

1. This study does not cover all the candidate species for aquaculture in Australia due to limited participation of scientists and aquaculture producers. Moreover, it is challenging to quantify research effort and depth or to assess adoption of research results. In the future, adoption of research results should be reported by the aquaculture industry under the coordination of either FRDC or NAC. Annual review of research progress and industry development for selected species is possible via small projects led by an experienced scientist and representative of the targeted industry.
2. It is important to select species/industries that could be significantly improved via a combination of focused research and technology adoption in the next 10 years. Technology adoption should be promoted among producers from more consolidated species to the others with assistance of research institutions where needed. Ideally, technology development should focus on a cluster of species that have the same barriers or opportunities and similar biology.
3. Explore options to develop a user-friendly App for (i) scientist to update research progress, (ii) producers to inform customers of available products and inform scientists with emerging challenges or need for technology improvement, (iii) customers to check the origin and learn

some key features of the aquaculture product(s) they intend to buy in markets or provide feedbacks regarding quality, preference and demand; and (iv) other relevant stakeholders to have an overview of current status of aquaculture in Australia. This App would allow FRDC to continuously collect relevant information about aquaculture development and products.

Extension and Adoption

The results of this project will be made available to the public in form of a final project report, 02 scientific papers and 1 magazine article. A 2-page facts sheet will be composed once the final project report is approved and shared with all relevant individuals and parties, especially project participants. Adoption of project results hopefully will be reflected in strategies planning for aquaculture development of FRDC and CSIRO.

Project coverage

Two manuscripts for publication in scientific journals will be prepared following the submission of this report.

Appendices

LIST OF RESEARCHERS

Project Lead	Dr Tung Hoang Principal Research Scientist CSIRO Agriculture & Food Bribie Island Research Centre, 144 North Street, Woorim, QLD 4507 Email: Tung.Hoang@csiro.au
Project member	Dr Joshua Fielding Senior Research Portfolio Manager Fisheries Research and Development Corporation Email: Joshua.Fielding@frdc.com.au
Project member	Dr Harry King (1964 – 2019) Senior Research Scientist CSIRO Agriculture & Food Castray Esplanade, Hobart, TAS 7001
Project member	Dr Pollyanna Hilder Research Scientist CSIRO Agriculture & Food Castray Esplanade, Hobart, TAS 7001 Email: Polly.Hilder@csiro.au

REFERENCES

Bostock J, McAndrew B, Richards R, Jauncey K, Telfer T, Lorenzen K, Little D, Ross L, Handisyde N, Gatward I, Corner R (2010) Aquaculture: global status and trends. *Phil. Trans. R. Soc. B* **365**: 2897–2912.

Cai J, Zhou X, Yan X, Lucente D, Lagana C (2017) Top 10 species groups in global aquaculture 2017. Food and Agriculture Organization of United Nations, Italy.

Chapman W (2020) AU INDUSTRY (ANZSIC) REPORT A0200: Aquaculture in Australia. IBISWorld.

CRCNA (2020) Northern Australia Aquaculture Industry Situational Analysis. Project A.1.1718119 – Stage I Report.

Department of Agriculture and Water Resources (2017) *National Aquaculture Strategy*. Canberra, August. CC BY 4.0.

Dvoretsky AG, Dvoretsky VG (2020) Aquaculture of green sea urchin in the Barents Sea: a brief review of Russian studies. *Reviews in Aquaculture* **12**: 2080-2090.

FAO (2020) Fisheries and Aquaculture Statistics 2020. Food and Agriculture Organization, Roma, Italy.

FRDC (2008) To 100,000 tonnes and beyond. FISH June issue.

Gentry RR, Froehlich HE, Grimm D, Kareiva P, Parke M, Rust M, Gaines SD, Halpern BS (2017) Mapping the global potential for marine aquaculture. *Nature Ecology & Evolution* **1**: 1317–1324.

Han Q, Keesing J, Dongyan L (2016) A Review of Sea Cucumber Aquaculture, Ranching, and Stock Enhancement in China. *Reviews in Fisheries Science & Aquaculture* **24**:326-341.

Hair CA, Pickering TD, Mills DJ (2012) Asia–Pacific tropical sea cucumber aquaculture. *Proceedings of an international symposium* held in Noumea, New Caledonia, 15–17 February 2011. ACIAR Proceedings No. 136. Australian Centre for International Agricultural Research: Canberra. 209 pp.

Irvin S, Coman G, Musson D, Doshi A and Stokes C (2018) *Aquaculture viability. A technical report to the Australian Government from the CSIRO Northern Australia Water Resource Assessment, part of the National Water Infrastructure Development Fund: Water Resource Assessments*. CSIRO, Australia.

Metian M, Troell M, Christensen V, Steenbeek J, Pouil S (2020) Mapping diversity of species in global aquaculture. *Reviews in Aquaculture* **12**: 1090–1100.

Williamson JE (2015) Sea Urchin Aquaculture in Australia. In: Echinoderm Aquaculture, edited by Nicholas P. Brown & Stephen D. Eddy. Wiley.

Appendix 1: Specific comments on finfish species by the participating scientists

Species	Comments
Black bream *Acanthopagrus butcheri*	+ No commercial activity. A well-researched species for a niche opportunity. Highly regarded by the Chinese as an excellent fish for steaming. + The fish is robust (could be farmed in relatively harsh inland conditions), easy to grow and are generally resistant to disease. It survives salinities from fresh to hypersaline. + However, their very slow growth rate means they are not a commercial species for aquaculture. A perfect species for restocking.
King George whiting	+ Research efforts in Australia have mainly concentrated on hatchery techniques. + Very limited grow-out trials have been conducted, although these demonstrated relatively slow growth.
Pink snapper	+ One of the constrainers was the slow growth rate and that it competes with a currently sustainable fishery. + Slow growth could be improved through better diets and breeding.
Australian snapper	+ Slow growth is the major negative for this species, but a big one. Potentially genetic improvement programs to increase growth rates.
Mahi-mahi	+ Broodstock availability: tropical species that are caught off fads, generally want to catch fish around 2kg as larger fish prone to have myxosporidium. Broodstock spawn all year so excellent egg availability. + Quality of seed/fingerlings: only slight deformity is sometimes seen as shorter fish, good mouth development and no opercula, lordosis or scoliosis deformities. + Complexity of larval phase: can experience very high larval death at metamorphosis likely cause nutrition and or gas exchange. Mahi grow rapidly (2 kg from egg in six months). Intense physiological requirements, i.e. nutrition/gas exchange combined with the need for high quality water quality means the fish require advanced culture technologies to support growth. Mahi-mahi grow quickly and die quickly. Male mahi-mahi are highly aggressive to each other as generally there is a dominant male with a harem of females. If another male is in the tank the dominant male will kill it. Development of monosex populations will be required for successful industry development. + Site selection that meets the high standards of water quality of these oceanic fish or the development of saltwater RAS to supply consistent water quality. Mahi-mahi is a fantastic species that

	requires serious financial input to meet technology requirements to allow successful industry development. + No current production in Australia to my knowledge, however, research into the commercial production of mahi-mahi in Australia started in 1982 and has been on/off until 2010.
Golden snapper	+ High incidences of deformities was an issue in 1995-1998. Recent micro diet developments may address that issue? The Northern Territory planned to re-start small-scale snapper culture using previous techniques with the incorporation of new micro-diets. + The main bottleneck is lack investment/investor interest. Whilst market value for tropical snappers is generally on the low side, locally they are considered a premium product and could be (but currently aren't) marketed as such interstate. + The techniques developed for snappers also have relevance to groupers and other hard-to-breed species. Improved nutrition during the larval rearing/juvenile phase is required.
Cobia	+ Nationally, sea cage culture is an opportunity awaiting assessment. In Queensland, production is currently constrained to marine ponds. Industry in QLD needs to invest in hatchery facilities as the government hatchery moves away from a supply role. + Cobia aquaculture is highly promising. The major constraints in my opinion include (i) ectoparasites and other diseases usually occurred at high stocking densities and (2) unavailability of commercial diets for this species and its different development stages. + Recommended research priorities: health/diseases, nutrition, farming technology, market development and consumer preference.
Atlantic salmon	+ The barriers to expansion to meet demand, are mainly around availability of grow-out sites and community concerns over environmental impacts not to mention negative media influence. Atlantic salmon farming is a strong industry however expansion will only be possible with new sites and associated new offshore infrastructure and smolt nurseries. + The lack of available sites has caused producers to overstock and increase hypoxia, environmental impact and increased disease risks (year-class separation, biosecurity, chronic stress, pathogen amplification). Global warming is further limiting suitable sites for cage farming though a movement offshore is a potential solution. + However, offshore farming involves higher production costs and increased risk - engineering of cage systems is not adequate to guarantee stock security in extreme conditions. RAS systems offer the opportunity to shorten the production cycle and reduce seasonal fluctuations in size and quality, though animal welfare, maturation and deformity risks are high. Ultimately, a move to full RAS

