Australia's National
Science Agency

Protein

A Roadmap for unlocking technology-led growth opportunities for Australia

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Acknowledgement

CSIRO acknowledges the Traditional Owners of the land, sea and waters, of the area that we live and work on across Australia. We acknowledge their continuing connection to their culture, and we pay our respects to their Elders past and present.

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Foreword

Australia has long history in agriculture, and around the world we are recognised as leaders in agricultural excellence. CSIRO's own history in agriculture spans more than 100 years, from ridding the land of prickly pear back in 1926, to helping transform our cattle industry through introduction of the Brahman breed, to now developing nutritious grains that combat chronic disease.[1]

Today Australia has an opportunity to leverage its agricultural strengths to grow our economy in new markets, to extend our leadership in existing industries, and to sustainably produce and export more food to meet a growing global demand for protein.

By 2050, the Food and Agriculture Organisation estimates we will need to produce 60 per cent more food to feed an expected 9.7 billion people. Currently, 75 per cent of the world's food is produced from five animals and 12 plants.[2] This concentration makes our food system more vulnerable to threats like disease, pests, and weather. It also presents a tremendous opportunity when you consider the vast biodiversity and nutrient dense foods on the planet that could be incorporated into our diets.

Protein is vital to our health, and as global populations grow and consumer preferences change, we will need to produce more of it, more sustainably, from more sources. But we can't just do what we've done before – we need solutions from science to help create these new markets.

As this *National Protein Roadmap* details, the solution is in agricultural and foodtech innovation to develop new and improved protein-based food products, and new ways to get more value from our traditional animal protein sources. As with any great innovation, it starts with a clear market vision of a better future for Australia, and targets our science at giving Australia an unfair global advantage.

Building on our strengths in agriculture and our reputation as a clean, safe, and high-quality food producer, Australia has a huge opportunity to become a global leader in high quality, value-added protein. We estimate this is nearly an additional $13 billion market opportunity that will complement – not compete – with our traditional animal protein industries.

Australia is already a significant global producer of premium protein products – like our beloved steaks, lamb, prawns, and barramundi – and there are opportunities to enhance our leadership. Our beef is so highly sought after in export markets that food fraud could impact our growth. This *Roadmap* outlines the opportunity to build on the premium status of our beef with technology to verify the provenance of a product at any point along the supply chain and uncover impersonators.

But the protein market opportunity cannot be met by animal proteins alone. Australia already has strong cropping industries that our science can leverage to grow our plant-based protein output, and if we invest in our manufacturing capability, we can supercharge that growth. We export more than 70 per cent of the bulk protein commodities we produce – like grains, legumes, and meat – and ironically buy them back as finished products. We could capture significantly more value if we invest in our processing and manufacturing facilities to convert these into higher value products for international markets, just as we've demonstrated already creating companies like v2food to bring plant-based protein products onto the mainstream market.

Finally, this *Roadmap* also outlines other protein opportunities for Australia, like sustainable aquaculture with a new white-flesh fish industry, and non-traditional forms of protein like cultivated meat and yeast-based precision fermentation-derived products.

There is room for growth across all protein sectors, but we will need to work together to achieve our goals. In 2021, together with our partners at the Department of Industry, Science, Energy and Resources; Meat & Livestock Australia; the Grains Research & Development Corporation and others, CSIRO launched a Future Protein Mission to co-develop new products and solutions to help our protein industries reach their full potential.

Australia has often been called the food bowl of Asia, but it's time to become the delicatessen of the world – the source of high value, high profit, premium and trusted food products that others strive to copy, but simply can't match. Wouldn't it be great for Australia to be a world leader in food innovation? It's now up to us all to help bring that vision to life, and this *Roadmap* outlines the key science and technology focus areas which will be the building blocks of our success.

Dr Larry Marshall
Chief Executive, CSIRO

1 CSIRO (2020) BARLEYmax. Viewed 14 February 2022 <https://www.csiro.au/en/research/production/food/BARLEYmax-BUcase-study>.

2 Searchinger T and Hanson C (2014) Closing the 'Food Gap' Means Renewing the Global Commitment to Crop Breeding . Viewed 14 February 2022, <https://www.wri.org/insights/closing-food-gap-means-renewing-global-commitment-crop-breeding>.

Contents

Size of the prize for Australian protein

10.47 million more consumers

For Australian protein products between 2018 and 2030

65 million tonnes

Total domestic and export demand for Australian protein products in 2030

8.65 million tonnes

Additional demand for Australian protein products in 2030 compared to 2018

Source: AgriFutures (2020) The changing landscape of protein production.

Demand is significant and can only be met through a combination of animal proteins, plant proteins and novel protein production systems.

Australian protein industries at a glance

492,000 kt

of animal-based protein consumed globally.[3]

5,000 kt meat

> 4 billion eggs

≈ 9 billion L milk produced in Australia.[4]

≈ 260 kt

of fisheries products (including fish, crustaceans and molluscs) produced in Australia.[4]

> $21 billion

in exports of Australian animal-based proteins, including dairy and live exports.[4]

28,000 businesses

in Australian animal-based protein industries.[5]

≈ 210,000 employed

in Australian animal-based protein industries.[6]

≈ $10 billion

in exports of grains, oilseeds and pulses.[7]

≈ $3 million

in exports of plant-based protein alternatives.[8]

≈ 550 employed

in the Australian plant-based protein alternatives industry.[8]

3 OECD (2021) OECD Agriculture Statistics. Viewed 11 January 2021, <https://stats.oecd.org/BrandedView.aspx?oecd_bv_id=agr-data-en&doi=4bde2d83-en>. Covers beef and veal, pork, poultry, sheep and fish.

4 See Appendix B protein snapshots.

5 Counted as businesses with one or more employees operating in livestock farming, fisheries and aquaculture, hunting and trapping, meat and seafood product processing and manufacturing, and dairy product processing and manufacturing. ABS (2021) Counts of Australian Businesses, including Entries and Exits. Viewed 11 January 2022, <https://www.abs.gov.au/statistics/economy/business-indicators/counts-australian-businesses-including-entries-and-exits/latest-release>.

6 Counted as 'sheep, beef cattle and grain', 'dairy cattle', 'poultry', 'other livestock', 'aquaculture', 'fishing' and 'hunting and trapping' industries. Australian Bureau of Agricultural and Resource Economics and Sciences (2020) Agricultural commodities and trade data - Australian economy - farm sector.

7 Australian Bureau of Agricultural and Resource Economics and Sciences (2021) Agricultural commodities June quarter 2021: Value of agricultural, fisheries and forestry exports (fob), Australia.

8 Food Frontier (2021) 2020 State of the Industry Australia's Plant-Based Meat Sector.

Technology-led opportunities for Australia

	Current state	Conservative 2030 scenario		Ambitious 2030 scenario
Total Australian protein sector (domestic + exports)	$56 billion	$76 billion	Additional technology-led opportunity	$89 billion
Roadmap opportunities	$16.7 billion	$22.1 billion	**$13 billion**	$34.9 billion
Integrity systems for red meat exports	$15.3 billion*	$16.5 billion	$570 million	$17.1 billion
Plant-based products	$140 million	$3.0 billion	$6 billion	$9.0 billion
Red meat for health and wellness markets	$1 billion	$1.4 billion	$3.8 billion	$5.1 billion
Precision fermentation	Negligible	$750 million	$1.45 billion	$2.2 billion
White flesh fish	$300 million	$460 million	$1.04 billion	$1.5 billion
Insect protein sources	Negligible	$12 million	$32 million	$44 million
Total jobs in Roadmap opportunities		4,490 jobs	9,860 jobs	14,350 jobs

Note: Four additional opportunities have been qualitatively explored in this roadmap but their economic size and potential growth have not been quantitatively assessed.

Sources: Estimate of current state for the Australian protein sector is taken from FIAL (2019) Protein Market: Size of the Prize Analysis for Australia; estimate of conservative scenario in 2030 for the Australian protein sector is taken from AgriFutures (2020) The changing landscape of protein production. All other estimates are CSIRO calculations.

*Estimate of current state for integrity systems for red meat exports is the current revenue Australia earns from red meat exports with its current integrity systems in place, estimates of conservative and ambitious scenarios in 2030 for integrity systems for red meat exports are the estimated 2030 export revenue from red meat exports with low (conservative) and high (ambitious) enhancement of these systems to enable traceability and verifiable credentials.

Executive summary

Our objectives

To create almost an additional $13 billion in science and technology driven protein opportunities for Australia by 2030, products and ingredients must meet or exceed consumer needs and the industry should focus on value-adding in areas where Australia has a competitive advantage.

To become a global leader in high quality, value-added protein, the focus should be on product quality and attributes, including health, welfare and environmental credentials.

Purpose of roadmap

To develop, in collaboration with stakeholders, a blueprint to guide investments in science, technology and infrastructure initiatives that contribute to the protein industry's productivity and profitability, sustainability, regional prosperity and global competitiveness.

Why now for protein?

Growing global protein demand, changing consumer preferences, and increasing investment and innovation are all driving an intensified focus on the protein industry. Now is the time to build a sustainable and resilient Australian food system that delivers protein for discerning local and global consumers.

Why Australia?

Australia is well positioned to capitalise on the growing protein opportunity to become a global leader through growth and expansion of established products and markets, and the sustainable development of novel and differentiated protein products. The nation's agriculture and food industry is supported by a strong history of research and production excellence, proximity to growing Asian markets, a reputation for producing premium and safe food products, strong biosecurity, and commitments towards growth and development of sovereign value adding capabilities.

Strategic science and technology focus areas

1 Strengthening product integrity and market access

Continuing to invest in the essential R&D and infrastructure that underpin the global competitiveness of Australian protein products and ingredients. This will ensure Australian manufacturers have the systems needed to demonstrate and communicate the positive attributes of their products, whether through food safety measures, supply chain traceability, or compliance with local or international trading partner standards and regulations. This will in turn reduce technical trade barriers, position Australia favourably in trade negotiations and support Australia's preferential access to key markets, such as **expanding Australian red meat exports into new geographies.** Although product integrity and market access are key strategic focus areas across Australia's protein industry, this roadmap specifically explores **integrity systems in the red meat sector**.

2 Optimising quality and cost competitiveness

Continuing to invest in the essential R&D and infrastructure that underpin the quality[9] and cost competitiveness of Australian protein products and ingredients. This will ensure Australian manufacturers have the inputs needed to produce higher value products and that Australian protein is preferred by customers and consumers. While quality and cost optimisation is important across the protein industry, this report explores **plant-based protein ingredients** and **crop breeding and pre-breeding**.

3 Maximising resources and circularity

Transforming what is currently considered low value or waste into high value products and ingredients and incorporating circularity principles into the supply chain. This will capture value and increase producer and processor profitability through product and market diversification. Examples of opportunities to transform waste and lower value by-products into higher value products include **red meat co-products** for health and wellness markets and **insect protein** sources for food and feed.

4 Enabling the scale-up of high growth sectors

Identifying sectors that are currently relatively small in Australia but have high growth potential and supporting their scale-up. This will capture additional value and increase profitability, alongside more mature existing sectors. Examples of high growth sectors include local, sustainable **white flesh fish** and **plant-based products**.

5 Developing novel production systems

Identifying new methods for producing protein through targeted investments in R&D and infrastructure. This will involve having a focused and targeted investment portfolio aimed at capturing value, optimising resources and leveraging Australia's comparative advantages. Examples of novel production opportunities include **precision fermentation** and **cultivated meats**.

The science, technology and infrastructure investment priorities identified for each of these opportunities are shown in Table 1.

9 In this context, quality means meeting or exceeding customer expectations regarding the properties and attributes of food items, including its appearance, texture, flavour, nutritional content and its ethical and sustainable production.

Ecosystem priorities

In addition to the strategic science and technology areas, this roadmap also sets out five priorities to guide activities for whole of ecosystem benefit and to monitor progress. For each priority, areas of consideration are identified.

Producers, communities and regions

Producers, communities and regions recognise the role that the protein industry plays in food production and economic prosperity; and see being part of the Australian protein industry as attractive now and into the future.

- Support primary producers with technology adoption, data and insights
- Develop an appropriately skilled workforce
- Engage and co-develop with Australian First Nations Peoples
- Support the development of regional communities to support agriculture
- Stabilise high-protein crop price and demand

Customers and consumers

Customers and consumers are engaged and seek high value, high quality, and trustworthy Australian products.

- Conduct consumer sentiment and sensory research
- Develop consumer communication and engagement plans for non-traditional proteins
- Early community engagement for cultivated meat
- Support consumer acceptance of insect proteins

Environment

Australian protein production increases while also protecting ecosystem health and biodiversity, and meeting consumer and market expectations for sustainability and biosecurity.

- Sustainability considerations for red meat production
- Whole-of-food-system view of healthy sustainable diets
- Consumer access to lower environmental impact food products and knowledge
- Understand impact through Life Cycle Analysis

Coordination and collaboration

The Australian protein industry sees the significant global opportunity for all types of protein and is coordinated and collaborative in pursuing this opportunity.

- Establish dedicated industry development for novel protein production
- Learn from international protein industry development (policy and scale-up)
- Engage with industry incumbents
- Share knowledge across industry
- Develop new business models and supply chains
- Coordinate and collaborate for animal protein product integrity
- Support cross-sector collaboration
- Facilitate the development of protein innovation clusters and accelerators

Policy and regulation

The Australian protein industry is well supported by policy and regulations that enable the industry to compete globally and deliver high quality products to local and export markets.

- Deliver streamlined compliance for protein exporters
- Review process for aquaculture farm licenses
- Provide regulatory clarity for new and novel foods
- Enable a safe but proactive regulatory environment for precision fermentation
- Develop science-informed food safety standards for cultivated meats
- Develop insect industry guidelines
- Continue policy and government infrastructure support

Table 1: 2022-2030 science technology and infrastructure investment priorities for identified opportunities

SCIENCE AND TECHNOLOGY FOCUS AREA	INDUSTRY OPPORTUNITIES	2022-2030 SCIENCE, TECHNOLOGY AND INFRASTRUCTURE INVESTMENT PRIORITIES
Strengthening product integrity and market access	**1: Integrity systems in the red meat sector**	• Verify the biological and geographical origin of production • Research and infrastructure to help establish and utilise data from production systems • Design new systems-based compliance • Conduct preventative risk assessments • Support compliance infrastructure
	2: Expanding Australian red meat exports into new geographic markets	• Support the development of logistics and cold chain management • Research to support new product innovation • Maintain and enhance reputation for clean, safe and natural products
Optimising quality and cost competitiveness	**3: Plant-based protein ingredients**	• Optimise fractionation technology • Secure capital for infrastructure • Obtain market information for plant-based products • Set supported production targets • Support research infrastructure development • Research to support technology and process development for protein extraction
	4: Crop breeding and pre-breeding	• Develop supply chain infrastructure • Invest in R&D programs
Maximising resources and circularity	**5: Red meat co-products for health and wellness markets**	• Remap the carcase • Research to understand new product markets and value chains • Research to understand customer needs and willingness to pay • Process engineering for co-product collection and transformation • Support evidence-based claims • Develop and demonstrate origin marker technology
	6: Insect protein sources for food and feed	• Investigate feasibility of co-location and sharing • Research to support insect waste management potential • Research to understand the nutritional profile of insects • Support progressive insect infrastructure scale-up • Support regulatory process development for insects

Key: Traditional protein Plant protein Non-traditional protein

SCIENCE AND TECHNOLOGY FOCUS AREA	INDUSTRY OPPORTUNITIES	2022-2030 SCIENCE, TECHNOLOGY AND INFRASTRUCTURE INVESTMENT PRIORITIES
Enabling the scale-up of high growth sectors	**7: Scaling up local, sustainable white flesh fish production**	• Investment in cross-sector infrastructure and services • Identify suitable white flesh fish species • Understand consumer expectations for aquaculture • Research to support aquaculture production enhancement • Research to understand and address aquaculture-environmental interactions and climate impacts
	8: Plant-based products	• Scaling up processing infrastructure • Services and skills to support food manufacturers and start-ups • Investment in collaborative R&D and prototyping facilities • Establish domestic ingredient supply chains • Invest in plant-based product R&D
Developing novel protein production systems	**9: Precision fermentation**	• Investigate and support pilot scale facilities • Support collaboration with adjacent sectors and infrastructure for precision fermentation scale-up • Services for precision fermentation scale-up • Research to support microorganism engineering and strain development and optimisation • Research to support feedstock selection, optimisation, and process improvement • Research to understand manufacturer and consumer needs • Life Cycle Analysis to understand impact • Research to understand nutritional profile of precision fermentation products • Precision fermentation product development
	10: Cultivated meats	• Optimise cell culture media • Identify cell sources for cultivated meat • Cultivated meat product development • Research to support food safety • Research to inform bioprocess development • Research to understand consumer preferences


4x4

Australia's Protein Roadmap

Introduction

Australia has an opportunity to cement its international position as a protein leader and drive economic growth by responding to increasing global demand while minimising the environmental impact of protein production. Australia's various existing and emerging protein industries will complement each other in growing Australia's protein output to meet global demand and improve food security.

This report aims to provide a blueprint for capturing the opportunities arising from the growth in the global demand for Australian protein. These include building on markets for traditional protein sources and positioning Australia as a global leader in the sustainable development of novel and differentiated protein ingredients and products. The report identifies several strategic focus areas that aim to showcase science- and technology-led value-adding for Australia's protein industry. Specific opportunities are identified for these focus areas, as well as some of the challenges that need to be overcome to capitalise on these opportunities; *however, the opportunity for Australia stretches beyond those identified within this report.* By identifying research and development, infrastructure and ecosystem priorities, the report is designed to help inform the next series of investments amongst various stakeholder groups (e.g., industry, government and research).

This report draws upon consultation with stakeholders from across the supply chain, international food and innovation organisations, CSIRO's research expertise and various state and Commonwealth government departments (see Appendix A). Demonstrating the collaboration that will be required to seize growth opportunities and sustainably grow Australia's protein industry, this research activity and resulting report has been sponsored by a diverse set of organisations from across Australia's protein landscape (see page i).

What is protein?

Commonly referred to as the building blocks of life, proteins play many critical roles in the body, including helping to build muscle mass, make hormones and enzymes, and making and repairing cells.

Rich dietary sources of protein include animal products (such as meat, fish, dairy and eggs) and plant sources (such as nuts, cereals and legumes). Other non-traditional sources of protein include insects and some cultured and fermented products – many of which are not yet common in Australian diets.

Figure 1: Protein sources

Why now?

Food is the single strongest lever available to optimise both human health and environmental sustainability.[10] **Growing global protein demand, changing consumer preferences, and increasing investment and innovation are all driving an intensified focus on the protein industry. Now is the time to build a sustainable and resilient Australian food system that delivers nutritious protein for discerning local and global consumers.**

Global protein demand, measured in terms of total macronutrients consumed, is expected to increase 20% between 2018 and 2025 to 271 million tonnes,[11] driven by a growing global population and a rising middle class. Meeting this demand is essential to improving global food security, and will require increased production of livestock (including fish), which will remain an important part of the global food system,[12] alongside complementary increases in plant-based and non-traditional protein sources (such as insects).

Consumer preferences, globally and in Australia, are also changing presenting further opportunity for value-adding. For example, while Australia remains one of the world's largest beef consumers, with 2020 per capita consumption averaging 23.4 kg,[13] there has been a steady decline in this consumption over the past two decades.[14] At the same time, other countries have witnessed increased consumption (China's beef consumption rose from 3.19 kg per capita in 2010 to 4.19 kg in 2020[15]). In Australia, approximately two-thirds of consumers have maintained their level of red meat consumption over the past 10 years, while 28% have reduced their intake and 9% have increased their consumption.[16] Common reasons for eating less red meat are based on cost, followed by health, environmental and animal welfare concerns.[17] Growing global demand and still significant domestic demand for red meat mean that even as per capita domestic consumption of red meat declines, the overall demand for Australian protein, including from both traditional and emerging plant and non-traditional sources, will remain high.

There is also growing consumer and investor interest in plant-based and non-traditional proteins, with meat alternative products becoming more embedded in the mainstream marketplace, providing additional and complementary protein options for consumers. While the market for these proteins is growing quickly, it is still relatively new and small compared to more traditional proteins.

Consumers are increasingly basing their food purchasing decisions not only on price and brand, but also on high-value attributes that demonstrate the quality and added value of the food products. There is growing consumer interest and awareness of provenance and traceability, nutritional value, sustainability and environmental credentials (e.g., carbon footprint, sustainable packaging). This provides messaging opportunities for animal protein industries and opportunities for ambitious industry-wide programs for Australia to differentiate itself. In some cases, various credentials will also be requested by Australia's trading partners and global trading rules,[18] making them essential for continued market access.

10 EAT-Lancet Commission (2019) Summary Report of the EAT-Lancet Commission. Stockholm.

11 FIAL (2019) Protein Market: Size of the prize analysis for Australia. Werribee, VIC.

12 Colgrave ML, Dominik S, Tobin AB, Stockmann R, Simon C, Howitt CA, Belobrajdic DP, Paull C and Vanhercke T (2021) Perspectives on Future Protein Production. Journal of agricultural and food chemistry 69(50), 15076–15083. DOI: 10.1021/ACS.JAFC.1C05989.

13 Meat & Livestock Australia (2021) State of the Industry Report: The Australian red meat and livestock industry 2021.

14 Meat & Livestock Australia (2021) State of the Industry Report: The Australian red meat and livestock industry 2021.

15 OECD (2021) Agricultural output | Meat consumption. Viewed 15 December 2021, <https://data.oecd.org/agroutput/meat-consumption.htm>.

16 Meat & Livestock Australia (2021) Consumer sentiment research: Australian perceptions about the red meat industry. Viewed 17 November 2021, <https://www.mla.com.au/marketing-beef-and-lamb/consumer-sentiment-research/>.

17 Meat & Livestock Australia (2021) Consumer sentiment research: Australian perceptions about the red meat industry. Viewed 17 November 2021, <https://www.mla.com.au/marketing-beef-and-lamb/consumer-sentiment-research/>.

18 Australian Bureau of Agricultural and Resource Economics and Sciences (2020) Global responses to climate change: opportunities for Australian agricultural producers. ABARES Insights (10).

Increased recent investments both in innovative protein businesses and sustainable production systems reflect demand for diversification. Focus on climate risk by investors alongside other environmental, social, and governance (ESG) elements is driving these investments in complementary, sustainable protein solutions which in turn can push Australia towards achieving its climate targets. For example, traditional protein and food companies are also investing in non-traditional protein, including Norco (Australia's oldest dairy cooperative) investing in Eden Brew (animal-free dairy start-up), and JBS (a global food company) acquiring Vivera (a Dutch plant-based food manufacturer) and becoming the majority shareholder of BioTech Foods (a Spanish cultivated meat start-up). Protein companies are also investing in sustainable and regenerative production systems and value chains, including around soil carbon and fertility, biodiversity, reduced or eliminated chemical use and emissions reduction. An example is Danone and Nestle's investments in regenerative agriculture.[19]

Why Australia?

Australia is a significant player in the global protein market. The nation is well positioned to capitalise on the growing protein opportunity to become a global leader[20] through growth and expansion of established products and markets and the sustainable development of novel and differentiated protein products.

Australia's advanced agricultural (including aquaculture) sector produces a healthy surplus – estimated to feed around 60 million people annually.[21] In 2020, Australia was the second largest beef and veal exporter after Brazil and the world's largest sheepmeat exporter.[22] Australia's strong agriculture and food industry and commodity-based exports provide significant advantages in becoming a global protein leader. There are growth commitments across the agricultural industry that support and drive momentum for Australia's protein opportunity, including the agriculture industry's bold target to exceed $100 billion in farm gate output,[23] or $200 billion in value-add by 2030.[24] CSIRO's Future Protein Mission and the Australian Government's National Agricultural Innovation Agenda[25] further support the opportunity, alongside the growing appetite for sovereign manufacturing and value adding, which has a significant focus on food manufacturing, as outlined in the Modern Manufacturing Strategy.[26] Additionally, Australia has strengths in crop exports, with total export value of grains, oilseeds and pulses at a five year average of $10.5 billion over 2015-20.[27]

Further advantages include Australia's trade partnerships and proximity to rapidly growing Asian markets. Australia has a strong international reputation for being 'clean and green', producing premium and safe food products, including traceable, high-quality red meat production, which provides opportunities in premium markets.[28] Australia's reputation is important for maintaining long term market access[29] and enables Australian producers to command a premium price for their product. This reputation (derived from decades of traditional meat and grain exports) is enabled by Australia's world class regulatory system, strong biosecurity and focus on food safety.

19 Danone (n.d.) Regenerative agriculture. Viewed 24 January 2022, <https://www.danone.com/impact/planet/regenerative-agriculture.html>. Nestlé Global (n.d.) Supporting regenerative agriculture. Viewed 24 January 2022, <https://www.nestle.com/csv/global-initiatives/zero-environmental-impact/climate-change-net-zero-roadmap/regenerative-agriculture>.

20 In this context, a global leader is a country that embraces strategic thinking, innovation and technology advancement through setting goals, prioritising them and taking responsibility to accomplish them; it focuses on skills and capability building to ensure its workforce has the tools to accomplish the goals; it prioritises sustainability and considers the environmental consequences of its decisions; and it prioritises long-term relationship building both internally and internationally through clear and diplomatic communication. As a result, a global leader is likely to have a relatively large per capita share of the export market in which they lead and is likely to be close to the technology frontier for that market.

21 CSIRO Futures (2017) Food and Agribusiness Roadmap. CSIRO, Canberra.

22 Meat & Livestock Australia (2021) Value of Australian beef exports falls in 2020. Viewed 9 November 2021, <https://www.mla.com.au/prices-markets/market-news/2021/value-of-australian-beef-exports-falls-in-2020/>.

23 National Farmers Federation (2020) 2030 Roadmap: Australian Agriculture's Plan for a $100 Billion Industry. Barton, ACT.

24 FIAL (2020) Capturing the prize- The A$200 billion opportunity in 2030 for the Australian food and agribusiness sector.

25 Australian Government (2021) National Agricultural Innovation Policy Statement. Canberra.

26 Australian Government (2020) Make It Happen: The Australian Government's Modern Manufacturing Strategy. Canberra.

27 Australian Bureau of Agricultural and Resource Economics and Sciences (2021) Agricultural commodities June quarter 2021: Value of agricultural, fisheries and forestry exports (fob), Australia.

28 Deloitte Australia (2013) Positioning for prosperity? Catching the next wave.; CSIRO Futures (2020) Growth opportunities for Australian food and agribusiness: Economic analysis and market sizing. CSIRO, Canberra.

29 Meat & Livestock Australia (2021) Market access. Viewed 8 November 2021, <https://www.mla.com.au/marketing-beef-and-lamb/international-markets/market-access/#>.

Australia's biosecurity system enables international market access. One of the greatest disruptions to the global protein industry over recent years has been the emergence of African Swine Fever (ASF), which was discovered in China in 2018. ASF is a highly contagious and lethal virus for pigs (humans remain unaffected), transmittable when pigs come into direct contact with infected animals, indirect contact with contaminated objects or are fed contaminated pork products. ASF has never occurred in Australia. The emergence of ASF, particularly in China, has accelerated Chinese demand for imported beef, a trend that was already growing due to growing populations and increasing income levels. From 2017 to 2020, the volume of imported beef into China tripled with trade from Brazil, Argentina and Australia reaching unprecedented levels.

Australia's significant research capability and expertise across agriculture, food and health also helps to favourably position the nation. Australia has a long history of research excellence in agriculture and food, including in crop, livestock and aquaculture breeding; animal management and innovative farming systems; disease management; genetics; processing automation; waste to energy conversions; and food science. Health and nutrition are also research strengths, including the interplay between health, food and consumer choice, and in delivering innovation to food, health and wellness industries.

In mature industries, such as the livestock industry, increased demand for protein will be met through technical innovations that enhance production efficiency and sustainability, as well as using currently under-utilised parts of the carcase.[30] Australia has significant research and industrial experience to draw upon in developing these technical innovations.

Alongside research institutions, Australia also has a growing ecosystem of companies focused on developing innovative food processing technologies and creating new value-added foods and ingredients. There are numerous start-ups and established companies operating in Australia and working on developing novel and differentiated protein products.

Focusing on science and technology

Science and technology innovation helps improve productivity, can provide social and environmental benefits, builds resilience, and enhances international competitiveness.[31]

Australia's protein opportunity is considerable. Like all of CSIRO's previous roadmaps, this roadmap explores how science and technology can drive the opportunities by supporting Australia's protein industry to respond to increased global demand while minimising the environmental impact of production. The report identifies five science and technology focus areas and outlines example protein industry opportunities for each area. For each example opportunity, priorities for science, technology and infrastructure investment out to 2030 are identified.

Businesses have a vital role to play in driving protein related science and technology innovation, and can realise significant value in doing so. Science and technology innovation can help businesses create new products and services, increase the quality of existing goods and services, and be more productive and profitable. Innovation can also enable businesses to become more competitive internationally and can help businesses maintain a social licence to operate.[32]

While not a focus of this roadmap, businesses also have a vital role in driving non-R&D innovation such as business model innovation that helps to ensure new technologies can be translated into scalable, commercial outcomes that reach and meet the needs of consumers.