	production will ensure that the species can be produced close to urban centres, thus reducing the cost of transport to market. + Atlantic salmon will continue to dominate Australian aquaculture, as it has progressed into a highly industrial activity, and the product is very well placed in the national and international consumer markets as a 'common' and highly nutritious and healthy protein source. The industry is well placed with full control of the production cycle to markets. + Expansion and a changing climate are likely to also impact on animal welfare and prevalence of disease and pests. The industry is well placed to respond to climate change and health issues through its breeding program and associated research. + With continued expansion of the international industry the local industry needs to remain competitive with production costs and products. There has been increasing pressure on availability of feed ingredients.
Yellowtail king fish	+ Nutrition and disease management are the major biological constraints. + Markets and price, however, are the major limitations for expansion in Australia.
Blue fin tuna	+ Knowledge based solutions for the ecologically sustainable growth of aquaculture in Spencer Gulf including carrying capacity and targeting information on juvenile SBT in the Great Australian Bight (Dec-March) have been provided by the SARDI Aquatic Sciences group.
Sand whiting	+ Require better finishing diet (i.e. floating, low fat, growth promoting)
Cachama	+ This species performs well in semi-intensive earthen ponds. It is rustic, fast-growing and easy to breed (few breeding programs current undergoing). Protein requirement is low for grow-out phase (24 - 26% CP). Excellent survival at high stocking densities. Good markets in South America (Brazil, Colombia, Peru, etc.), US, Asia and Europe. China started cachama aquaculture maybe 5 years ago and now is the top cachama producer of the world. Countries like Brazil and Colombia increase commercial productions steadily over time. + Harvest sizes depend upon market preference, e.g. 1 – 2.0 kg fish in Brazil but plate size (350 – 450 g after 4 - 6 month of culture) in Colombia. + The "smoked cachama ribs" has been recognized as one of the potential value-added products from these species.
Whitebait	More research on larval rearing needed.

Golden trevally	More research for the grow out technique. I think the market need to be increased (larger demand) to create the stable output. This is very important for the farmers to invest and produce this species.
Tilapia	+ Australia imports this species for sales in shops but does not consider farming this species because of the impacts caused by similar species in Northern Australia. Water management and fish health are the most limited aspects in the growth of this industry. + Global aquaculture production of tilapia will increase thanks to its lowest production cost among all finfish species for aquaculture and increasing market demand for tilapia fillet. + Cooperative model for tilapia culture (same as pultry and swine) is growing fast, allowing an annual growth of the industry up to 10 - 15% in some countries. + Farmers need high-quality fingerlings for tilapia culture.
California yellow tail	As most of marine finfish species the biggest constraints are diseases incidence and specific feeds to attend the species nutritional demands and requirements. More research is needed in the health and disease space, and there is necessity to promote the development of specific feeds for grow-out stages.
Snubnose pompano	Excellent species to farm, targeting more affordable products

Appendix 2: Specific comments on crustacean species by the participating scientists

Species	Comments
Black tiger prawn *Penaeus monodon*	+ Difficult to grow in intensive systems, poor public perception of farmed prawns + Need to improve discharge treatment to open new areas for culture. Need to domesticate to provide consistent supply of high health post larvae + The development of one or more hatchery and grow-out sites in Northern Australia has great potential to expand the sustainable growth of this sector + Main barrier is commercializing a viable supply of clean and genetically improved P. monodon stock for the Australian industry
Kuruma prawn *Penaeus japonicus*	+ The main issue is the small market locally, the cost of production and for live export, and now with the primary industry producer switching to fish due to their location within the White Spot zone in SEQ, it is an even smaller chance of this species farming growing/sustaining. Note, I noted 1-ton production for the industry as a nominal figure in case the industry partner returns to farming this species in future. The species is easy to domesticate, but it has a fundamental issue of the commercial viability of the largely 'live' export market.
Banana prawn *Penaeus merguiensis*	+ More research in general are needed
Ornate spiny lobster *Panulirus ornatus*	+ The greatest constraint is the commercial production of seeds followed by performing formulated diets for grow-out
Blue swimmer crab *Portunus amatus*	+ Proof of concept trials used prawn farm ponds, but prawn farms were already very profitable and have become very productive since. The blue swimmer crabs are aggressive- kg yield is low even with multiple juvenile crops per year so $ yield needs to be high! Originally small crabs for high-value soft-shelling were proposed as a WSSV-proof alternative to prawns, but recent advice raises doubts about *Portunus* resilience against WSSV. Import of cheap soft-shelled juvenile mud crabs scupperred hopes for industry- but the dream is for marketing live soft-shelled crabs. Served fresh overseas! The technology is not complicated- but shedding systems may need to be far more high intensity than our industry partners originally thought- but this means that maintaining health of the moulting crabs becomes extremely important. We developed a self-cleaning mini-container holding system (for ultra clean feeding trials- see my mud crab response). + Interest in BSC as a premium diversification option should WSSV reach Australia was prompted by occasional accidental 'natural'

	recruitment of BSC in Queensland prawn farms. The threat seemed very real. The NT WSSV scare saw DAC's mudcrab broodstock destroyed in 2000, and a BSC sample from BIRC also returned a 'false-positive' for WSSV in a national survey soon afterwards. + The Qld CIV project developed all facets of blue swimmer crab production to the point of sufficient reliability and productivity for commercialization. This was demonstrated by one company that operated a fully integrated soft-shell crab production system, incorporating hatchery, nursery, earthen pond grow-out, shedding and post-harvest product packaging facilities. + However, as the CIV project ended, an unprecedented upsurge in *P. vannamei* prawn imports prompted Qld prawn farmers to compete by dramatically raising prawn yield in earthen ponds. Cheap imports of soft-shell crabs were also rising but crab yield in ponds was restricted by aggression and cannibalism. The improved productivity of prawn ponds eroded the presumed financial benefit of switching to growing juvenile crabs for shedding. + A quantum improvement of grow-out and refinement of shedding systems is needed to improve economies of scale/reduce production cost. + There is potential to grow crabs individually in super-intensive, compartmentalized systems that prevent cannibalism and achieve effective stocking rates of greater than 50 pcs/m^2. + The possibility was explored at BIRC as an offshoot of the soft-shell blue swimmer crab work. Juvenile crabs can be held at near 100% survival rate for long periods, but growth was poor. Dietary or behavioral issues may arise. Crabs have previously been fed simply with 'off-the-shelf' prawn diets, but globally crab diets will be more common today. Further, the impact of confinement on the crab's behaviour (or indeed its 'appetite') needs to be considered. + Forcing synchronous moults, either by environmental or hormonal means, could perhaps reduce crab predation in ponds. Traditionally, overseas, this is done 'manually' by multiple-leg autotomy (triggering a moult). Unfortunately, the steroid hormones and analogs that could be trialed to do this humanely in bulk are often also 'insecticides' (insects and crustaceans share many neurophysiological pathways). Consumers may find use of 'insecticides' in production of seafood unacceptable. / + Density-limiting aggression and cannibalistic behaviour is the major hurdle to getting this to work in Australia. Mud crab aquaculture is widespread throughout Asia but cannibalism is managed through low stocking density. + Domestic market for locally produced soft-shell product, price and volume, has not been tested in years. A price premium will need to be achieved as local product will directly compete with low cost imported mud crab soft-shell product. Advantages include (i) soft-shell crab is the most commercially viable product for the species due to its high value; (ii) current state of knowledge indicates