By targeting and investing in the application of research, science and/or technology alongside appropriate infrastructure, Australia can accelerate innovation, growth and, in some cases, sustained competitive advantage across the protein industry, from pre-farmgate through to domestic and export markets. To help support and build the Australian protein industry, several broader ecosystem priorities are also identified.

30 Colgrave ML, Dominik S, Tobin AB, Stockmann R, Simon C, Howitt CA, Belobrajdic DP, Paull C and Vanhercke T (2021) Perspectives on Future Protein Production. Journal of agricultural and food chemistry 69(50), 15076–15083. DOI: 10.1021/ACS.JAFC.1C05989.

31 CSIRO Futures (2020) Value of science and technology.

32 CSIRO Futures (2020) Value of science and technology.

Roadmap outline

Science and technology focus areas	Industry opportunities
1 Strengthening product integrity and market access	● Integrity systems in the red meat sector ● Expanding Australian red meat exports into new geographic markets
2 Optimising quality and cost competitiveness	● Plant-based protein ingredients ● Crop breeding and pre-breeding
3 Maximising resources and circularity	● Red meat co-products for health and wellness markets ● Insect protein sources for food and feed
4 Enabling the scale-up of high growth sectors	● Scaling up local, sustainable white flesh fish production ● Plant-based products
5 Developing novel production systems	● Precision fermentation ● Cultivated meats

Key: ● Traditional protein ● Plant protein ● Non-traditional protein

Ecosystem priorities

Producers, communities and regions	Producers, communities and regions recognise the role that the protein industry plays in food production and economic prosperity, and see being part of the Australian protein industry as attractive now and into the future.
Customers and consumers	Customers and consumers are engaged and seek high value, high quality, and trustworthy Australian products.
Environment	Australian protein production increases while also protecting ecosystem health and biodiversity, and meeting consumer and market expectations for sustainability and biosecurity.
Coordination and collaboration	The Australian protein industry sees the huge global opportunity for all types of protein and is coordinated and collaborative in pursuing this opportunity.
Policy and regulation	The Australian protein industry is well supported by policy and regulations that enable the industry to compete globally and deliver high quality products to local and export markets.

1 Strategic science and technology focus areas

Australia is already a significant global protein producer and exporter, benefiting from well-established and sophisticated supply chain capacity and capability, particularly for animal-derived proteins (see Appendix B for snapshots on Australia's protein sectors). As global demand for protein continues to grow, particularly in Asia, new domestic and export markets will open, triggering opportunities for Australia's established protein industry, as well as the development of new Australian protein value chains that complement already existing animal and plant protein industries.

Various estimates, scenarios and targets have been developed for the size of the opportunity for Australian protein producers from the domestic market and exports. For example, The Australian Farm Institute and AgriFutures estimated business-as-usual organic growth for Australian proteins at almost $20 billion by 2030 compared to 2018.[33] The vision of the Red Meat Advisory Council's *Red Meat 2030* is to double the value of Australian red meat sales (domestic plus exports) by 2030, moving from $28.5 billion in 2018-19 to $57 billion in 2030.[34] FIAL used scenario analysis to estimate that shifting Australia's protein production mix to match projected global consumption for high-value proteins could create an additional $55 billion in 2025 compared to business-as-usual approaches.[35]

This roadmap includes scenario-based market sizing estimates of a range of science- and technology-led opportunities for the Australian protein industry, which sum to almost an additional $13 billion by 2030. This figure represents the difference between a conservative scenario based on expected organic growth versus what could occur through a more ambitious but still realisable growth scenario involving targeted science, technology and infrastructure investments. Not all opportunities discussed in this report have been sized.

Building on Australia's current strengths as a protein producer, this roadmap identifies five strategic focus areas that showcase how targeted science, technology and infrastructure investment drive value-adding opportunities for Australia's protein industry. Industry growth opportunities are identified within each of the five strategic focus areas and span the value chain, including pre- and post- farmgate. These focus areas and opportunities have been identified through stakeholder consultation and desktop research.

By proposing actions to develop technologies (advancing their Technology Readiness Level (TRL) – Appendix C) and embedding these technologies in applicable infrastructure, this roadmap aims to position Australia as a global leader in the sustainable development of novel and differentiated protein ingredients and products.

Figure 2 provides an overview of Australia's potential future protein system, illustrating the interconnectedness and circular nature of the different parts of the system from pre-farmgate through to domestic and export markets.

33 AgriFutures (2020) The changing landscape of protein production.

34 Red Meat Advisory Council (2021) Red Meat 2030.

35 FIAL (2019) Protein Market: Size of the Prize Analysis for Australia.

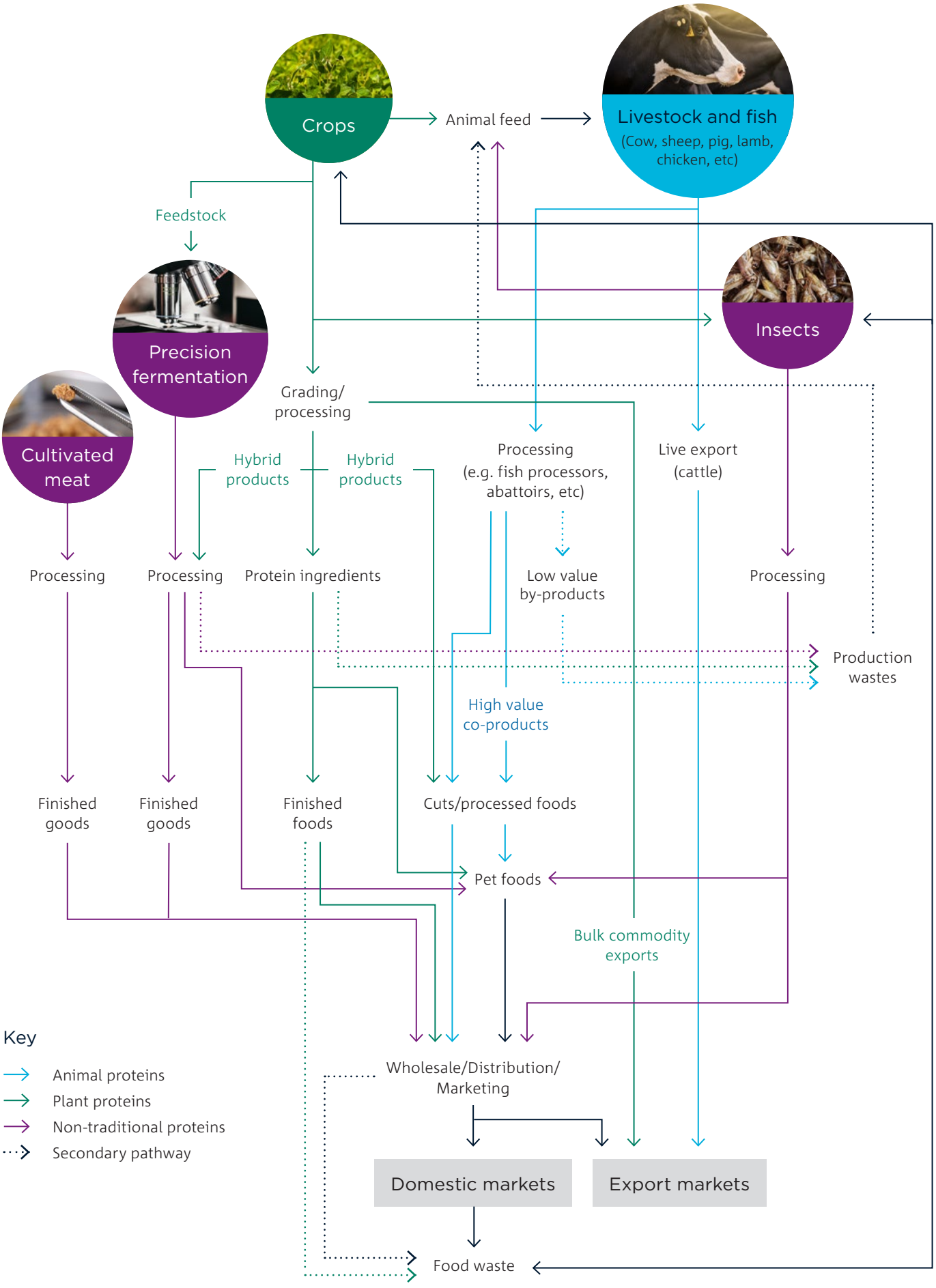


Figure 2: Vision of Australia's protein system

1.1 Strengthening product integrity and market access

Continuing to invest in the essential R&D and infrastructure that underpin the global competitiveness of Australian protein products and ingredients will ensure Australian manufacturers have the systems needed to demonstrate and communicate the positive attributes of their products.

These attributes or 'verifiable credentials' are increasingly required to meet consumer expectations and maintain market access. When making food purchases, consumers are increasingly basing their purchasing decisions not only on the traditional attributes of price and brand, but also on other high-value attributes that demonstrate the quality and added value of the food products. Examples of these attributes include carbon footprint, animal welfare, disease free status, water use efficiency, traceability and origin of ingredients, nutrition, sustainable packaging, presence of chemical residues, fair trade and organic.

A meta-analysis of 80 studies concluded that consumers are hypothetically willing to pay a 30% premium for sustainable food products.[36] This demand for high-value attributes is also being seen among Australia's trading partners and global trading rules,[37] making them essential for continued market access. For example, in response to the EU's strict new feedstock requirements for biodiesel, Australian farmers adopted innovative lifecycle assessment techniques to demonstrate they grow low-emission canola, thus securing Australian canola's largest export market worth $1 billion.[38] Events such as this are driving Australian exporters to find innovative ways to rapidly respond and strengthen their integrity systems.

The next generation of agriculture and food technologies and tools including digital and advanced technologies, as part of Agriculture 4.0 and Industry 4.0, can deliver productivity, sustainability and traceability credentials that in turn strengthen product integrity. Such credentials can support Australia's preferential access to key markets, reduce technical trade barriers and position Australia favourably in trade negotiations. Although product integrity and market access are vital for all protein types, the example explored in this roadmap is **integrity systems in the red meat sector**. The red meat sector in Australia is already a large, mature sector and most of its production is exported. By investing in the R&D and infrastructure that underpin product integrity and market access, there are significant opportunities to **expand the reach of Australian red meat exports into new geographies** and increase the sector's global competitiveness.

36 Li S and Kallas Z (2021) Meta-analysis of consumers' willingness to pay for sustainable food products. Appetite 163. DOI: 10.1016/J.APPET.2021.105239.

37 Australian Bureau of Agricultural and Resource Economics and Sciences (2020) Global responses to climate change: opportunities for Australian agricultural producers. ABARES Insights (10).

38 CSIRO (2017) Australia secures $1.0 billion EU canola export market. Viewed 8 November 2021, <https://www.csiro.au/en/news/news-releases/2017/australia-secures-$1-billion-eu-canola-export-market>.

Opportunity 1: Integrity systems in the red meat sector

2030 opportunity

To expand and integrate integrity systems across the supply chain to deliver farm to plate traceability and trusted credentialling.

Potential market size[39]

Current state
- $15.3 billion in export revenue

Conservative 2030 scenario
- $16.5 billion in export revenue

Ambitious 2030 scenario
- $17.1 billion in export revenue

Difference between conservative and ambitious scenarios: **$570 million** in export revenue (See Appendix D for the economic methodology).

Science, technology and infrastructure priorities

- Verify the biological and geographical origin of production
- Research and infrastructure to help establish and utilise data from production systems
- Design new systems-based compliance
- Conduct preventative risk assessments
- Support compliance infrastructure

What is driving this opportunity?

Given Australia exports the majority of its red meat (e.g., 78% was exported in 2019-2020), there is an opportunity to further expand existing integrity systems for red meat products and deliver positive attributes and trusted credentialling. The demonstration of these high-value attributes, including trusted provenance and sustainability metrics will open new markets, and ensure market access is maintained if (and when) verification requirements are imposed on Australian products by export markets.

Currently, some credentials can be verified in Australia, such as carbon, water use and animal welfare. However, credentialling is not widespread across the industry and appears to occur on a case-by-case basis depending on the preferences of specific buyers. Further, the current compliance process for delivering verifiable credentials is often manual and costly, and places administrative and regulatory burden on participants across the value chain.

Consumer and market expectations for verified product integrity, positive attributes and credentialling will likely drive innovation in the protein industry. Consumers (as well as quick service restaurants and hotels) are increasingly basing their food purchase decisions not only on the traditionally common attributes of price and brand, but also on quality, value-add and ethical attributes[40] such as sustainability and animal welfare.

Verification required for product credentials depends on public standards set by the importing country, and private standards set by individual importers of a product. However, there is a gap in the industry understanding of which positive attributes and credentials are most needed and demanded by consumers.

39 Estimate of current state for integrity systems for red meat exports is the current revenue Australia earns from red meat exports with its current integrity systems in place, estimates of conservative and ambitious scenarios in 2030 for integrity systems for red meat exports are the estimated 2030 export revenue from red meat exports with low (conservative) and high (ambitious) enhancement of these systems to enable traceability and verifiable credentials.

40 Burnier PC, Spers EE and De Barcellos MD (2021) Role of sustainability attributes and occasion matters in determining consumers' beef choice. Food Quality and Preference 88.

In export markets, Australia's existing focus on the integrity of red meat products can help command a price premium. Australia's strong focus on biosecurity and food safety, for example through the National Livestock Identification System (NLIS), has helped Australia obtain a competitive advantage in a global market.[41] Despite this, food fraud remains a costly challenge.[42]

A pilot project has been initiated to distinguish Australian beef and lamb from meat produced in other countries. However, challenges arise in maintaining traceability at the processor stage while still ensuring speed and efficiency.

Expanded and integrated digital integrity systems could manage and track criteria for how red meat products have been produced, including traceability and origin of ingredients, nutrition, sustainable packaging, fair trade and organic, labour conditions, carbon footprint, water use, animal welfare, chemical residues, and impacts to biodiversity and air quality. Critical to enabling traceability and credentialling is ensuring any new system is designed for all value chain participants. Further, providing real time access to this information may enable value chain participants to command better price premiums for their products. As such, this system must be real time, interoperable and not a proprietary system that has significant adoption barriers.

To help realise this opportunity, Australia already has experience expanding integrity systems for the purposes of improving meat quality and profitability. For example, Meat Standards Australia (MSA) created a grading system to provide detailed feedback about each individual carcase. This consistent benchmarking system allows producers to evaluate and alter management practices to improve eating quality.[43] In a similar manner, the Argyle Foods Group and Integrity Systems Company have collaborated to optimise supply chain management using performance data across an animal's lifetime. The system uses the MLA Group Data Platform to connect a broad range of farm and livestock management data to inform decision making and improve the profitability of the red meat sector.[44]

Pursuing the opportunity to expand existing systems may become necessary as retailers and export markets are expected to increasingly demand traceability and credentialling as minimum standards. This expected shift means expanding existing integrity systems is unlikely to be something that the end user pays for directly. However, these verified credentials may also be valuable to help mitigate trade risks from fraudulent and counterfeit Australian products sold overseas.