		feasibility of containerised RAS growout/ shedding systems (including SMART systems for stock management); (iii) in a shedding facility juvenile crabs can moult in astonishingly small containers; (iv) they double weight when they moult, and substantially repairs injuries. Current disadvantages include (i) survival and growth rate in earthen ponds is restricted by aggression and cannibalism; (ii) the high productivity (kg/m^2) solution (containerised system is capital intensive and has high operating costs; (iii) growth rate appears unusually slow when crabs are reared in containers. The reasons for this are presently unclear.
Mud crab *Scylla serrata*	+	Mud crabs are farmed successfully overseas as a replacement in WSSV hit prawn farm areas- hence ACIAR was concerned to see that this was placed on a sustainable footing with seed production and ultimately with nutrition. The crab popularity in Australia also required pond trials to get answers of its feasibility in Australian farms- the news wasn't good. If you have an marine earthen pond in the Australian tropics you grow prawns in it - it's an iconic, valuable species but the stocking densities possible for mud crabs are too low to tempt our farmers. Containerized production was contemplated by an industry partner - but in our FRDC/ACIAR work we uncovered troublingly slow growth in sole mud crabs in containers. Portunid crabs should be amongst the world's fastest growing crustaceans. Its a fact that often animals grow better, get an extra pick-me-up, in a natural environment rather than a clean aquarium. We made our feeding trial set up as clean as possible so the crabs in containers would be as nominally 'healthy' as possible- survival is fantastic and yet the growth of isolated mud crabs is nothing like that reported for free-ranging crabs. There could be two problems, maybe our ideal of free-ranging crab growth is biased - the small ones get eaten. Or maybe mud crabs are not biologically suited to life in a box. There is a bit of work remaining to do there. I cover this is more detail in the published review.
Moreton Bay bug *Thenus orientalis*	+	Hatchery technologies developed for rock lobster culture, which has received a greater level of R&D, are transferrable to *Thenus* spp. culture. It is generally acknowledged that larval culture is challenging for lobster species. The technical challenge is lower for *Thenus* spp. compared with rock lobster species because the larval cycle is simpler and far shorter. However, maintaining the high quality, hygienic conditions required by phyllosoma larvae over the culture period is key to success of the hatchery phase and technically demanding.
	+	*Thenus* spp. are offshore species not tolerant of wide water quality variability and culture systems need to accommodate this. This limits sites and systems appropriate to the species. ABLP are utilizing high intensity, indoor RAS for hatchery and grow-out production.

	+ Internationally, *Thenus* spp. lobsters, commonly referred to as flathead lobsters, are not held in the same regard as rock lobster species and value is generally lower.
Yabbies *Cherax aldidus*	+ The yabbies industry has dropped from over 300 t/year to around 34 t/year due to (i) mining bloom: people in rural WA could obtain very high paying FIFO jobs, so there was no longer a need to earn income from yabbies; (ii) locust spraying: Although not confirmed industry leaders believe that aerial spraying of insecticides killed most of the regions freshwater crayfish. + As trapping removes the largest, fastest growing yabbies from a population, leaving smaller slower growing animals to breed, this results in negative genetic selection for growth. Genetic selection &/or introduction of fresh stock from "virgin" previously un-trapped waterbodies is likely to provide significant gains in growth and production.
Redclaw *Cherax quadricarinatus*	+ The problem with redclaw is that they are a tropical species and cannot survive below 10C. This means that live transport of chilled product in aircraft is problematic and when they arrive at their destination, they cannot be stored in restaurant cool rooms without poor survival. This was the reason for the boom and bust in redclaw production from Ecuador 1994-1998, often referred to as "poor marketability" but more accurately was poor survival from farm gate to plate meant a lack of repeat orders for this product. For this simple reason they will not achieve the high prices obtained for live freshwater crayfish overseas. If the redclaw industry is to grow it should be based upon low input farming for either local restaurants or the export of processed meat. At present the industry is doing the exact opposite embracing expensive, intensive hatchery production of juveniles. Furthermore, the global market already has a large supply of small processed crayfish from USA and China. / Development of local markets would be a preferred strategy to the transport/live holding limitations of this tropical species, unless transport and holding issues can be resolved. + Overseas: China has grown crawfish culture (*P. clarkii*) from 200,000 to 1.2 million ton in 10 years. Do not meet demand for local market (+300000 t needed). Sale price is high (US$12/kg). Markets in US and Europe are under supplied. Increased production needs: (1) government policy, (2) transfer available technology (ours which is tested commercially to produce 5,000 ton/cycle), (3) Set up nucleus for genetic program to supply high quality juveniles, (4) extension services needed, (5) effort for market recognition as niche (gourmet) product and commercialization strategy, (6) research in zero fish meal diets, genetic line selection and intensification on zero exchange systems.

Margaret River marron *Cherax tenuimanus*	+ The marron aquaculture industry was killed by a change in Dept Fisheries WA regulations soon after FRDC Project 2000/215 was completed. This permitted the harvesting and sale of marron from gully dams in the southwest of WA. Because these dams are constructed across streams, farmers were able to sell not only marron grown on their property, but also those in the catchment that migrated downstream into their dam. Commercial marron farmers could not compete with this influx of essentially wild caught product and most left the industry to be replaced by marron dam harvesters. We predicted that this harvesting was unsustainable and eventually size and supply would decline, this has now occurred. A simple change in regulations is required to support semi-intensive pond aquaculture as opposed to wild stock trapping. There may be some additional benefit in exploring strategies to increase density while not decreasing growth – most likely due to improved pond shelters/hides, domestication or formulated diets. Dept Fisheries and UWA have recently recommenced selective breeding of marron for aquaculture due to the gains from our previous project being lost as industry were unable to run the genetic selection program that we initiated with FRDC. Marron are a prime aquaculture candidate that has never reached its potential. The major problems appear to be 1) lack of investment in well-constructed farms, 2) poor management of many existing farms and 3) farmers/universities ignorance of previous research and instead attempting to undertake their own poorly designed trials.
Giant freshwater prawn *Macrobrachium rosenbergii*	+ *Macrobrachium spinipes* is a native freshwater prawn of northern Australia and PNG. It is comparable in size to the giant freshwater prawn *(M. rosenbergii)* that is farmed in Asia exceeding USD 2 billion in value annually. *M. spinipes* is the closest living relative of *M. rosenbergii* and is one of the largest in its genus and is of commercial importance in wild fisheries. Except for attempts to undertake its hatchery trials, no attempt has been made to-date to assess its potential as alternative native species for culture. If *M.spinipes* can be domesticated and farmed successfully, this could provide a new aquaculture industry for northern Australia and also relieve growing pressure on wild stocks from overfishing. It is also a priority species for culture by indigenous groups throughout northern Australia, and thus research to adapt and optimize hatchery and pond culture protocols and to develop local expertise in domestication and husbandry has great potential for this species since the large ones fetch a very high market price. In parallel, we need to develop a comprehensive understanding of *M. spinipes* wild population structure to determine the scale at which wild stocks should be managed to guide wild conservation and allow effective restocking programs to be developed. + Based on my university's (QUT) over 20 years' experience in aquaculture R&D, the species appears to be adaptable to a wide

	range of habitats and is an ideal candidate for domestication, and hence an ideal addition to the limited number of cultured species in Northern Australia. Thus far, most of the aquaculture production is limited to commercial operations of shrimp, barramundi and crayfish and will likely continue to be so. While we have theoretical capacity to support research and development (to adapt farming technologies developed for *M. rosenbergii*) for *M. spinipes* farming, there is a need to demonstrate the farming of this species with several private sector organizations interested in supporting this research. + Need more research on genetics, selective breeding and nutrition/ feed
Whiteleg shrimp *Penaeus vannamei*	+ In my country one of the major concerns is the "environmental permit" which is a huge barrier to bank funding and other supports. + Research priorities should be focused on improving high welfare practices in maturation, improve management practices in all production sectors of the species + Sustainable shrimp production requires implementation of available intensive bio-secured technologies, improve SPF postlarvae quality availability from genetic programs, improve commercial diets through the introduction of ingredients specific for the species, develop better immune stimulant additives and control diseases through biosecurity, genetic SPR lines and better diets. + Need more research on improving the quality of broodstock and postlarvae

Appendix 3: Specific comments on crustacean species by the participating scientists

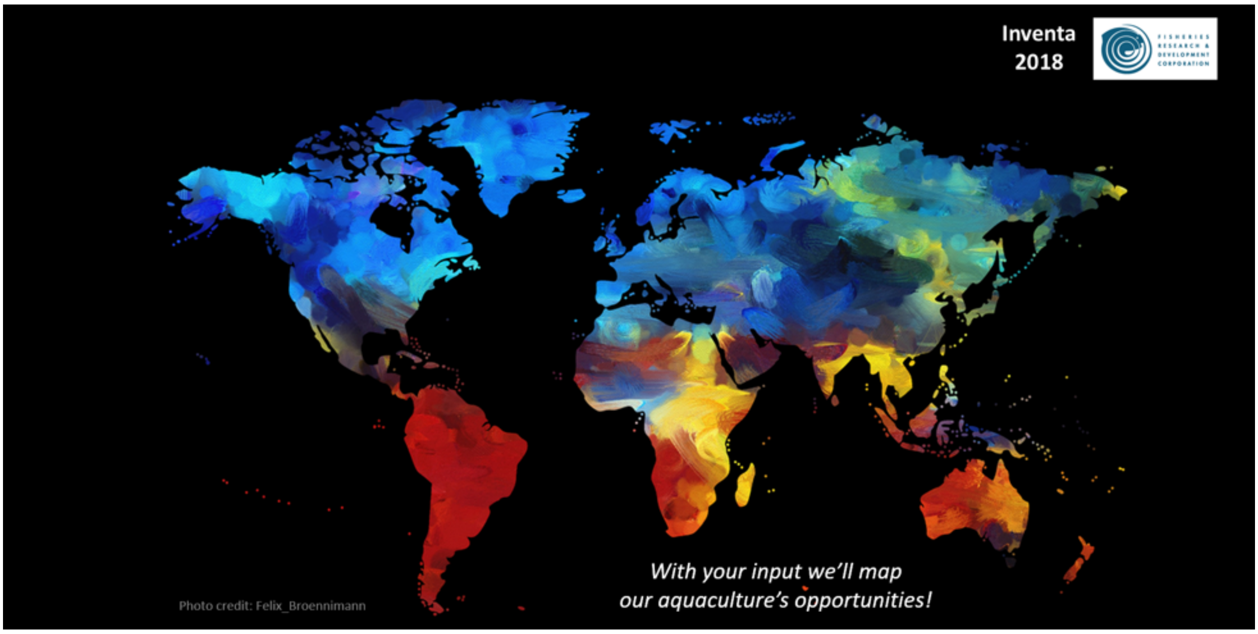
Species	Comments
Sydney blood cockle *Anadara trapezia*	+ Currently Anadara is wild harvested in NSW (no aquaculture).
Doughboy scallop *Chlamys asperrima*	+ Currently this species is only harvested by recreational fishers
Abalones *Haliotis spp.*	+ There is still high demand for Australian abalone overseas, and demand probably is greater than supply. The national market is basically untried and significant opportunity exists to test this and expand into, especially with value added product and with the growing multi-cultural population. The industry needs to change from multiple small/medium scale farms to an industrial scale, adopting the benefits of selective breeding and new technology for grow out. + Further research into abalone nutrition will aid in the potential of value adding activities
Silver-lipped pearl oyster *Pinctada maxima*	+ More needs to be done on the reproductive aspects including gametogenesis and inducing spawns. + Disease is a large issue in Australia
Native rock oyster *Saccostrea cuculatta*	+ There is potential with tropical rock oyster production in North Western Australia in partnership with traditional owners.
Commercial scallop *Pecten fumatus*	+ Currently no aquaculture production although there has been
Portuguese oyster *Crassostrea angulata*	+ This species will be cultivated for the better quality so that better price for farmers
Suminoe oyster *Crassostrea arakensis*	+ This species will be cultivated for the better quality so that better price for farmers
Bluff/dredged oyster *Ostrea chilensis*	+ There is high demand of the market for this species, however disease/bio-security barriers should be removed so the industry can be recovered.
Venerid clam *Tapes dorsatus*	+ Research demand for this species is high and on different areas such as broodstocks (selection, maturation), larviculture (diets, disease control, rearing system), grow-out (health management, water quality), post-harvest and market.

Inventa 2018: Invitation & Input Arrangement

You are invited to take part in our INVENTA 2018, a jointly-funded study of the FRDC (Fisheries Research and Development Corporation, Australia) and CSIRO that audits research effort on aquaculture species and industry adoption in Australia and globally. The purpose of this study is to identify opportunities for and barriers to the development of aquaculture for new species. Findings from the study will be used to prioritise RD&E strategies that could increase commercial production of potential species. The results of Inventa 2018 will be presented in different formats, e.g. database, extension materials and reports and shared with all participants, preferably in early 2019. No respondents will be individually identified in our report. More information about the study is available at www.inventa2018.com

Your consent to participate Inventa 2018 will be requested in the next session of this form. This study has been approved by CSIRO's Social Science Human Research Ethics Committee in accordance with the National Statement on Ethical Conduct in Human Research (2007). If you have any questions concerning your participation in the study or complaints about its conduct, please contact the Manager of Social Responsibility and Ethics on (07) 3833 5693 or by email at csshrec@csiro.au.

Thank you for spending your valuable time, taking part in Inventa 2018!
Tung Hoang
Project Leader
Email: Tung.Hoang@csiro.au; Phone: +61.3.6232 5377 or Mobile: +61.413 407 510
* Required



Participant Consent

I, the participant, acknowledge that

(1) I have agreed to participate in INVENTA 2018 being conducted by the FRDC and CSIRO.

(2) I have been provided with information about the project including information storage and usage. I understand my participation in the research will involve either of the following activities: completion of an on-line survey or participation in an interview via Skype or a face-to-face discussion.

(3) I understand that my participation in the project is entirely voluntary and that I am free to withdraw from the study at any time and without having to provide a reason for my withdrawal.

(4) I understand that the interview, if any, will be recorded for reference purposes to help ensure accuracy of the data.

(5) I understand that I may ask for part of all of the information provided by me to be removed from the study without penalty or explanation at any time before 31 December 2018.

(6) I understand that the information I provide for this research is not restricted by any parties or individuals, and will be populated in an FRDC-hosted database, which is accessible by researchers, aquaculture producers and other interested parties or individuals for research, development and extension purposes. I am aware that the information I provide will be used for the production of scientific publications and extension materials.

(7) Information provided by me, in the form of completed on-line survey or interview recording, if any, will only be accessed by members of the research team (Dr Tung Hoang, Dr Joshua Fielding and Dr Harry King) and used for the purposes outlined above. It will be stored securely in an Excel file by CSIRO during the study and by the FRDC after the completion of INVENTA 2018.

(8) I have been provided with contact details of the investigating officers and understand that I can contact them at any point during the study. I have also been provided with the contact details of an independent ethics officer at CSIRO should I wish to raise any concerns or complaints about the conduct of the research.

1. Please confirm your consent to participate in Inventa 2018. *

Mark only one oval.

- ( ) Yes, I confirm
- ( ) No

Your contact details

2. Full name *

____

3. Email address *

Please provide so that we can communicate with you for further collaboration.

____

4. Which organization are you employed by or do you own?

If you are not employed, please name your most recent employer.

____

5. In which country are you located? *

____

6. Do you allow us to publish your contact details in a database hosted by FRDC Australia so that interested parties or individuals can contact you for collaboration? *

Mark only one oval.