Australia's comparative advantages

The existing integrity practices and systems across the red meat supply chain place Australia in a favourable position to access export markets ongoing. Integrity practices across the red meat and livestock industry include plans to become carbon neutral by 2030[45] and the global leadership role Australia took against the use of meat and bone in ruminant feed.[46] This, paired with national identification and traceability systems, can support Australia's industry performance over time despite future increases to integrity requirements from red meat export markets.

41 Integrity Systems (2021) National Livestock Identification System. Viewed 18 January 2022, <https://www.integritysystems.com.au/identification--traceability/national-livestock-identification-system/>.

42 McLeod R (2017) Counting the Cost: Lost Australia food and wine export sales due to fraud.

43 Meat & Livestock Australia (2021) Grading. Viewed 18 January 2022, <https://www.mla.com.au/marketing-beef-and-lamb/meat-standards-australia/msa-beef/grading/>.

44 Integrity Systems (2021) Turning data into dollars. Viewed 18 January 2022, <https://www.integritysystems.com.au/about/news--events/news/2021/new-project-links-data-to-add-dollars-for-supply-chain/>.

45 Meat & Livestock Australia (2021) CN30: Carbon Neutral by 2030. Viewed 20 December 2021, <https://www.mla.com.au/research-and-development/Environment-sustainability/carbon-neutral-2030-rd/cn30/>.

46 Meat & Livestock Australia (2019) Quality Assurance. Viewed 20 December 2021, <https://raremedium.com.au/quality-assurance/>.

Regional opportunities

Digital integrity systems can have numerous benefits for regional and rural areas demonstrating their importance to Australia's red meat industry profitability long-term.[47] These benefits include improvements to industry connectivity and access to real time data which can reduce operational costs and on-farm risks by enhancing decision making.[48] Other initiatives, such as soil and water geochemistry mapping of Australia's agricultural regions (discussed below), could support regions' ability to prove product origin and also demonstrate and communicate their region as a positive attribute to consumers.

Implications for the Australian agricultural and food system

Integrity systems can improve livestock management and associated business decisions; however, delivering products with additional attributes and credentials will require investment, participation and compliance across the supply chain. Improved data transfer through digital integrity systems can help enhance land and livestock management by improving operational efficiency, productivity and capacity to manage remote areas. This is because real time data (e.g., Internet of Things (IoT) agricultural technology sensors), machine learning and artificial intelligence feedback provided by product credentialling systems (such as traceability and grading) can help producers, processors, brand owners and retailers improve decision making. As positive attributes and integrity credentials are currently delivered on a case-by-case basis, notable investments would be required to expand and enhance digital and connectivity systems to verify additional attributes across the industry. More information regarding the participation and compliance required across the food system is discussed in section 2.4.

Existing infrastructure and R&D underpinning opportunity

Research supporting this opportunity is varied, from understanding consumer preferences in Australia and key export markets and associated product innovation, through to sustainability practices across the value chain, and the development and integration of digital and other systems to help irrefutably prove certain high-value credentials of a product. Due to the broad and varied nature of the supporting research for this opportunity, research providers across the nation have programs that may be relevant in supporting industry. These include universities, state and commonwealth research agencies, MLA, AMPC and CRCs such as the Food Agility CRC and the Future Food Systems CRC.

Many technology systems and platforms underpin this opportunity. These include but are not limited to:

- Simple barcode systems like those provided by GS1 Australia.
- Internet of Things (IoT) smart sensor networks, for example, smart cattle ear tags, temperature sensors in transport and spatial data collected from satellites or drones.
- Digital systems like Integrity Systems Company's (subsidiary of MLA) suite of programs that aim to guarantee the integrity of Australia's red meat industry from food safety, quality assurance and traceability perspectives. These include the on-farm systems of the National Livestock Identification System (NLIS) and the Livestock Production Assurance (LPA) program, together with the electronic National Vendor Declaration (eNVD) system.
- Novel printed systems, like the Sydney-based firm NanoTag Technology which uses printed micro-dot systems linked to a Voice Response Technology (VRT) scanning platform. The VRT relies on a small pocket reader that uses infra-red scanning to pick-up and analyse a unique micro-dot matrix pattern printed on the packaging of meat products. The pocket reader verifies the authenticity of the product, including its pack date, batch number and factory of origin.[49]

While R&D is enabling rapid innovation in this field, most systems rely on digital connectivity in some way. This requires strong regional infrastructure, including high speed and reliable broadband access in rural and remote areas.

47 MLA (2021) Digital agriculture, Viewed 20 December 2021 <https://www.mla.com.au/research-and-development/digital-agriculture/>

48 MLA (2021) Digital agriculture, Viewed 20 December 2021 <https://www.mla.com.au/research-and-development/digital-agriculture/>

49 Condon, J. (2018) New technologies address beef counterfeit and substitution challenge. Beef Central. Viewed 22 November 2021 <https://www.beefcentral.com/trade/new-technologies-address-beef-counterfeit-and-substitution-challenge-video/>; NanoTag Technology. (2021) Viewed 22 November 2021 <https://www.nanotag.co/food>.

2022-2030 science, technology and infrastructure investment priorities

Verify the biological and geographical origin of production: Existing approaches for tracing agrifood products often depend on labels that are then tracked through the supply chain. Even when the labels are digitised, such approaches are unable to prevent the substitution of the product or counterfeiting of labels. Products that are fraudulently mislabelled as Australian erode trust in 'Brand Australia' as safe and high-quality products that fetch a price premium. Developing national provenance infrastructure as a publicly available repository for all underpinning information would enable the independent testing of agrifood products for their biological and geographical origin of production, and irrefutably verify supply chain information. By mapping the soil and water geochemistry and environmental isotopes of the Australian landscape at a fine scale, predictive mapping techniques can then be applied to these markers over time and space to create region-specific fingerprints enabling agricultural products to be traced back to their region of origin. Statistical models can link the elemental composition of foods to the digital 'map' of region-specific fingerprints stored on national provenance infrastructure.

Research and infrastructure to help establish and utilise data from production systems: Developing trusted approaches to harvest and analyse real-time, sensor-based data from agricultural and food production systems will be important to drive productivity and evidence credentials for key selling features. These production system credentials include measures of animal welfare, organic farming practices, deforestation, Halal, among many others. Adoption of Industry/Agriculture 4.0 technologies to track this data across the value chain can support all participants to better align business decisions with efficiency or quality targets. For example, sensor-based red meat grading results can be provided to farmers to help improve breeding or specific livestock conditions. Further, satellite technologies may be able to predict soil biomass to help minimise the impact of livestock grazing on crop fields.[50] An example of an initiative that aims to help interconnect and better utilise such productivity and compliance data in the agricultural supply chain is the proposed Australian AgriFood Data Exchange platform.[51] To help build trust between technology companies and farmers concerned about data sharing on the platform, data governance frameworks will be developed as part of the initiative which is further supported by data policy guidance included in the Australian Farm Data Code.[52]

Design new systems-based compliance: Designing and testing new systems-based compliance processes that integrate innovations in automated compliance and verification, data privacy, automated data collection and analytics (including isotope ratio analysis, elemental analysis, genomics) can reduce risks around food safety and biosecurity throughout the production, processing and export of protein products. This is particularly relevant for processing plants, where compliance can transition away from duplicative audit-based systems to one of continuous assurance. The Australian Government has existing plans to improve traceability of agricultural exports and modernise export regulations and systems, through support for CSIRO's Trusted Agrifood Mission. The Mission aims to build on Australia's reputation as a trusted and reliable supplier internationally by developing new tools and technologies in key focus areas such as automated compliance.[53]

Conduct preventative risk assessments: Identifying emerging food safety hazards and biosecurity threats and developing novel risk assessment (e.g., molecular risk assessment) and management approaches could help to address risks before they impact market access.

Support compliance infrastructure: Developing new science to automate the conversion of legislation into machine-readable rules will save time and improve compliance. Optimising and redesigning supply-chain processes with reliable and immutable data workflows will mean that compliance statements continuously and provably correspond to the tangible product. Designing new digital tools such as telepresence and sensor technologies could help to remotely augment export compliance audits of processing facilities. Together, these technologies can be used to build trust and potentially reduce or replace existing on-site audits.

50 Meat & Livestock Australia (2018) Integrating spatial technologies in a mixed farming system to increase production efficiency of crop grazing. Viewed 3 February 2022, <https://www.mla.com.au/research-and-development/reports/2018/integrating-spatial-technologies-in-a-mixed-farming-system-to-increase-production-efficiency-of-crop-grazing/>.

51 KPMG Australia (2021) New data exchange to revolutionise Australian agrifood. Viewed 3 February 2022, <https://home.kpmg/au/en/home/media/press-releases/2021/09/new-data-exchange-revolutionise-australian-agrifood-sector-14-september-2021.html>.

52 National Farmers' Federation (2018) Australian Farm Data Code. Viewed 3 February 2022, <https://nff.org.au/programs/australian-farm-data-code/>.

53 CSIRO (2021) Australian exports to capture greater value. Viewed 9 December 2021, <https://www.csiro.au/en/news/news-releases/2021/australian-exports-to-capture-greater-value>.

CASE STUDY

Integrity systems in the red meat sector

This case study seeks to estimate the potential additional red meat export revenue that could be earned in 2030 from enhanced integrity systems as outlined in Opportunity 1. Due to a lack of data on the economic impact of enhanced integrity systems, an alternative method was developed to estimate the size of this opportunity. For further details and data sources please see the appendix.

1. **Price premium consumers might pay for integrity systems-enabled verifiable credentials**

Based on stakeholder guidance, consumers might pay a premium of between 3% and 7.5% for Australian red meat with verifiable credentials.

2. **Potential uplift in export prices**

Using recent beef, veal and sheepmeat export prices, the potential export prices were estimated at between:

- $8.4 million per kt for beef and veal and nearly $8.4 million per kt for sheepmeat with the conservative 3% price premium and
- $8.7 million per kt for beef and veal and around $8.8 million per kt for sheepmeat with the ambitious 7.5% price premium.

3. **Calculating export volumes in 2030**

Extending forecasted growth rates for beef, veal and sheepmeat exports out to 2030:

- beef and veal exports will increase to 1,492 kt shipped weight (sw) in 2030
- sheepmeat exports will increase to 534 kt (sw) in 2030.

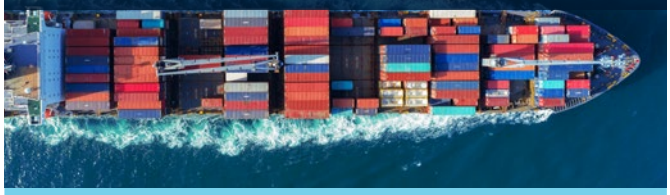
4. **Proportion of red meat exports with verifiable credentials in 2030**

It is assumed that between 10% (conservative scenario) and 50% (ambitious scenario) of Australian red meat exports will have verifiable credentials in 2030.

Based on this approach, the two scenarios were developed:

- The conservative scenario combines the low-price premium (3%) and the low proportion of red meats exports with verifiable credentials (10%) by 2030. This results in an estimate of $16.5 billion in export revenue.
- The ambitious scenario combines the high price premium (7.5%) and the high proportion of red meat exports with verifiable credentials (50%) by 2030. This results in an estimate of $17.1 billion in export revenue.

Opportunity 2:
Expanding Australian red meat exports into new geographic markets



2030 opportunity

To grow the volume and value of Australian red meat exported into new and emerging South East Asian markets.

Potential market size

This opportunity has not been quantified. However, it is anticipated that expanding Australian red meat exports into new geographic markets will provide significant economic benefits to producers and consequent economic benefits across the red meat value chain.

Science, technology and infrastructure priorities

- Support the development of logistics and cold chain management
- Research to support new product innovation
- Maintain and enhance reputation for clean, safe and natural products

What is driving this opportunity?

Growing global demand for protein, particularly demand from nearby Asian countries, presents significant opportunities for Australia's protein industry to increase export values and volumes through targeted and differentiated premium offerings. Influencing demand for higher-value protein products is Asia's growing middle class and urbanisation rates. In 2018, 55% of the world's population resided in urban areas, increasing to an expected 68% in 2050,[54] with the Asian middle class set to increase from 2 billion in 2020 to 3.5 billion in 2030.[55] While this growth in global demand can have implications on food security, Australia is in a favourable position to produce and export increasing amounts of food over the coming decades.

Australia is well known for its red meat exports and was the second largest exporter of beef after Brazil in 2020.[56] While Australia already extensively exports to Asia, with its most valuable beef and veal export markets being China and Japan (2019-20), South East Asian markets represent a growing opportunity to stabilise Australia's market position and target new areas of growth. As South East Asian markets develop and grow, the most attractive priority countries and cities for Australian red meat exports include Jakarta, Indonesia; Kuala Lumpur, Malaysia; Bangkok, Thailand; Ho Chi Minh City, Vietnam; Manila, Philippines; and Singapore.[57]

Income and population growth are key drivers in the consumption of meat proteins.[58] South East Asia is a fast-growing and diverse region with improving household incomes and changing consumer preferences. Consumers in these regions associate beef with superiority and good taste, with imported beef products associated with 'premium quality' and 'better taste', driving price premiums.[59] Attractive consumer segments in this region include both affluent families with children and individuals between 18-44 due to their focus on nutrition, safety and premium eating, and therefore alignment to Australia's red meat offering.

54 United Nations, Department of Economic and Social Affairs, Population Division (2019) World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). United Nations, New York.

55 Buchholz K (2020) This chart shows the rise of the Asian Middle Class. Statista, Hamburg. <https://www.weforum.org/agenda/2020/07/the-rise-of-the-asian-middle-class> (accessed 8 November 2021).

56 Meat & Livestock Australia (2021) Value of Australian beef exports falls in 2020. Viewed 9 November 2021, <https://www.mla.com.au/prices-markets/market-news/2021/value-of-australian-beef-exports-falls-in-2020/>.

57 Meat & Livestock Australia (unpublished). Australian red meat opportunity in Southeast Asia.

58 OECD-FAO (2021) OECD-FAO Agricultural Outlook 2021-2030: Meat. Rome.

59 Meat & Livestock Australia (2021) Global beef industry and trade report.

While beef is mostly used in local traditional cuisines as a special family treat, international beef dishes such as Japanese beef gyudon, shabu-shabu, Korean bulgogi and western-style steak are becoming more widely adopted by urban South East Asian consumers.[60] Sheepmeat is widely featured in Malaysia, Indonesia, Singapore and Brunei during the Islamic festive seasons, particularly around the months of Ramadan and Idul Fitri.[61] This market is also an attractive Australian opportunity, in terms of maximising resources, as many of the desired cuts in traditional cultural dishes (e.g. thin sliced hot pots) differ from 'western style' centre of plate meat dishes which can help optimise carcase utilisation.

Positioning Australia's red meat industry to become the premium meat choice for convenient cook-ready meals is just one example of targeted and differentiated new product innovations for these markets. Safe, efficient and transparent supply chains can also add value to Australia's product and reputation.

Australia's comparative advantages

Australia's proximity to and familiarity with rapidly growing markets in Asia affords many advantages over other nations. The nation's location and reputation for clean, green and premium produce can continue to be leveraged for growth opportunities for Australia's exports. Further, the well-developed business relationship between Australia and South East Asia is also a key driver of beef trade between the two neighbours.[62] Also contributing to Australia's advantage are temporary factors in other nations, such as the drought in the United States and disease outbreaks such as African Swine Fever in meat importing countries.[63]

Regional opportunities

Growing Australia's presence and premium offerings into South East Asian markets will provide opportunities to livestock and processing organisations across the nation. These organisations are generally located in regional Australia, with growth of these organisations contributing support for Australia's regions and equally requiring the support of the community. North Queensland's $10 million export hub development and improvements to the Townsville Port could help Australia's expansion of red meat exports.[64] Additionally, Western Australia offers large regional lands well suited to grass-fed meat production, and its close proximity to South East Asia provides shipping time and time zone benefits.[65]

Broader opportunities in regional areas may be realised from investments into cattle supply chains, including the Australian Government's $100 million Beef Roads Program. This program, designed to upgrade key roads necessary for transporting cattle, could help regional and rural areas by reducing freight costs and strengthening links to markets more broadly.[66]

Implications for the Australian agricultural and food system

New product development of differentiated and premium offerings for South East Asian markets may provide spill-over benefits for Australian markets in the form of new products. Stimulating greater demand for Australian red meat will require more efficient utilisation of the carcase (Opportunity 5) and will require integrity systems across the supply chain to deliver farm to plate traceability and credentialling (Opportunity 1). Increasing Australia's red meat production will require increased commitment and action towards sustainability to do more with less, alongside increased production from Australia's cropping industry to supply animal feed. If more crops are diverted towards human protein consumption (e.g., via Opportunity 3 and 8), implications for the system may include animal feed scarcity.

60 Meat & Livestock Australia (2019) Red Meat Market Snapshot for South East Asia Beef and Sheep. Viewed 14 January 2022, <https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/os-markets/red-meat-market-snapshots/2019/mla-ms-south-east-asia-beef-sheep-2019-1.pdf>.

61 Meat & Livestock Australia (2019) Red Meat Market Snapshot for South East Asia Beef and Sheep. Viewed 14 January 2022, <https://www.mla.com.au/globalassets/mla-corporate/prices--markets/documents/os-markets/red-meat-market-snapshots/2019/mla-ms-south-east-asia-beef-sheep-2019-1.pdf>.

62 CRCNA (2019) Capturing the ASEAN Agricultural Opportunity for Northern Australia.

63 Australian Bureau of Agricultural and Resource Economics and Sciences (2021) Snapshot of Australian Agriculture 2021. ABARES Insights (2). DOI: 10.1071/9780643094659.

64 CRCNA (2019) Capturing the ASEAN Agricultural Opportunity for Northern Australia.

65 Coriolis (2017) Western Australian Meat Industry Snapshot.

66 The Department of Infrastructure Transport Regional Development and Communications (2021) Northern Australia Roads Program and Northern Australia Beef Roads Program. Viewed 25 January 2022, <https://investment.infrastructure.gov.au/projects/key-projects/northern-australia-programs.aspx>.

Existing infrastructure and R&D underpinning opportunity

Research supporting this opportunity is predominantly facilitated by MLA. MLA conducts customised marketing and market access activities in country, and provides market research and trend analysis. Food engineering and meat science are underpinning research themes for this opportunity, alongside supply chain R&D which is supported by universities such as Deakin University through its Centre for Supply Chain and Logistics, Victoria University, and CRCs such as the Food Agility CRC and the Future Food Systems CRC.

Australia currently exports red meat to over 100 countries,[67] and has significant existing supply chain infrastructure in place to facilitate this industry. MLA has offices located in significant export markets to promote and grow demand for Australian red meat, alongside Australia's Austrade posts in relevant countries.

2022-2030 science, technology and infrastructure investment priorities

This opportunity will benefit from the development of research, systems and infrastructure to support Opportunity 1.

Support the development of logistics and cold chain management: Logistics and cold chain management remain some of the key challenges to market access in South East Asia. Maintaining the integrity of meat from Australia to customers overseas is costly and carbon intensive and should be addressed through research into both logistics and appropriate product development. Priority research areas include improving shelf stability and integrity of products, which could be achieved via different processing and packaging technologies; and best practice and novel practices for sustainability of an end-to-end supply chain. New developments include biodegradable food packaging able to extend shelf life,[68] automated cold storage systems for reducing waste,[69] as well as technologies able to reduce or eliminate the need for refrigeration.[70] The value of extended shelf life can be demonstrated from the United Arab Emirates' (UAE) easing of shelf life restrictions in 2017 which was estimated to produce an additional $100 million in returns for Australia's red meat industry.[71]

Research to support new product innovation: Alongside product innovation to help maintain integrity throughout the supply chain, new product innovation is required to support the red meat industry to meet the needs of new markets and address the demands of these consumers. Opportunities identified by MLA include meat products to help satisfy demand driven by consumers' desire for food sharing occasions and special occasions, healthy options for growing families, safe and trusted meat products for peace of mind, convenient cook ready meals, snacking-on-the-go, and luxury experiences.[72]

Maintain and enhance reputation for clean, safe and natural products: Australia benefits from a global reputation in the supply of clean, safe, and natural food products which is often viewed as a shared resource across the food and agricultural industry.[73] Maintaining and enhancing this competitive advantage is vital to accessing new geographic markets in future. A variety of new developments could support or enhance Australia's red meat offering and reputation. This includes developments to improve the safety of red meat products such as antimicrobial surveillance processes and technology investments, research into management of new diseases or improvements to integrity and traceability systems along the value chain (see Opportunity 1).[74] Further, the development of products with clean labels could help address increasing health concerns over red meat and processed meat consumption. This could include developments that reduce or remove the need for additives, nitrates and phosphates to meet consumer health needs.[75]

67 Meat & Livestock Australia (n.d.) International markets. Viewed 21 January 2022, <https://www.mla.com.au/marketing-beef-and-lamb/international-markets/>.

68 Packaging World (2019) Biopolymer materials and technologies flourish. Viewed 21 January 2022, <https://www.packworld.com/issues/sustainability/article/13373842/biopolymer-materials-and-technologies-flourish>.

69 Netherlands Ministry of Foreign Affairs (2018) Automation and Robotics in Thailand.

70 Field M and Prof. Consulting Group (2021) Final report Review of Pressurised CO2 technology (Farther Farms) and its ability to reduce reliance on a chilled supply chain - Literature Review.; Prof. Consulting Group (2021) ASAP IXON technologies platform literature review.; 915 Labs (2020) A Healthier Way to Process Food. Viewed 3 February 2022, <https://www.915labs.com/>.

71 Meat & Livestock Australia (2020) Opportunities in the Middle East. Viewed 2 February 2022, <https://www.mla.com.au/news-and-events/industry-news/opportunities-in-the-middle-east/>.

72 Meat & Livestock Australia (unpublished). Australian red meat opportunity in Southeast Asia.

73 Hatfield-Dodds S, Hajkowicz S and Eady S (2021) Stocktake of Megatrends shaping Australian Agriculture (2021 Update).

74 Meat & Livestock Australia (n.d.) Food safety and traceability. Viewed 21 January 2022, <https://www.mla.com.au/research-and-development/food-safety/#>.

75 Tobin A, McDonnell C, Olivier S, Knoerzer K and Sikes A (2020) Review of emerging (food industry) clean technologies for potential high value red meat opportunities.

1.2 Optimising quality and cost competitiveness

There are many aspects to consider in optimising the quality and cost competitiveness of Australia's growing protein industry. Some of these aspects are addressed in other sections of this report, for example strengthening product integrity (section 1.1), or maximising circularity through developing novel co-products from lower value red meat materials (section 1.3).

While quality and cost optimisation is important across the entire protein industry, examples of optimising quality and cost competitiveness explored in this roadmap include **plant-based protein ingredients** and **crop breeding and pre-breeding** for favourable downstream characteristics beneficial for animal feed and plant-based food products. Ensuring Australian manufacturers have the inputs needed to produce higher value products and that Australian protein is preferred by customers and consumers requires continued investment in the essential R&D and infrastructure that underpin quality (nutrition, taste, texture, functionality, etc.) and cost competitiveness.

If Australia is to successfully produce the ambitious levels of plant-based products described in this report (see Opportunity 8: Plant-based products), the entire supply chain, including the ingredients and crop breeding need to be considered. Currently, many of the ingredients used in Australian plant-based products are imported and Australian manufacturers of the finished products have little control over the quality and cost of these ingredients. The opportunities in this section focus on developing a domestic end-to-end supply chain for Australian plant-based proteins.

Opportunity 3: Plant-based protein ingredients

2030 opportunity

To produce locally made protein concentrates and isolates to meet domestic consumption, replace imports and expand into a broader range of products for local and export markets.

Potential market size

This opportunity has not been quantified. However, it is anticipated that producing locally made protein ingredients will provide significant economic benefits to producers and consequent economic benefits across the plant food value chains.

Science, technology and infrastructure priorities

- Optimise fractionation technology
- Secure capital for infrastructure
- Obtain market information for plant-based products
- Set supported production targets
- Support research infrastructure development
- Research to support technology and process development for protein extraction

What is driving this opportunity?

Protein ingredients, such as protein flours, concentrates and isolates, are a key component in the manufacture of most plant-based food products. As demand for these products rises, so does the demand for protein ingredients. Protein ingredients can also be used in a range of other food products such as yoghurts and cereals as a fortificant, or sold as a powder product. The global protein ingredients for meat alternatives market (including plant-based and microbial sources) is expected to grow from US$1.5 billion in 2020 to US$2.5 billion in 2026.[76] While plant-based food products can be made using minimally processed grains and semi-processed grains (e.g. pulse flours) as inputs, this opportunity focusses on higher protein purity concentrates and isolates.

76 Frost & Sullivan (2021) Global meat analogues protein ingredients growth opportunities.

There is a significant opportunity to develop new, market-differentiated products that are competitive in the growing landscape due to taste, texture, function and nutritional attributes; in turn, there is opportunity to develop ingredient offerings that deliver these attributes. Most plant protein ingredients currently used and consumed in Australia are imported, which has risks associated with quality, lead times and logistics of offshore purchasing. There is an opportunity to create a new industry in Australia that replaces imports of protein ingredients, provides new export opportunities and generates economic growth. By using Australian grown materials, final manufactured foods will support local value chains and have benefits associated with Australian Made labelling and improved country-of-origin claims. This could also allow for the development of new technologies and domestic R&D capabilities in the value-added plant protein sector.

Australia's comparative advantages

Australia's advantages related to this opportunity include the existing and potential production scale of crops that are well-suited to processing to produce high quality protein ingredients. Australia's proximity to Asia also provides advantages for export and access to markets.

Regional opportunities

Investing in regional infrastructure is advantageous for this opportunity. Building crop processing, fractionation and manufacturing facilities close to the growing source can improve the economics of transporting inputs and products. For example, connection to the inland rail will enable efficient goods transportation. Locations should consider planned facilities or hubs for plant-based products; and the crops grown in a given region and their suitability to fractionation and use as a protein ingredient (the main crop types grown by region are displayed in Figure 3, page 37). Locations should also consider closeness to market, particularly in the case of ingredients and products intended for export.

Implications for the Australian agricultural and food system

Protein extraction operations embedded as part of a supply chain could provide price floors and stabilise prices for bulk commodity crops.[77]

Whether through contracts with manufacturers or market predictions, improved consistency of demand for protein ingredients could enable farmers the confidence to grow such crops with greater certainty and secure offtakes for their produce. If a significant portion of commodity crops are used for downstream processing, this may reduce the supply for other parts of the agricultural system. However, increasing overall crop production for in-demand crops may mitigate such impacts.

Existing infrastructure and R&D underpinning opportunity

Plant protein flours, concentrates and isolates are extracts of increasing protein purity derived from plant material. To obtain a concentrate or isolate, crops undergo a series of processes where protein is extracted from the plant in high concentration. Currently, chemical or 'wet' extraction is the most mature technology used.[78] Dry fractionation is an emerging process which requires substantially less solvent. The resulting protein isolate or concentrate is used in the manufacture of plant-based food products; used as a fortificant additive in a variety of products (e.g., yoghurts, cereals); or sold as a commercial protein powder product.

Many research organisations support the development of an Australian protein ingredient industry with dedicated R&D. These include, but are not limited to CSIRO, universities and state governments. While Australia has protein extraction research experience and infrastructure, it has very limited domestic commercial isolate and concentrate production. Most plant protein isolates currently used and consumed in Australia are imported. Operational and publicly announced fractionation plants are described in Table 2 (current at time of writing).

Stakeholders have cited that protein extraction infrastructure is a limiting factor for the growth of the industry, particularly for SMEs. The plant-based protein ingredients and crop inputs case study described in Opportunity 8 (section 1.4) provides an overview of the projected protein product demand and current infrastructure. Despite the current lack of infrastructure, the industry is geared to ramp up in the coming years.

77 AgriFutures Australia (2020) The Changing Landscape of Protein Production: Opportunities and Challenges for Australian Agriculture. Wagga Wagga, NSW.

78 Kumar M, Tomar M, Potkule J, Verma R, Punia S, Mahapatra A, Belwal T, Dahuja A, Joshi S, Berwal MK et al. (2021) Advances in the plant protein extraction: Mechanism and recommendations. Food Hydrocolloids 115.