- Yes, I do
- Maybe. Check with me before the database is published.
- No, I don't

Check point

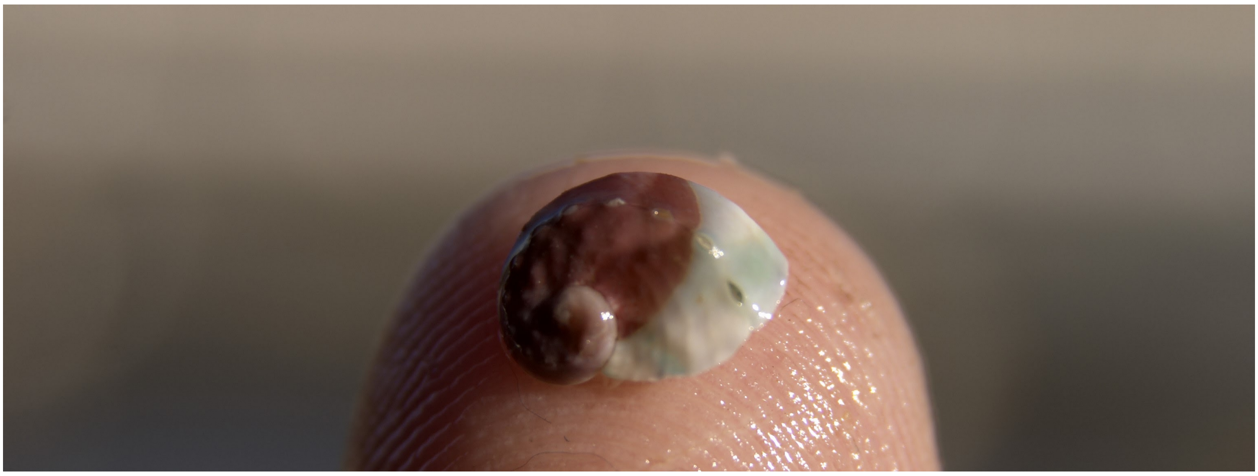
For this study we would like to capture input from (i) researchers and (ii) aquaculture producers & consultants. We also welcome the views of relevant stakeholders (regulators, policy makers, consumers, traders, investors, etc.).

7. Which of these groups do you would like to represent? *

Mark only one oval.

- Researchers *Skip to question 8*
- Aquaculture producers *Skip to question 14*
- Aquaculture consultant *Skip to question 14*
- Other stakeholders *Skip to question 21*

Abalone spat. Photo credit: CSIRO.



Researchers

General information

8. How many species have you conducted research on? *

Mark only one oval.

- 1
- 2
- 3
- 4
- 5
- More than 5

9. In the next 5 - 10 years, if funding were available, which of the following groups you would focus your research on? *

Mark only one oval.

- Finfish
- Crustaceans
- Molluscs
- Algae and/or seaweeds
- Other: ____________

10. Have you ever worked for the private aquaculture sector *

Mark only one oval.

- Yes
- No

11. Which of the following factors would you consider when evaluating a candidate species for aquaculture? Which is the most important in your opinion?

Select as many as desired for the first column (For consideration), but ONLY one for the second column (Most important) please.

Check all that apply.

	For consideration	Most important
Biological attributes	☐	☐
R&D capital (i.e. volume of global research)	☐	☐
Market demand	☐	☐
Profitability	☐	☐
Regulation	☐	☐
Consumer product preference	☐	☐
Social license	☐	☐
Other	☐	☐

12. If "Other" please specify

13. How many species would you like to report on for Inventa 2018? *

____

Skip to question 22

Aquaculture producers or consultants

14. How many years have you worked in the private aquaculture sector? *

____

15. What best describes your main role as an aquaculture producer? *

Mark only one oval.

- Owner/Founder
- Technical manager
- Financial manager
- Technical staff
- Consultant
- Other: _______________________________

16. How many species have you worked on in your aquaculture career? *

Mark only one oval.

- 1
- 2
- 3
- 4
- 5
- More than 5

17. In the next 5-10 years which of the following groups of aquaculture species would you focus your production on? *

Mark only one oval.

- Finfish
- Crustaceans
- Molluscs
- Algae or seaweeds
- Other: ____________

18. Which of the following factors would you consider when evaluating a candidate species for aquaculture? Which is the most important in your opinion?

Select as many as desired for the first column, but ONLY one for the second column please.

Check all that apply.

	For consideration	Most important
Biological attributes	☐	☐
R&D capital (i.e. volume of global research)	☐	☐
Market demand	☐	☐
Profitability	☐	☐
Regulation	☐	☐
Consumer product preference	☐	☐
Social license	☐	☐
Other	☐	☐

19. If "Other" please specify

20. How many aquaculture species can you discuss with us? *

____

Skip to question 22

Other stakeholders

21. Which category best describes you as a stakeholder? *

Mark only one oval.

- ( ) Trader
- ( ) Consumer
- ( ) Investor
- ( ) Regulator
- ( ) Policy maker
- ( ) Development agency
- ( ) Non Government Organization (NGO)
- ( ) Other: _______________________________

Your plan to provide information

Photo credit: jarmoluk

22. Which of the following options do you prefer? *

Mark only one oval.

- Complete our on-line survey form (10 - 15 min per species). We highly recommend this input method. *Skip to section 9 (null)*
- Telephone or Skype interview (will be extremely helpful if you could complete the online surveys before we talk) *Skip to question 23*
- Face-to-face discussion with the research team (only possible in Australia and quite limited due to limited budget)

Please follow the link provided after you click the "SUBMIT" button.

Interview

We appreciate your willingness to discuss with us. Please provide further information so that we can schedule a meeting with you.

23. What is your telephone number or Skype ID? *

24. Please nominate a date that we can talk *

Example: January 7, 2019

We will contact you shortly to arrange our meeting

This content is neither created nor endorsed by Google.

Google Forms

Inventa 2018: Species Audit by Researcher

Thank you for participating in our study. We look forward to receiving your valuable inputs on the aquaculture species you have worked on.

* Required

1. Please provide your email address *

We need this information for cross-reference with other information you have provided or will provide.

2. Which country do you report for this species? *

if you have studied different species in different countries.

The species: general information

From this section you will be asked to provide information for ONE species. If you are working on multiple species, please repeat the whole process once finish this. Thank you!

Photo credit: Engin_Akyurt

3. Common name of the species *

Please input the most popular name of the species

4. Scientific name *

e.g. Lates calcarifer

5. What prompted your research interest in this species? *

Check all that apply.

- [ ] Its potential for aquaculture
- [ ] Personal interest (e.g. on its biological attributes)
- [ ] Assignment by employer or research leader/supervisor
- [ ] Request/recommendation by funding body
- [ ] Request/recommendation by the aquaculture industry
- [ ] Recommendation based on market studies

Other: [ ]

6. What are the current markets of this species in your country? *

Check all that apply.

- [ ] Local
- [ ] National
- [ ] Limited export (to a few countries)
- [ ] Global export (to many countries)
- [ ] Do not know

7. What are consumer preferences for this species in your country? *

Check all that apply.

- [ ] Live
- [ ] Fresh whole
- [ ] Fresh head on gutted & gilled
- [ ] Frozen whole
- [ ] Fresh fillet/portion
- [ ] Frozen fillet/portion
- [ ] Smoked
- [ ] Roe

Other: [ ] ______________________

Your research

8. What year did you start your research on this species? *

____

9. How many years have you spent studying this species? *

____

10. Which functional areas have you studied for this species? Which ones do you think still warrant substantial investigation?

Check all that apply.

	Investigated by you (till today)	Still warrant substantial investigation
Genetics/Selective breeding	☐	☐
Nutrition	☐	☐
Health/Disease/Biosecurity	☐	☐
Environmental requirement	☐	☐
Husbandry techniques	☐	☐
Farming systems	☐	☐
Water quality	☐	☐
Waste treatment	☐	☐
Animal welfare	☐	☐
Markets, marketing, logistics, supply chains	☐	☐
Product development	☐	☐
Economics	☐	☐
Environmental interactions	☐	☐
Law, policy, regulation	☐	☐

11. Which aquaculture production stage(s) has your research targeted? For which stages do you think existing technologies may be adopted for its aquaculture?

Check all that apply.

	Your research target	Adopt existing technologies
Broodstock (collection, domestication or selective breeding)	☐	☐
Maturation and induced spawning	☐	☐
Larval rearing	☐	☐
Fingerling or juvenile production	☐	☐
Grow-out	☐	☐
Harvest	☐	☐
Processing	☐	☐
Transport	☐	☐

12. Were the results of your research adopted by the private aquaculture sector? *

Mark only one oval.

- ◯ Yes, largely
- ◯ Yes, partly
- ◯ Not yet
- ◯ I do not know

13. If you have led or participated in FRDC project(s), please provide the project code(s)

____

14. Did you receive any support for your research from the private aquaculture industry? *

Mark only one oval.