Table 2: Australian fractionation facilities

FACILITY	DESCRIPTION	LOCATION
Australian Plant Proteins wet fractionation facility	Wet fractionation for the extraction of proteins from pulses to produce an 85-90% protein powder, operating at 1,500 tpa scale. Australian Plant Proteins (APP) primarily uses faba beans, though has also made isolates from yellow peas, mung beans, chickpeas, red lentils and yellow lentils. APP successfully optimised faba bean powder production through a CSIRO Kick-Start project.[79] Then in 2021, APP secured a $45.7 million investment to allow the company to double its protein output by early 2022.[80]	Horsham, VIC
Unigrain fractionation facility[81]	With construction set to be underway in mid-2022, the facility will process 40,000 tpa of field peas and faba beans, with potential for later expansion. It will be the first fully integrated pulse-milling and dry fractionation process in Australia.	Ballarat, VIC
Wide Open Agriculture protein isolate facility	The $1.6m pilot plant will produce food-grade modified sweet lupin protein and be used to refine the process and develop new intellectual property. It will also investigate the use of modified lupin protein for plant-based burgers, drinks, and other foods. It will expand to other crops such as chickpeas, lentils and faba beans.[82] Curtin University originally developed the prototype process which was translated to a pilot-scale process at CSIRO's Food Innovation Centre.[83] In December 2020, Wide Open Agriculture and research partners were able to produce food-grade, lupin protein isolate using industrial grade food processing equipment.[84]	Kewdale, WA
Multiple fractionation and manufacturing facilities[85]	Led by Australian Plant Proteins, in partnership with Thomas Foods International and AGT Foods Australia, a $378m project has been announced for the construction of three new plant protein manufacturing facilities. This is expected to increase South Australia's total pulse protein production to 25,000 tpa. The project is also supported by federal and state funding.	Multiple sites, SA

When exporting products made using plant protein ingredients (such as the meat, dairy and milk alternatives discussed in Section 1.4) existing animal product cold supply chains could be leveraged. Alternatively, it may be more efficient to transport the protein ingredients or flours as a dry powder for rehydration and assembly at the export destination. This option may save transport costs but would entail spray drying technology to achieve a dry powder, and infrastructure to process the powder and produce the end product at the destination.

2022-2030 science, technology and infrastructure investment priorities

Optimise fractionation technology: Existing plants operating or planned at scale are wet fractionation facilities. Wet fractionation is a commercially established technology that has been employed for protein extraction in many countries. Wet extraction presents the drawbacks of high energy and water costs, as well as the use of solvents. To support the positioning of any novel end-products as 'clean and green', investment will be required in new technology treatments and handling processes to remove solvents from the products as well as mitigate their environmental impact. This technology development effort could be alongside the use of renewable energy sources.

Dry fractionation involves the extraction of protein from crops without the use of solvents. Dry systems yield benefits of greater water and energy efficiency; however, they present the challenges of low product protein concentration, which can typically reach 60% protein compared to the 80-90% achievable with wet extraction processes. Further, dry systems currently yield a product with more unwanted flavours than wet fractionation. However, dry fractionation approaches could be complemented by breeding and pre-breeding approaches (discussed below) to enable a product which has better sensory and nutritional characteristics. Combined wet and dry fractionation systems have also been suggested to potentially maximise the quality of the protein extract while ensuring the most sustainable operation.

79 CSIRO (2021) Australian Plant Proteins: Optimised faba bean protein extraction. Viewed 24 December 2021, <https://www.csiro.au/en/work-with-us/funding-programs/programs/csiro-kick-start/app>.

80 Berry K (2021) Australian Plant Proteins secures $45.7m investment. Viewed 17 November 2021, <https://www.foodanddrinkbusiness.com.au/news/australian-plant-proteins-secures-45-7m-investment>.

81 Grain Central (2021) Unigrain to build pulse fractionation plant. Viewed 17 November 2021, <https://www.graincentral.com/news/unigrain-to-build-pulse-fractionation-plant-at-smeaton/>.

82 Cotton I (2021) Wide Open Agriculture to proceed with construction of $1.6m lupin protein pilot plant. Viewed 20 December 2021, <https://smallcaps.com.au/wide-open-agriculture-proceed-construction-lupin-protein-pilot-plant/>.

83 Janakievski F, CSIRO, Dwyer S and Wide Open Agriculture (2021) Cracking lupin wide open: from test sausages to protein ingredient. ECOS.

84 Wide Open Agriculture (2020) Food-grade lupin protein produced at pilot-scale using industrial equipment.

85 Berry K (2022) $378m project to quadruple plant protein manufacturing capabilities. Viewed 7 March 2022, <https://www.foodanddrinkbusiness.com.au/news/378m-project-to-quadruple-plant-protein-manufacturing-capabilities>.

Secure capital for infrastructure*:* Capital is a key barrier to scaling infrastructure, particularly for start-ups and SMEs. For example, the capital cost of a fractionation plant is in the order of $50 million and building times can be up to two years. Each additional level of scale presents risk to companies. To connect funding with investment opportunities, joint ventures could be conducted between large companies seeking to invest, and smaller companies with technology seeking to scale-up. Attracting and incentivising investment is also important. The Australian Government's Modern Manufacturing Strategy is an example of a policy measure to support the development of new infrastructure.[86] Consideration could be given to attracting international investment from companies already active in plant-based foods who are looking to establish supply chains within Australia.

Obtain market information for plant-based products: Investment has been constrained by a lack of market information on the size and scale of the opportunity within Australia and overseas. Market information is also needed on the ease of substitution between protein sources in different types of products. Further, the demand for Australian plant-based products enables a greater understanding of the gap between existing plant processing capacity and the anticipated need towards 2030. Industries bodies could assist in providing this information.

Set supported production targets: Setting government-supported targets for protein manufacturing to meet a given global market share for protein ingredients could provide certainty for infrastructure investments. Announcements could be made to establish facilities to meet such targets and seek investment into protein production companies.

Support research infrastructure development: New processes and products could be supported through the development of incubators and joint research programs between research and industry. Facilities with multiple capabilities, such as wet and dry extraction equipment, extruders and advanced fibres could be established. This could take the form of shared R&D facilities for various food start-ups to hire and use, with links to universities and research institutes to access talent and R&D expertise. Such a pilot facility could take the form of a research and innovation hub dedicated to plant proteins, where plant-based food development and protein ingredient R&D can be conducted together.

Research to support technology and process development for protein extraction: New fractionation technologies are still being developed and tested. R&D for both emerging and established processes can help refine technologies, develop new high-quality products, improve cost-competitiveness of products, and enable expansion into other protein sources. In the long-term, product and processing innovations will be important to be internationally competitive.

There is significant potential for R&D to achieve more efficient processes and higher value products. Broadly, the value of the protein product is impacted by its protein content, nutrition, allergenicity and organoleptics (taste and texture). General R&D priorities for plant protein ingredients include:

- Improved extraction (higher efficiency or quality products) and more sustainable extraction (e.g., water, energy use); e.g., dry milling, hydrodynamic cavitation and ultrasound-assisted extraction. Emerging fractionation approaches, such as dry fractionation, could reduce costs and water usage requirements.
- Extraction from a wide range of plant sources including soy, lupin, chickpea, faba bean, lentils, mung bean and field pea. Many of these crops are regionally adapted and investment could be made on the basis of crop growing location.
- Removal of anti-nutritional components and unwanted flavours for use in plant-based products. The presence of 'off-flavours' results in additional processing and additive requirements, increasing production costs, potentially reducing consumer acceptance and driving negative perceptions of end products.
- Isolate functionality. Isolate products which have favourable characteristics, such as binding or emulsification properties, are potentially more valuable for use in a wider range of plant-based products. This could also include designing new blends of different protein types (such as cereal and pulse blends) to optimise nutrition and functionality.
- Valorising waste streams. High quality isolates can be directed to high value food products. By-product streams (e.g., fibre and starch) can be diverted for other uses to improve overall price point of the protein product. Stakeholders recommended planning waste stream offtakes ahead of time to prevent inefficient value chain changes later down the track.
- Upcycling of other industry waste streams.
- Integration of Industry 4.0 principles and technologies, such as automation, robotics, IoT, deep learning and analytics.

86 Australian Government (2020) Make It Happen: The Australian Government's Modern Manufacturing Strategy. Canberra.

Opportunity 4:
Crop breeding and pre-breeding

2030 opportunity

To expand domestic production of higher protein crops with favourable downstream characteristics.

Potential market size

This opportunity has not been quantified. However, it is anticipated that improvements to crop performance, resilience and quality will provide significant economic benefits to producers and consequent economic benefits across the plant food value chains.

Science, technology and infrastructure priorities

- Develop supply chain infrastructure
- Invest in R&D programs

What is driving this opportunity?

Australian grown high value crops are important inputs for downstream uses across Australia's agriculture and food system, including for animal feed, plant-based food products, and commodity sale. Improving the performance, resilience and favourable characteristics of desired crops is therefore advantageous for the sector. Increasing the overall yield of crops could also provide benefit by increasing wholegrain exports.

Breeding and pre-breeding programs can be used to develop differentiated crop varieties with various traits and advantages. For example, crops can be developed that have higher protein content; or that have fewer off-flavours, off-colours, allergens and antinutritional factors, rendering them more suitable for downstream processing. These attributes can make it easier to extract protein ingredients that are of higher protein concentration making them more valuable as a versatile ingredient for food manufacturing.

Breeding and pre-breeding can also be used to make crops that are more resilient or adapted to a broader range of environments, allowing expansion of cropping in new regions to increase overall production volume. For some high protein crops, increased volumes will potentially be valuable to meet demand for local production of plant-based ingredients and foods.

Similar to the discussion of integrity and traceability systems along the red meat value chain (Opportunity 1), another increasingly sought after attribute in international markets for grains is low-emissions credentials. Crops could potentially be designed with characteristics to increase carbon deposition in the soil. Having robust methods for greenhouse gas measurement and accounting is also becoming increasingly important for market access.

Selective crop breeding is one aspect of the broader equation in maximising crop outcomes for input into the food system. Management practices are also important in maximising yield, quality and protein content of crops. Management of crops needs to be responsive to the environment and local ecosystems, as well downstream market signals. A broader range of research and technologies apply to optimising crop management and supporting primary producers and supply chain stakeholders.

Australia's comparative advantages

Australia has significant capacity and experience in crop breeding. Australia has a globally recognised grains industry at scale, which provides a platform for development of inputs to concentrates, isolates and food products. Australia has significant crop exports, with total export value of grains, oilseeds and pulses at a five year average of $10.5 billion over 2015-20.[87] Most breeding in pulses and legumes to date has focused on yield or agronomic traits, not protein content or quality.

Regional opportunities

This opportunity centres around regional cropping of protein rich plants. High protein crops that are commonly used for plant-based foods and protein ingredients include: soy, chickpeas, lentils, faba beans, mung beans, lupins, and higher protein grain varieties. The opportunities for specific crop types vary depending on their suitability to environmental conditions by region. Table 3 provides an overview of strong plant protein candidates.

Figure 3 provides an overview of major growing regions for various crop types across the country. The overview provided is general and does not include recent growth developments and potential to leverage expertise in areas such as Northern Australia. The Cooperative Research Centre for Developing Northern Australia has conducted an analysis on existing and potential grain cropping opportunities in Northern Australia, where for example protein cropping could be further integrated with sugar cane production.[95]

Table 3: Protein crop candidates

CROP	PROTEIN CONTENT	PLANT-BASED PRODUCT CHARACTERISTICS[88]
Soy bean	~40%[89]	Emulsifying; beany, off-flavours present. Common allergen.
Chickpea	19-24%	Slight beany flavour, easily masked; buttery, starchy texture; minimal colouring. Uncommon allergen.
Lentil	14% (green), 27% (red)[90]	Emulsifying; foaming; mushy texture; nutty flavour; various colours. Possible allergen.
Faba bean	25%[91]	Emulsifying; nutty, creamy flavour.
Mung bean	26%[91]	Minimal beany flavour, easily masked. Possible allergen.
Lupin	35%[91]	Emulsifying; foaming; mild beany off-flavour. Common allergen.
Field pea	18%[91]	Thick texture; earthy, savoury flavour; off flavours present. Uncommon allergen.
Wheat	~10-13%[91]	Elastic, chewy; doughy flavour; brown colour.
Canola	17-26%[92]	Emulsifying; off colour and flavour.
Sunflower	15%[93]	Nutty, neutral flavour. Green/brown colour.
Hemp seed	20-25%[94]	Nutty, slightly green or hay-like flavour.

87 Australian Bureau of Agricultural and Resource Economics and Sciences (2021) Agricultural commodities June quarter 2021: Value of agricultural, fisheries and forestry exports (fob), Australia.

88 CSIRO analysis from a variety of sources.

89 Rizzo G and Baroni L (2018) Soy, soy foods and their role in vegetarian diets. Nutrients 10(1), 1–51. DOI: 10.3390/nu10010043.

90 AEGIC (2021) Australian Pulses.

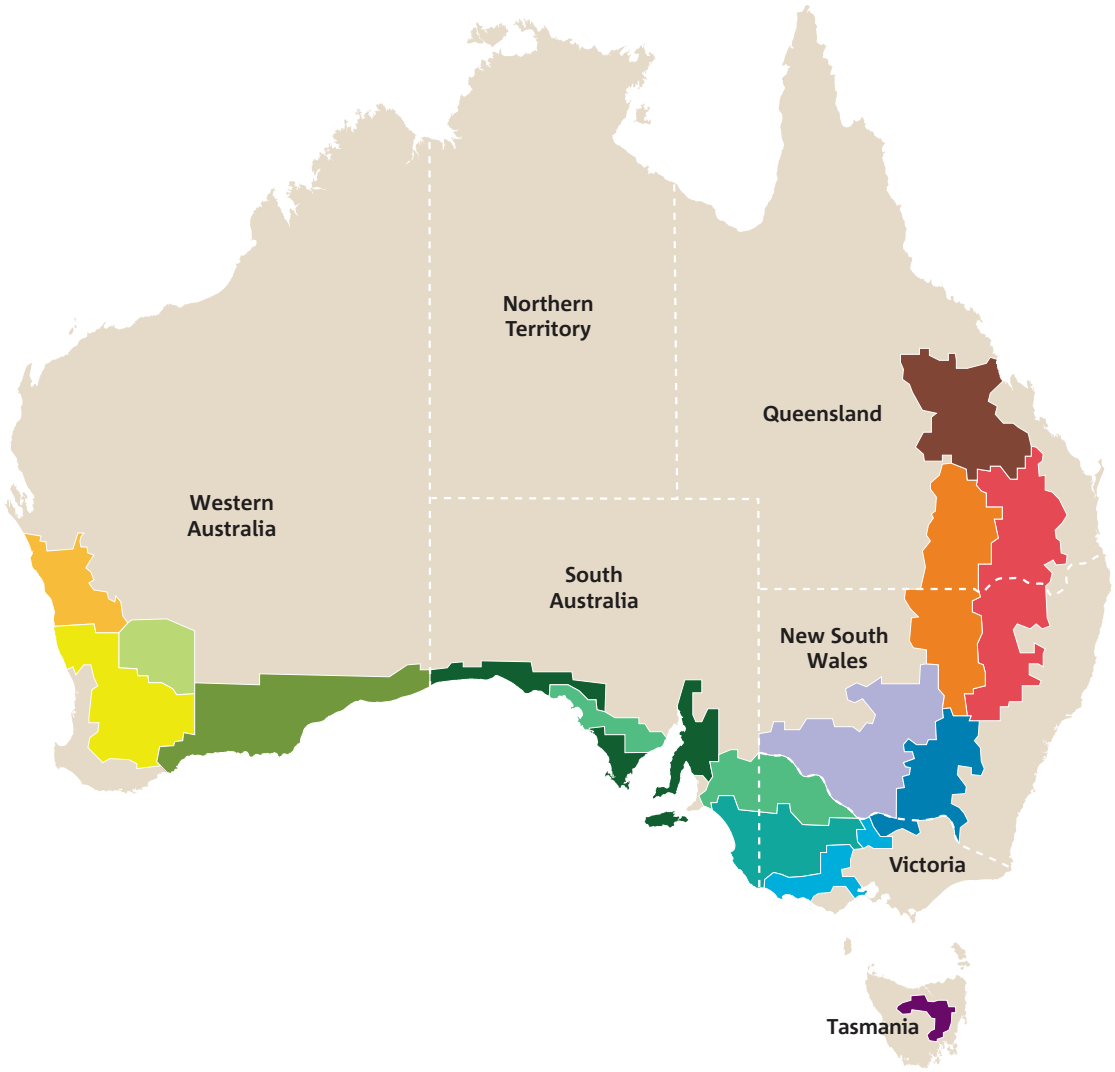
91 Yara (n.d.) How to increase wheat protein content. Viewed 7 February 2022, <https://www.yara.com.au/crop-nutrition/wheat/how-to-increase-wheat-protein-content-and-quality>