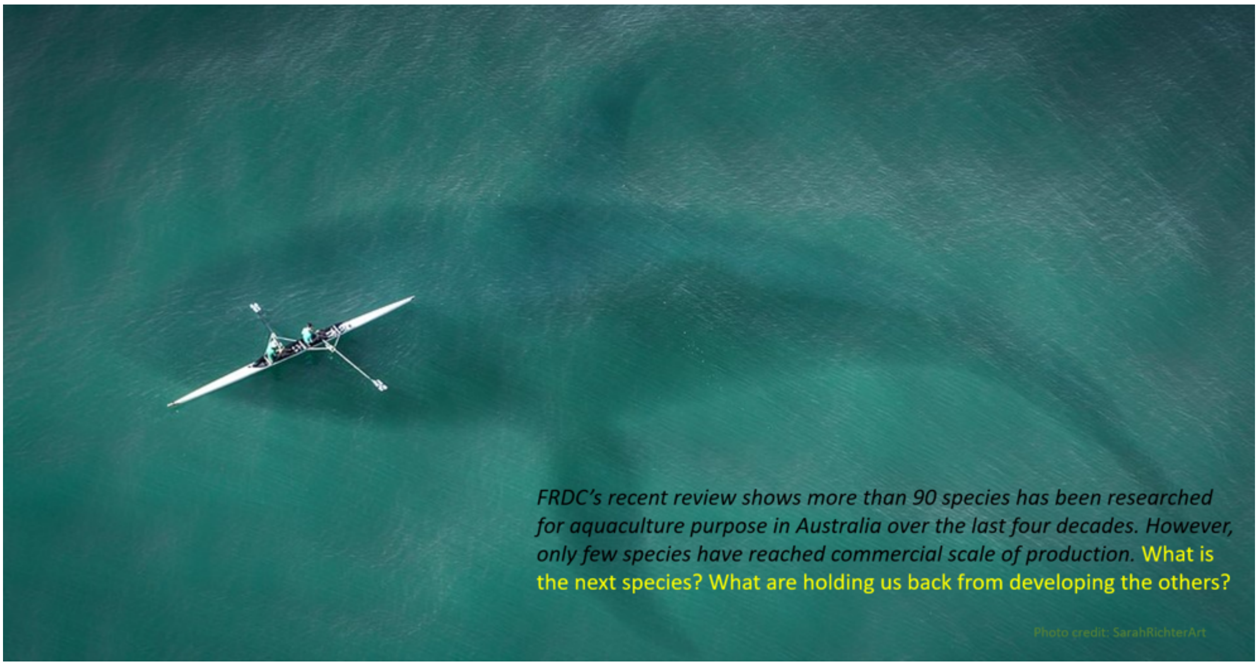
- ( ) Yes
- ( ) No

15. Can you provide us a list your publications about this species by sending email to Tung.Hoang@csiro.au later on? *

Mark only one oval.

- ( ) Yes. Remind me by email please.
- ( ) Maybe. Remind me by email please.
- ( ) Sorry, I can't

Aquaculture Potential



16. From your professional experience please rate the following attributes of this species with respect to its potential for aquaculture (anywhere in the world)? *

Mark only one oval per row.

	Unfavourable	Neutral or Uncertain	Favourable
Availability of broodstock	⬭	⬭	⬭
Control of reproduction in captivity	⬭	⬭	⬭
Consistent supply of quality seed	⬭	⬭	⬭
Knowledge of nutritional requirements and access to feeds	⬭	⬭	⬭
Susceptibility to diseases/parasites	⬭	⬭	⬭
Tolerance to high rearing densities	⬭	⬭	⬭
Survival in grow-out phase	⬭	⬭	⬭
Growth rate to market size	⬭	⬭	⬭
Possibility to adopt existing technologies	⬭	⬭	⬭
Market scale	⬭	⬭	⬭
Domestic market price	⬭	⬭	⬭
Potential for export	⬭	⬭	⬭
Flesh yield	⬭	⬭	⬭
Value add	⬭	⬭	⬭
Access to production sites	⬭	⬭	⬭

17. Which of the following attributes does this species possess? *

Check all that apply.

- [ ] Easy to reproduce in captivity
- [ ] Grow-out period is less than 12 months
- [ ] Can be farmed intensively in sea cages
- [ ] Can be farmed intensively with existing longline/basket/other technology
- [ ] Can be marketed for premium prices
- [ ] Has attracted substantial R&D interest
- [ ] Grows well on plant-protein-based diets
- [ ] Wild catches have been banned or are very limited
- [ ] Estimated production cost is US$ 3/kg or lower
- [ ] Has been traded regionally or globally

18. Can you evaluate the current level of development for the farming of this species? *

Mark only one oval per row.

	I don't know	Experimental	Technically feasible	Commercially viable
Broodstock collection or domestication	◯	◯	◯	◯
Maturation and induced spawning	◯	◯	◯	◯
Larval rearing	◯	◯	◯	◯
Fingerling or juvenile production	◯	◯	◯	◯
Grow-out	◯	◯	◯	◯
Harvest	◯	◯	◯	◯
Processing	◯	◯	◯	◯
Transport	◯	◯	◯	◯

19. Which of the following barriers may hamper increased aquaculture production of this species in the country for which the R&D was conducted? *

Check all that apply.

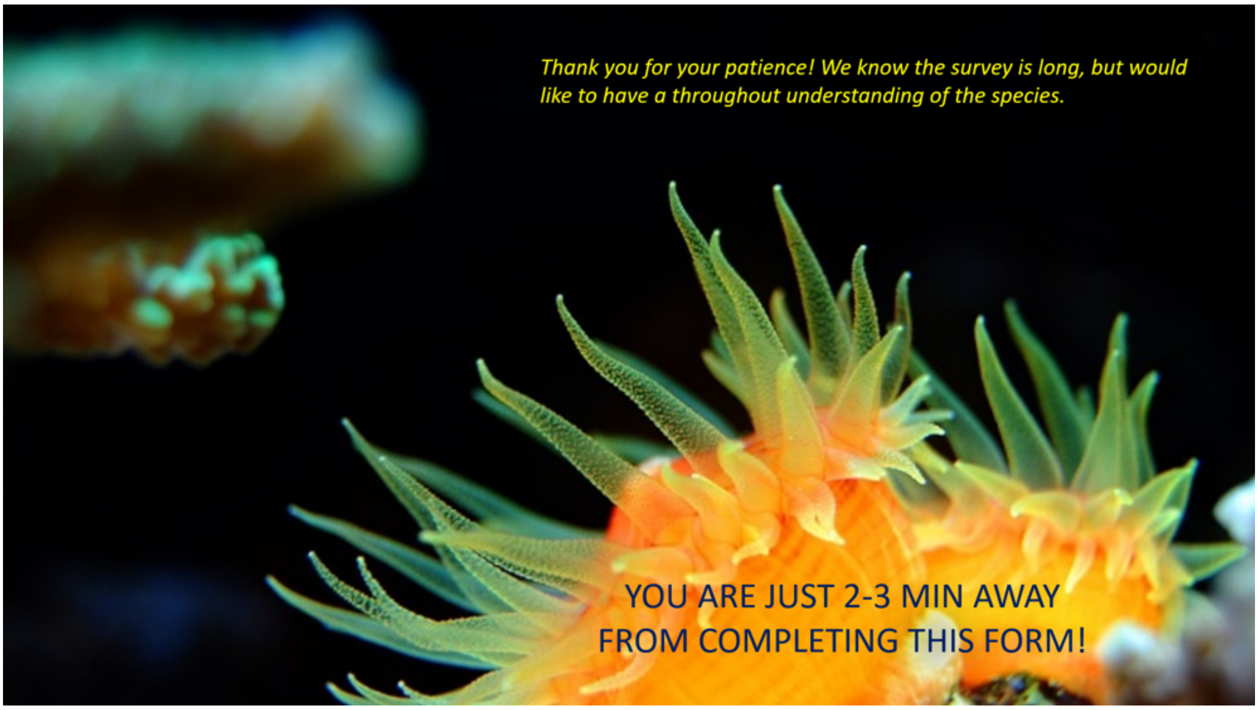
- [ ] Unfavourable regulations (i.e. environmental, trading or animal welfare issues)
- [ ] Low market demand
- [ ] Low profit or high production cost
- [ ] Limited sites for production
- [ ] Lack of skilled labour
- [ ] Increasing incidence of infectious diseases
- [ ] Insufficient supply of quality seed (broodstock/egg/fry/juvenile)
- [ ] Heavy dependence upon fish meal
- [ ] Too small industry
- [ ] Low diversity or lack of value-added products for the consumer
- [ ] Poor downstream capacity (processing, logistics, marketing, etc.)
- [ ] Increasing concern about environmental impacts
- [ ] Lack of investment throughout the supply chain
- [ ] Poor infrastructure (road, electricity, transport, etc.)
- [ ] Lack of public interest (including consumers, traders, investors, regulators, etc.)
- [ ] Limited funding for research & development
- [ ] Poor growth rate
- [ ] Poor survival

20. Can you evaluate the availability and accessibility of essential inputs for the farming of this species in the country for which the R&D was conducted? *

Check all that apply.