92 Chmielewska A et al (2020) Canola/rapeseed protein – nutritional value, functionality and food application: a review. Critical Reviews in Food Science and Nutrition 61(22), 3836-3856. DOI: 10.1080/10408398.2020.1809342

93 Goncalves J et al (2021) Sunflower seed byproduct and its fractions for food application: An attempt to improve the sustainability of the oil process. Food Science 86(5), 1497-1510. DOI: 10.1111/1750-3841.15719

94 Irakli M et al (2019) Effect of Genotype and Growing Year on the Nutritional, Phytochemical, and Antioxidant Properties of Industrial Hemp (Cannabis sativa L.) Seeds. Antioxidants 8(10), 491. DOI: 10.3390/antiox8100491

95 ST Strategic Services and Pivotal Point Strategic Directions (2020) Northern Australian broadacre cropping situational analysis.



Western region

WA Northern
Winter: Wheat, barley, oats, triticale, lupins, field peas, canola, faba beans, chickpeas

WA Central
Winter: Wheat, barley, oats, triticale, cereal rye, lupins, field peas, canola, faba beans, chickpeas

WA Eastern
Winter: Wheat, barley, oats, triticale, lupins, field peas, canola, faba beans, chickpeas

WA Sandplain and Mallee
Winter: Wheat, barley, oats, triticale, lupins, field peas, canola, faba beans, chickpeas

Northern region

NSW Central (north)
Winter: Wheat, barley, oats, chickpeas, triticale, faba beans, lupins, field peas, canola, safflower
Summer: Sorghum, sunflowers, maize, mungbeans, soybeans, cotton

NSW North West – Qld South West
Winter: Wheat, barley, oats, chickpeas, triticale, faba beans
Summer: Sorghum, sunflowers, maize, mungbeans, soybeans, cotton

NSW North East – Qld South East
Winter: Wheat, barley, oats, chickpeas, triticale, faba beans, millet/panicum, safflower, linseed
Summer: Sorghum, sunflowers, maize, mungbeans, soybeans, peanuts, cotton

Qld Central
Winter: Wheat, barley, oats, chickpeas
Summer: Sorghum, sunflowers, maize, mungbeans, soybeans, cotton

Southern region

SA Mid-north – Lower Yorke, Eyre
Winter: Wheat, barley, oats, triticale, lupins, field peas, canola, chickpeas, faba beans, vetch, safflower

SA – Victoria Mallee
Winter: Wheat, barley, oats, triticale, cereal rye, lupins, vetch, canola, field peas, chickpeas, faba beans, safflower

SA – Victoria Border – Wimmera
Winter: Wheat, barley, oats, triticale, lupins, field peas, canola, chickpeas, faba beans, vetch, lentils, safflower

Victoria High Rainfall
Winter: Wheat, barley, oats, triticale, lupins, field peas, canola

NSW – Victoria Slopes
Winter: Wheat, barley, oats, triticale, lupins, field peas, canola

NSW Central (south)
Winter: Wheat, barley, oats, chickpeas, triticale, faba beans, lupins, field peas, canola, safflower

Tasmania
Winter: Wheat, barley, oats, triticale, lupins, field peas, canola

Figure 3: Australia's crop growing regions

Source: Australian Export Grains Innovation Centre

Implications for the Australian agricultural and food system

Higher value crops for downstream processing may provide greater revenue to farmers, alongside greater offtake certainty and price stability. The ability to grow high value crops more effectively in new areas can also benefit the broader agricultural and food system. The ability to grow low emission grains and demonstrate such credentials may also enable greater market access for processors utilising the grains.

Existing infrastructure and R&D underpinning opportunity

Australia has significant research expertise in crop breeding and pre-breeding across its public research agencies (CSIRO and state-based), universities, and Research and Development Corporations (e.g., the GRDC and AgriFutures Australia), as well as private plant breeding companies. For example, the GRDC currently supports breeding programs for chickpea, faba bean, field pea, lentil, milling oats, mung bean, peanut and soybean.[96]

Underpinning research themes include traditional selective breeding, as well as new plant breeding technologies including genetic approaches such as gene editing, genomics-based plant germplasm research and Targeting Induced Local Lesions In Genomes (TILLING). Pre-breeding involves a combination of gene editing and targeted breeding processes to achieve desired traits within crop varieties that otherwise would not have been achieved through traditional breeding approaches. Also important is the development and integration of new technologies, such as artificial intelligence, which for example CSIRO uses to link genome information, climate records and field data for improving crops and predicting performance.[97]

Research infrastructure for this opportunity is readily available, including greenhouses, access to fields for trials, and genomics and molecular biology laboratories.

2022-2030 science, technology and infrastructure investment priorities

Develop supply chain infrastructure: For the associated scale-up of new and existing crop varieties, supply chain infrastructure will need to keep pace with increased volumes of differentiated crops. This might require greater capacity for storage and segregation in the grain supply chain or even specialty supply chains. It is essential that differentiated, higher value crops are not compromised in transport or mixed with lesser quality crops. This may necessitate classification systems to distinguish high quality (or high protein content crops) from the rest, to ensure farmers are compensated appropriately. Stakeholders have noted that a lack of regional processing and export capacity has limited the ability for farmers to grow legumes in some areas. Digital infrastructure, including blockchain technologies, could be considered for tracking valuable crops across the supply chain.

Invest in R&D programs: To date, most crop breeding programs for pulses and legumes have focussed on performance and the visual appeal of the grain. There remains significant potential to optimise protein crops to improve their suitability for downstream products, with characteristics such as: protein content, removal of off-flavours and off-colours,[98] and removal of anti-nutritional components. Desirable criteria for a protein include: high protein in grain, high quality as judged by its protein digestibility corrected amino acid score (PDCAAS), essential amino acid content, water binding properties, solubility and emulsification properties. R&D activities include:

- Benchmarking current varieties to understand protein levels and exploring genetic diversity for desirable traits.
- Pre-breeding and breeding programs for protein content, removal of off-flavours and off-colours, removal of anti-nutritional components, and other characteristics which could improve crop performance in a wider range of conditions. The removal of unwanted compounds may be particularly important for crops that will be processed via dry fractionation, which is not currently able to achieve the same quality product as wet fractionation.
- Utilising machine learning to process the large plant genome datasets to identify target crop traits and support the design of new crop breeding experiments.
- Developing greenhouse gas emission measurement and accounting standards; alongside R&D to support farmer decision-making on crops and rotations to decrease overall emissions.

96 Grains Research & Development Corporation (2021) Breeding investments.

97 CSIRO (2021) Machine-learning for crop breeding. Viewed 24 December 2021, <https://www.csiro.au/en/research/plants/crops/Grains/Machine-learning>.

98 Boston Consulting Group and Blue Horizon (2021) Food for Thought: The Protein Transformation.

Learnings from Canada

The plant protein industry in Canada has seen significant investment and growth over recent years. As such, Canada's plant protein industry development may provide valuable lessons for scale-up in Australia.

Protein Industries Canada (PIC) is a leading industry-led non-profit organisation which aims to promote growth and innovation across the protein sector. The organisation is one of five 'superclusters' funded by the government with CA$150 million over five years to drive economic growth. The expected economic impact over 10 years is more than CA$4.5 billion and more than 4,500 jobs.[99] PIC has announced over 20 funded projects to date that focus on technology and capacity building. Together with industry, PIC have invested over CA$367 million into the Canadian plant-based food, feed and ingredients sector.[100] This includes a 2021 co-investment with a range of agri-food companies to develop pork and beef alternative products,[101] and a 2020 project to use novel artificial intelligence tools to develop high-protein yellow pea crop varieties.[102]

The supercluster model, which brings together SMEs, large companies, research and non-for-profits aims to provide an anchor for innovation, growth and job creation to advance Canada's plant protein ecosystem. Parallels to the supercluster model could be considered in the Australian context to supplement or bring together existing initiatives (e.g., CRCs, industry bodies, location or State-based clusters and special activation precincts, etc). Such a model in Australia has the opportunity to be even broader in scope to cover many complementary protein industries, such as the aquaculture and red meat sectors.

In 2021, PIC launched the roadmap *The Road to $25 Billion*, which outlines priorities to achieve a CA$25 billion increase to Canada's plant-based food, feed and ingredient sector by 2035. Its focuses include innovation, scale and capturing market value. Some key recommendations which are also relevant for the Australian context include:

- **Scale –** Construction readiness through understanding and supporting infrastructure needs and encouraging coordination of investment among jurisdictions. Establishing a pool of capital for small companies aiming to scale and create awareness of the opportunities for plant-based foods in the capital community.
- **Innovation –** Positioning the country as an innovation hub, with industry-led incubation and acceleration programs. Creating opportunities for collaboration between system players. Close relationships across the value chain to allow fast iteration and product development across the value chain. Re-skilling in digital skills and food and ingredient manufacturing.
- **International markets –** Capitalising on sustainability, food safety and quality to compete internationally. Identifying consumer preferences in key markets to inform ingredient and food production. Ensuring trade agreements and market access evolve at pace with the sector.

Canadian companies can also receive support through incentive and funding programs such as the Scientific Research and Experimental Development (SR&ED) tax incentive program, capital cost allowance (CCA) and Strategic Innovation Fund (SIF).[103]

99 Government of Canada (2021) About Canada's Innovation Superclusters Initiative - Innovation Superclusters Initiative. Viewed 8 February 2022, <https://www.ic.gc.ca/eic/site/093.nsf/eng/00016.html>.

100 Protein Industries Canada (2021) Protein Industries Canada announces investment into new plant-based products made using Canadian-grown crops. Viewed 10 November 2021, <https://www.proteinindustriescanada.ca/news/protein-industries-canada-announces-investment-into-new-plant-based-products-made-using-canadian-grown-crops>.

101 Protein Industries Canada (2021) New collaboration to develop high-quality meat alternatives. Viewed 10 November 2021, <https://www.proteinindustriescanada.ca/news/new-collaboration-to-develop-high-quality-meat-alternatives>.

102 Protein Industries Canada (2020) Protein Industries Canada invests in the development of new high-protein crop varieties | Protein Industries Canada. Viewed 8 February 2022, <https://www.proteinindustriescanada.ca/news/protein-industries-canada-invests-in-the-development-of-new-high-protein-crop-varieties>.

103 Invest in Canada (2021) Programs & Incentives. Viewed 10 November 2021, <https://www.investcanada.ca/programs-incentives>.

1.3 Maximising resources and circularity

Transforming what is currently considered low value or waste into higher value products and ingredients and incorporating circularity principles into the supply chain is another strategic focus area of this roadmap. Doing so can capture value and increase producer and processor profitability through product and market diversification.

While this roadmap focuses mainly on protein for human consumption, protein is also important for pet food, and is an essential input into the food system as feed for animals, including livestock and aquaculture. Although they do not usually command as high prices as human food markets, the pet food and animal feed markets are key users of co- and by-products from both animal and plant-based food production.

Examples of opportunities to transform waste into high value products explored in this roadmap include **red-meat co-products** for health and wellness markets and **insect protein** sources for food and feed.

Opportunity 5: Red meat co-products for health and wellness markets

2030 opportunity

To expand the volume of red meat co-products that are converted into value-added protein ingredients and products for health and wellness markets.

Market Size

Given data limitations, the following estimates are only for cattle-derived collagen (e.g., from connective tissue, cartilage, bones and hides for nutraceuticals and other products), bovine blood plasma co-products, red meat snacks and red meat protein powder. As such, it is likely an underestimate of the true value of the red meat co-product opportunity.

Current state

- $1 billion in product value (estimated)

Conservative 2030 scenario

- $1.4 billion in product value
- $675 million in manufacturing revenue
- 1,070 jobs

Ambitious 2030 scenario

- $5.1 billion in product value
- $2.6 billion in manufacturing revenue
- 4,070 jobs

Difference between conservative and ambitious scenarios: **$3.8 billion** in retail value (See Appendix D for the economic methodology.)

Science, technology and infrastructure priorities

- Remap the carcase
- Research to understand new product markets and value chains
- Research to understand customer needs and willingness to pay
- Process engineering for co-product collection and transformation
- Support evidence-based claims
- Develop and demonstrate origin marker technology

What is driving this opportunity?

Meat and Livestock Australia (MLA) estimate that approximately 20% of the carcase delivers 80% of its value, with some parts – considered co-products or by-products – often attracting little or no value.[104] Australia has an opportunity to shift this 20/80 balance and increase the revenue received by focusing on market and product diversification and expanding the volume of both red meat co-products and by-products that are converted into higher value-added protein ingredients and products, especially for health and wellness markets. While beef and sheep are primarily mentioned in this section, alternative red meat sources such as kangaroo and goat industries also offer opportunities for co-product and by-product creation.