	I don't know	Not available	Available	Highly available
Site for production	☐	☐	☐	☐
Wild-caught broodstock	☐	☐	☐	☐
Captive broodstock	☐	☐	☐	☐
Eggs/larvae/fingerlings	☐	☐	☐	☐
Larval feeds	☐	☐	☐	☐
Grow-out feeds	☐	☐	☐	☐
Drugs/chemicals for disease control	☐	☐	☐	☐
Conditioners for water quality management	☐	☐	☐	☐
Farming systems & equipment	☐	☐	☐	☐
Processing facilities	☐	☐	☐	☐
Transport to market	☐	☐	☐	☐
Skilled labour	☐	☐	☐	☐
Finance	☐	☐	☐	☐
Technical support	☐	☐	☐	☐

Photo credit: pixabay



Aquaculture Status

Photo credit: CSIRO (Australia)

21. What is the current or estimated production of this species in the country for which the R&D was conducted (MT/year)? *

Please type "999" if you don't know. Thank you!

22. Where is that production from? *

Mark only one oval.

- Only one company or farm
- Few companies or farms (i.e. 2 - 5)
- Many companies or farms (i.e. more than 5)
- I do not know

23. What is the current market price (US$/kg) of this species in the country for which the R&D was conducted? *

Please type "999" if you don't know. Thank you!

____

24. Do you plan to do more research on this species? *

Mark only one oval.

- Yes
- Maybe
- No *Skip to question 27*

Research Plans

25. Do you expect to seek funding from FRDC (Australia)? *

Mark only one oval.

- Yes
- No

26. Would you like to find industrial partners to discuss and conduct your research on this species? *

Mark only one oval.

- ( ) Yes
- ( ) No

Photo credit: pixabay

Additional comments

27. Please provide your additional comments, if any, about the future of this species regarding both opportunities and barriers.

Your valuable contribution to Inventa 2018 is highly appreciated!

Photo credit: StockSnap

Inventa 2018: Species Audit by Producer

Thank you for participating our study. We look forward to receiving your valuable inputs on the aquaculture species you have worked on. We will share the results of Inventa with you. Furthermore, your personal details will not be disclosed in our report.

* Required

1. Please provide your email address or your full name

Yours will be used to relate with previous reports and for our further communication.

____

2. Which country do you report for this species?

Mark only one oval.

- ( ) Australia
- ( ) Other: _______________________

The species: general information

3. Common name of the species *

Please use comma to separate multiple different names

____

4. Scientific name

This is helpful to us and could be provided as either full name (genus and species) or at least part of it.

____

5. Where is this species naturally distributed? *

Mark only one oval.

- Locally in your country
- Throughout your country
- Regionally or in a few countries
- Globally or in more than one continent
- I do not know

6. What are the current markets of this species? *

Check all that apply.

- [ ] Local
- [ ] National
- [ ] Limited export (i.e. to few countries)
- [ ] Global export (i.e. to many countries)
- [ ] Do not know

7. What types of product from this species are preferred by the consumer in your country? *

Check all that apply.

- [ ] Live
- [ ] Fresh whole
- [ ] Frozen whole
- [ ] Fresh fillet/portion
- [ ] Frozen fillet/portion
- [ ] Smoked
- [ ] Roe

Other: [ ] ______________________

8. From your professional experience please rate the following attributes of this species with respect to its potential for aquaculture? *

Mark only one oval per row.

	Unfavourable	Neutral or Uncertain	Favourable
Availability of broodstock	⬭	⬭	⬭
Ability to control reproduction in captivity	⬭	⬭	⬭
Knowledge of nutritional requirements and access to feeds	⬭	⬭	⬭
Susceptibility to diseases/parasites	⬭	⬭	⬭
Tolerance to high rearing densities	⬭	⬭	⬭
Survival in grow-out phase	⬭	⬭	⬭
Growth rate to market size	⬭	⬭	⬭
Possibility to adopt existing technologies	⬭	⬭	⬭
Domestic market prices	⬭	⬭	⬭
Market scale	⬭	⬭	⬭
Potential for export	⬭	⬭	⬭
Value add	⬭	⬭	⬭
Flesh yield	⬭	⬭	⬭
Access to production sites	⬭	⬭	⬭
Competition by similar products	⬭	⬭	⬭

9. Which of the following attributes this species likely posses?

Check all that apply.

- [ ] Easy to reproduce in captivity
- [ ] Grow-out period is less than 12 months
- [ ] Can be farmed intensively in sea cages
- [ ] Can be marketed for premium prices
- [ ] Has attracted substantial R&D interest globally
- [ ] Grows well on plant-based protein diets
- [ ] Wild catches have been banned or ar very limited
- [ ] Estimated production cost is US$ 3/kg or lower
- [ ] Has been traded regionally or globally

Your production

In this section we ask for information about production of this species.

10. Have you (or your company) produced it commercially?

Mark only one oval.

- ( ) Yes
- ( ) Not yet (e.g. still in experimental or planning stage)

11. Has been there any other producer of this species in your country?

Mark only one oval.

- ( ) No
- ( ) Yes, a few
- ( ) Yes, many
- ( ) I do not know

12. When did you (or your company) start producing this species commercially?

____

13. What made you or your company interested in producing this species?

Check all that apply.

- [ ] Easier than other/previous species
- [ ] Expected profitability
- [ ] High market demand
- [ ] Likelihood of long-term sales contract
- [ ] Your competitive strengths (i.e. you could be a market leder)
- [ ] Production was possible with existing systems/technologies
- [ ] Necessary technologies and inputs are available
- [ ] Production sites available
- [ ] Existing production permit
- [ ] Availability of support (e.g. permissions, capital or technical assistance)
- [ ] Similarity to other well-known aquatic product(s)

Other: [ ] ______________________

14. What production stages of this species does your company's business cover? Of those which are you most proficient in? Which one requires significant improvement to ensure business viablity?

Check all that apply.

	1. Covered	2. Proficient in	3. Requires improvement
Broodstock (collection, domestication or selective breeding)	[ ]	[ ]	[ ]
Maturation and induced spawning	[ ]	[ ]	[ ]
Larval rearing	[ ]	[ ]	[ ]
Fingerling or juvenile production	[ ]	[ ]	[ ]
Grow-out	[ ]	[ ]	[ ]
Harvest	[ ]	[ ]	[ ]
Processing	[ ]	[ ]	[ ]
Transport	[ ]	[ ]	[ ]
Others	[ ]	[ ]	[ ]

15. What products do/did you (or your company) produce?

Check all that apply.

- [ ] Broodstock
- [ ] Genetically improved broodstock
- [ ] Gametes (egg and/or sperm) or fertilised eggs
- [ ] Larvae
- [ ] Juvenile/fingerlings
- [ ] Food "fish" (fish as a general term for aquatic species)
- [ ] Roe

Other: [ ] ________________

16. What is/was the annual production of this species that you (or your company) produce/produced?

If you can't share with us, please type "999" and no unit

____

____

____

____

____

Sources of technological innovation

17. Does/did your company have an R&D unit?

Mark only one oval.

- ( ) Yes
- ( ) Yes, but no longer
- ( ) No

18. How have you (or your company) obtained the primary know-how for production of this species?

Check all that apply.

- [ ] Developed in-house
- [ ] Provided by other aquaculture producers
- [ ] Provided by commercial R&D providers
- [ ] Provided by a research institution or researcher(s)

Other: [ ] ______________________

19. What proportion (%) of the technology for production of this species has been adopted from overseas?

____

20. What proportion (%) has been adopted from other species?

____

21. Which of the following areas should be the target of more research on this species?

Check all that apply.

- [ ] Biology/Ecology
- [ ] Genetics/Selective breeding
- [ ] Nutrition
- [ ] Health/Diseases/Biosecurity
- [ ] Environmental requirement
- [ ] Husbandry techniques
- [ ] Farming systems
- [ ] Water quality
- [ ] Waste treatment
- [ ] Animal welfare
- [ ] Markets, marketing, logistics, supply chains
- [ ] Product development
- [ ] Economics
- [ ] Environmental interactions
- [ ] Policy, laws and regulation

Other: [ ] ____________________

22. Please write if you have some specific recommendations

____

____

____

____

____

Check point

23. Are you producing the species at the moment?

If you can't share with us, please type "999"

Mark only one oval.

- ( ) Yes
- ( ) No

Reasons for ceasing production

24. When did you stop production?

____

25. What were the problems?

Check all that apply.

- [ ] Lack of profitability
- [ ] Excessive losses to disease(s)
- [ ] Strong competition
- [ ] Lack of demand
- [ ] Excessive regulations

Other: [ ] _______________

26. Do those problems still exist for the species?

Mark only one oval.

- ( ) Yes
- ( ) Yes, partly
- ( ) Maybe
- ( ) No

27. Please add your additional comments, if any, about the factors that led you to cease production of the species.

____
____
____
____
____

Outlook

28. What is your (or your company's) plan for this species in the next 10 years?

Mark only one oval per row.

	Yes, definitely	Possibly	Unsure	No	Unable to disclose
Look for R&D partners	⬭	⬭	⬭	⬭	⬭
Call for investment	⬭	⬭	⬭	⬭	⬭
Increase production	⬭	⬭	⬭	⬭	⬭
Improve productivity	⬭	⬭	⬭	⬭	⬭
Conduct marketing activities	⬭	⬭	⬭	⬭	⬭
Reduce production cost	⬭	⬭	⬭	⬭	⬭
Adopt technological innovations	⬭	⬭	⬭	⬭	⬭
Increase production sites	⬭	⬭	⬭	⬭	⬭
Vertically integrate production	⬭	⬭	⬭	⬭	⬭

29. What is your prediction about this species' aquaculture in the next 10 years at national/regional/global scales?

Mark only one oval per row.

	Reduced	Stable at current levels	Slightly increased	Substantially increased
Production	◯	◯	◯	◯
Productivity (kg/m2 or kg/m3)	◯	◯	◯	◯
Demand	◯	◯	◯	◯
Market price	◯	◯	◯	◯
Production cost	◯	◯	◯	◯
Problems with diseases	◯	◯	◯	◯
Technological innovation	◯	◯	◯	◯
Farming area	◯	◯	◯	◯

30. Do you foresee any barriers that may hamper increased aquaculture production of this species?

Check all that apply.

- [ ] Unfavourable regulations (i.e. environmental, trading or animal welfare issues)
- [ ] Low market demand
- [ ] Low profit or high production cost
- [ ] Limited sites for production
- [ ] Lack of labour
- [ ] Increasing incidence of infectious diseases
- [ ] Insufficient supply of quality seed (broodstock/egg/fry/juvenile)
- [ ] Heavy dependence upon fish meal
- [ ] Low diversity or lack of value-added products for the consumer
- [ ] Poor downstream capacity (processing, logistics, marketing, etc.)
- [ ] Increasing concern about environmental impacts
- [ ] Lack of investment throughout the supply chain
- [ ] Poor infrastructure (road, electricity, transport, etc.)
- [ ] Lack of public interest (including consumers, traders, investors, regulators, etc.)
- [ ] Limited funding for research & development
- [ ] Poor growth rate
- [ ] Poor survival

31. Do you (or your company) plan to diversify production into other aquaculture species?

Mark only one oval.

- ( ) Sorry, I can't disclose
- ( ) No
- ( ) Maybe *Skip to question 32*
- ( ) Yes, single species *Skip to question 32*
- ( ) Yes, multiple species *Skip to question 32*

New Species

32. Which of the following groups does this new species belong to?

Mark only one oval.

- Finfish
- Crustaceans
- Molluscs
- Algae and/or seaweeds
- Other
- Sorry I can't disclose

33. Can you evaluate the current level of development for the farming of this species?

Mark only one oval per row.

	I don't know	Experimental	Technically feasible	Commercially viable
Broodstock collection or domestication				
Maturation and induced spawning				
Larval rearing				
Fingerling or juvenile production				
Grow-out				
Harvest				
Processing				
Transport				

34. Can you evaluate the availability and accessibility of essential inputs for the farming of this species in your country?

Check all that apply.

	I don't know	Available	Limited accessiblity	Highly accessible
Site for production	☐	☐	☐	☐
Wild-caught broodstock	☐	☐	☐	☐
Captive broodstock	☐	☐	☐	☐
Eggs/larvae/fingerlings	☐	☐	☐	☐
Larval feeds	☐	☐	☐	☐
Grow-out feeds	☐	☐	☐	☐
Drugs/chemicals for disease control	☐	☐	☐	☐
Conditioners for water quality management	☐	☐	☐	☐
Farming systems & equipment	☐	☐	☐	☐
Processing facilities	☐	☐	☐	☐
Transport to market	☐	☐	☐	☐
Labour	☐	☐	☐	☐
Finance	☐	☐	☐	☐
Technical support	☐	☐	☐	☐

35. Can you tell us the name of the species?

Mark only one oval.

- ◯ Yes
- ◯ No

New Species

36. Scientific name of the species

____

37. Which of the following areas would you recommend us to do more research for this species?

Check all that apply.

- [ ] Biology/Ecology
- [ ] Genetics/Selective breeding
- [ ] Nutrition
- [ ] Health/Diseases/Biosecurity
- [ ] Environmental requirement
- [ ] Husbandry techniques
- [ ] Farming systems
- [ ] Water quality
- [ ] Waste treatment
- [ ] Animal welfare
- [ ] Markets, marketing, logistics, supply chains
- [ ] Product development
- [ ] Economics
- [ ] Environmental interactions
- [ ] Policy, laws and regulation

Acknowledgement

Thank you for spending your valuable time with us. We will share you the results of our Inventa 2018 study, and keep you updated any new development as the result of it. If you can share information for another species with us, please submit this form and follow the link provided.

FRDC FINAL REPORT CHECKLIST

Project Title:	Auditing research effort on aquaculture species and industry adoption for production growth		
Principal Investigators	Tung Hoang, Joshua Fielding, Harry King, Pollyanna Hilder		
Project Number:	2017-171		
Description:	This report presents the results of our FRDC 2017-171 Project entitled "Auditing research effort on aquaculture species and industry adoption for production growth". Research effort and industry adoption on 44 species for aquaculture in Australia were audited to reveal both opportunities for and barriers to commercial aquaculture production. Similar audits were also conducted for 54 species overseas for reference purpose. The research was conducted by a team of CSIRO Aquaculture and FRDC staff. Data collection started in late 2018. Inputs were provided by scientists, aquaculture producers, experts, seafood traders and development officers both in Australia and 19 other countries. The report provides more insights about aquaculture development in Australia regarding research effort, research needs, barriers to further development and opportunities for growth. The information it provides is expected to be useful to aquaculture developers, producers and investors, scientists and research institutions, research management agencies, policy makers and governors.		
Published Date:		**Year:**	2020
ISBN:		**ISSN:**	
Key Words:	Aquaculture species, research effort, industry adoption, barriers, opportunities		

Please use this checklist to self-assess your report before submitting to FRDC. Checklist should accompany the report.

	Is it included (Y/N)	**Comments**
Foreword (optional)	N	
Acknowledgments	Y	
Abbreviations	Y	
Executive Summary	Y	
− **What the report is about**	Y	
− **Background – why project was undertaken**	Y	
− **Aims/objectives – what you wanted to achieve at the beginning**	Y	
− **Methodology – outline how you did the project**	Y	
− **Results/key findings – this should outline what you found or key results**	Y	
− **Implications for relevant stakeholders**	Y	

− Recommendations	Y	
Introduction	Y	
Objectives	Y	
Methodology	Y	
Results	Y	
Discussion	Y	
Conclusion	Y	
Implications	Y	
Recommendations	Y	
Further development	Y	
Extension and Adoption	Y	
Project coverage	Y	
Glossary	N	
Project materials developed	N	
Appendices	Y	
EXTENSION		
Extension plan developed?	**Y**	
Extension undertaken?	**N**	
If extension was undertaken, who was it undertaken with and was it successful? **(Detail answer in comments section)**		
If No, then is further extension necessary? **With who?** **How? (detail answer in comments section)**		