By-products are considered the unavoidable residual outputs from the production process that if not harvested as 'food grade' usually cannot be used and must be disposed of at a cost. Current by-product examples include connective tissues, bones and often blood. Co-products are secondary products that are still valuable but less so than primary cuts of meat. From an average 465kg live weight cattle, around 59% of this live weight is not boneless meat and can be handled for co-products.[105] This weight includes edible offal, hides and skins, rendered meat meal, tallow and blood meal. As Australia produced 2.4 million tonnes (by carcase weight) of beef and veal in 2018-19, co-products may present strategic upcycling and value adding opportunities for existing industry production.[106] This is due to the potential to extract highly nutritious and functionally available protein from human-inedible or lower value by-products.

Key markets for Australia's red meat co-products include overseas markets for human food (particularly in Asia and the Middle East where offal is commonly consumed) and feed for aquaculture and pets. Another growing market for co-products such as collagen and blood, is the growing health and wellness market, with some experts suggesting the nutraceuticals market as an attractive opportunity space given it has lower barriers to entry over the medical sector.[107]

Current and emerging global trends around convenience, snacking, wellness, and personalised nutrition may offer new uses and occasions for red meat beyond the traditional centre of plate protein. The global meat snacks market was estimated at over US$8.6 billion in 2020.[108] While primal cuts and ground meat products such as sausages and mince will continue to be staple meat dishes, there are many sources of nutrients throughout the whole carcase that can become value-added products.

Quality red meat-based ingredients that are high in protein and iron can be manufactured simply by drying or boiling (hydrolysis) and milling meat into a powder supplement. Connective tissues, bones, hides and skin portions of carcasses can unlock high quality collagen and protein peptides that are suitable for inclusion in food (for example food bars) and nutraceutical supplements. This is significant given the global collagen market was valued at over US$8.4 billion in 2020.[109] Offal meat, such as liver and thyroid glands, can be converted into powders and transformed into capsules for the nutraceutical market. MLA estimates put the value of beef liver capsule sales in Australia at over $500,000 per annum and over the counter thyroid supplement sales at over $120 million per annum.[110] The nutraceuticals market as a whole had a global market size of nearly US$429 billion in 2020.[111]

The processing sector is showing early signs of a paradigm shift to explore new diversified markets beyond commodity meat trading such as harvesting co-products. This shift may relate to opportunities such as the growing consumer interest in beef and sheep collagen-based products in various applications, including food and beverages, nutraceutical supplements, cosmetics and medical products.[112]

104 Meat & Livestock Australia (2020) Strategic Plan 2025. North Sydney, NSW.

105 Meat & Livestock Australia (2009) Co-products Compendium. North Sydney, NSW.

106 Meat & Livestock Australia (2020) The red meat industry. Viewed 17 January 2022, <https://www.mla.com.au/about-mla/the-red-meat-industry/>.

107 Grand View Research (2022) Nutraceuticals Market Size & Share Report, 2021-2030.

108 Technavio (2021) Global Meat Snacks Market 2021-2025.

109 Grand View Research (2021) Collagen Market. Viewed 29 November 2021, <https://www.grandviewresearch.com/industry-analysis/collagen-market>.

110 Meat & Livestock Australia (2020) Proof of Concept Development – Beef Thyroid Capsules. North Sydney, NSW; Meat & Livestock Australia (2019) Beef Liver Capsules – Proof of Concept Development. North Sydney, NSW.

111 Technavio (2021) Global Nutraceuticals Market 2021-2025.

112 Meat & Livestock Australia (2019) Collagen Business Case Report. North Sydney, NSW.

Overall, the absorptive capacity for innovation and the adoption of new business models, is arguably as important as the design of emerging technology platforms in this space. As such, MLA has worked with industry to produce various beef and sheep protein and collagen powders; and finished products such as odourless collagen supplements for coffees, meat and collagen bars, and natural meat extract flavour boosts for soups and seasonings. Other co-product opportunities for health and wellness markets include applications such as bone broth concentrates. Australia has approximately 8 million hides available each year, with Australian cattle renowned for being prion-free, having high animal welfare standards and making progress towards carbon neutrality. In terms of sheep, there are typically over 32 million sheep skins each year with Australia renowned for its disease and prion-free status. Depending on quality of the hide or skin, the yield from the processing into a powdered ingredient is approximately 30%. Australia has the capability to produce beef and sheep derived food and nutraceutical graded collagen for global markets, which could even provide new opportunities for processors and producers in the leather industry.

Australia's comparative advantages

Australia's red meat industry is well established, with large scale production and export volumes resulting in sufficient supply of inputs for red meat co-products. Further, Australia offers a globally competitive ecosystem for researching, developing, and testing of these co-product opportunities for health and wellbeing markets, as well as potential industry capacity to support production and processing. As an indication of the supporting industry size, the meat and meat product manufacturing sector in Australia employed approximately 60,000 people in 2021.[113] Further, Australia's agriculture, food engineering and medicine expertise can be leveraged to support the creation of red meat co-product innovations for health and wellbeing markets. Australia is recognised as a global leader in foodtech testing, reinforced by domestic access to world-renowned researchers, industry practitioners, and modern facilities.[114]

Australia's capability for co-product development is also demonstrated by numerous existing patents for collagen applications in food and medicine.[115] Nutraceutical capsules derived from liver and thyroid glands are also likely to be growth opportunities for Australia and research is already underway to progress these opportunities. For example, Australian researchers are developing faster freeze drying and milling and hydrolysis processes that are more sustainable and produce improved functionalities.[116] Co-product development may be further supported by Australia's existing production and processing industry protocols to receive prion-free, grass fed, organically verified, Halal or Kosher accreditations.

Regional opportunities

Rural and regional areas can offer innovation services, a trained workforce and the infrastructure needed to support red meat co-product development and delivery. To support product innovation and development, there is potential for government support through the Rural R&D for Profit, Waste to Profits project[117] as well as a range of service offerings in regional foodtech and agritech innovation hubs.[118] For commercial scale-up activities, numerous regions offer experience in agriculture production and processing, meat processors located close to source and established agriculture transport, distribution and logistics infrastructure.[119]

113 Australian Industry and Skills Committee (2021) National Industry Insights Report | Meat. Viewed 17 January 2022, <https://nationalindustryinsights.aisc.net.au/industries/food-and-pharmaceutical-production/meat>.

114 Austrade (2019) Australia: A land of food innovators. Viewed 8 November 2021, <https://www.austrade.gov.au/agriculture40/news/australia-a-land-of-food-innovators>.

115 Meat & Livestock Australia (2009) Co-products Compendium. North Sydney, NSW.

116 Meat & Livestock Australia (2020) Proof of Concept Development – Beef Thyroid Capsules. North Sydney, NSW; Meat & Livestock Australia (2019) Beef Liver Capsules – Proof of Concept Development. North Sydney, NSW.

117 Ramirez J, McCabe B, Jensen PD, Speight R, Harrison M, Berg L van den, O'Hara I, Ramirez J, McCabe B, Jensen PD et al. (2021) Wastes to profit: a circular economy approach to value-addition in livestock industries. Animal Production Science 61(6), 541–550. DOI: 10.1071/AN20400.re

118 Food & Beverage Industry News (2021) Western Australian Food Innovation Precinct now under construction. Viewed 20 December 2021, <https://www.foodmag.com.au/western-australian-food-innovation-precinct-now-under-construction/>.; Meat & Livestock Australia (2021) Environmental sustainability. Viewed 20 December 2021, <https://www.mla.com.au/research-and-development/Environment-sustainability/>.

119 Invest Regional NSW (2018) Agribusiness and food. Viewed 20 December 2021, <https://www.investregional.nsw.gov.au/sectors/agribusiness-and-food/>.

Implications for the Australian agricultural and food system

If higher value-added uses for red-meat by-products are realised in health and wellbeing markets, this may displace some lower value uses. While reduced cattle slaughter has increased by-product prices between 2020-2021, higher costs for farm inputs may reduce profitability in agriculture in 2021-2022.[120] As such, high value health and wellbeing innovations may better compete on price and divert by-product supply away from lower value applications such as use as a processed meat extender or as feed for aquaculture and pets.

Existing infrastructure and R&D underpinning opportunity

Several research organisations support R&D efforts that underpin this opportunity. They include but are not limited to MLA, Australian Meat Processor Corporation (AMPC), CSIRO, universities, state governments, and private research organisations. Underpinning research has focused on identifying and developing process technologies to increase the value of red meat offcuts, identifying high value extracts, and product development.

Infrastructure critical to this opportunity is generally that found in an abattoir and associated processing facilities. Blood, collagen and other valuable co-products need to be hygienically and efficiently collected at food or medical grade from the abattoir. This is done using various processes for blood collection. Initial collection is an area for continued improvement to ensure collection does not slow down the already established meat processing lines.

120 Meat & Livestock Australia (2021) Co-product prices skyrocket in 2021. Viewed 20 December 2021, <https://www.mla.com.au/news-and-events/industry-news/offal-prices-resurgent-in-2021/>.; Australian Bureau of Agricultural and Resource Economics (2021) Agricultural overview: December quarter 2021. Viewed 20 December 2021, <https://www.awe.gov.au/abares/research-topics/agricultural-outlook/agriculture-overview>.

Blood collection also requires collection points (e.g., tanks to pool product), chillers, centrifugal separation, spray dryers, and hydrolysers. While blood collection is not commonplace in abattoirs, mainly due to contamination risks, most of the technology required for further processing is currently available with process customisation.

Collection of collagen is often from hides and bones. There are several methods of extraction, generally requiring cleaning and acidification processing, hydrolysis, enzymolysis, decanting, concentration processing, and spray drying. These technologies are readily available, with process customisation required based on the inputs and desired yield. The efficiency of these processes can differ, however hot-pressure water extraction provides a useful example of a sustainable processing technology demonstrating high protein recovery from bone residue.[121]

Adapting high speed milling platforms for efficient extraction of water from meat and hides remains another area of investment activity. This could potentially unlock applications such as the production of functional free flowing powders and quality fertilisers.

2022-2030 science, technology and infrastructure investment priorities

Remap the carcase: Remapping the carcase and understanding how its components could be utilised as ingredients in food and other adjacent sector products is a key step that MLA is undertaking to progress this work.

Research to understand new product markets and value chains: The convenience, snacking (e.g. grab-and-go snacks), personalised nutrition and wellness markets (e.g. nutraceuticals) offer additional uses for red meat. For example, initial scoping has been conducted on the potential for red meat to form high protein snacks to help with blood glucose levels or high blood pressure.[122] Further research to understand and develop these opportunities is needed. Additional market sectors that may use red meat by-products as an input include pharmaceuticals, cosmetics, medical and biofuel industries.[123] For example, in 2018 a Finnish renewable fuel company announced strategic plans to acquire 51% of an animal fat and protein company to assist with the production of diesel biofuels in Europe.[124] Investigating these new markets and sectors will be important to ensure newly developed products can be adopted.

Research to understand customer needs and willingness to pay: Understanding changing consumer behaviours and needs—both end use consumers, and customers in other sectors who may use red meat co-products as an input—will be key to developing new products and attracting investment where there is a compelling case for Australian protein based inclusion.

Process engineering for co-product collection and transformation: Hygienic and fast collection of co-products for value adding is a challenge for some target products (e.g., collection of blood). Current collection solutions are too slow and reduce the speed of the processing lines. Research and engineering are required to enable integration of sustainable and efficient food and medical grade collection technologies with limited or no waste streams into abattoirs and processors. Further, the adoption of novel technology platforms and operating protocols for harvesting co-product components will also need to consider market trade-offs. There may be a need for knowledge transfer processes to help secure 'approval' from Halal markets or meet agreed waste stream levels by state Environmental Protection Agencies.

Support evidence-based claims: Health and wellness supplements are regulated by the Therapeutic Goods Administration (TGA) as complementary medicines. Research is required to support any new product health claims.

Develop and demonstrate origin marker technology: Food manufacturers are under increasing pressure to ensure the safety, security and provenance of every grocery item. New origin 'marker' technology able to analyse innate chemical fingerprints of food products can help to verify provenance claims and identify counterfeit goods for market acceptance.[125]

121 Deb-Choudhury S, Haines S, Knowles S, Finlay-Smits S, Middlewood P and Loeffen M (2019) Design and deliver novel meat extract concepts.

122 Meat & Livestock Australia (2017) Scoping the functional properties of red meat and opportunity spaces in preventative health and wellbeing.

123 Meat & Livestock Australia (2020) Strategic Plan 2025. North Sydney, NSW.

124 Neste (2018) Neste's acquisition of the share majority of Dutch animal fat trader Demeter closed. Viewed 7 February 2022, <https://www.neste.com/releases-and-news/nestes-acquisition-share-majority-dutch-animal-fat-trader-demeter-closed>.

125 Meat & Livestock Australia (2020) Global scan of technologies and systems enabling data capture and transfer across red meat supply chains.; Meat & Livestock Australia (2021) Red meat traceability information hub. Viewed 19 January 2022, <https://www.mla.com.au/research-and-development/food-safety/red-meat-traceability-information-hub/>.

Opportunity 6: Insect protein sources for food and feed

2030 opportunity

To expand local production of insects to provide new protein sources for food and feed and new pathways for food waste.

Potential market size

Current state

- Negligible

Conservative 2030 scenario

- $12 million in product value
- 40 jobs

Ambitious 2030 scenario

- $44 million in product value
- 140 jobs

Difference between conservative and ambitious scenarios: **$32 million** in annual revenue (See Appendix D for the economic methodology.)

Science, technology and infrastructure priorities

- Investigate feasibility of co-location and sharing
- Research to support insect waste management potential
- Research to understand the nutritional profile of insects
- Support progressive insect infrastructure scale-up
- Support regulatory process development for insects

What is driving this opportunity?

Insects have the potential to significantly contribute to feeding a growing human population, as well as contribute to animal feed, such as livestock, aquaculture and pet food. Insects are high in protein, varying between 40-70% depending on the species.[126] Insects have been part of cuisines globally for millennia, including Australian First Nations Peoples, and can help diversify diets into the future.

Many businesses operate globally producing a large variety of products. The Australian insect farming industry is now emerging with a focus on producing insects for animal feed, especially for pets, poultry and fish, as well as human consumption and waste management. Crickets and mealworms are currently commercially produced in Australia for human consumption. Additionally, crickets, mealworms and black soldier flies are commercially sold for pet food. Black soldier fly larvae is the only species currently being investigated for livestock feed in Australia, with mealworm receiving focus in international markets.

Insects offer many advantages, including feed conversion efficiency, high nutritional value and low environmental footprint. They are highly efficient in converting feed into food, with a feed conversion rate of approximately 50% compared to less than 20% for traditional livestock.[127] Insects have a high nutritional value and generally over 80% of the insect is edible. They are rich in protein, omega-3 fatty acids, iron, zinc, folic acid and vitamins B12, C and E.[128] Insect farming is also considered to have a low environmental footprint as it requires low amounts of land, water and energy. Insects can help transform existing food systems to become more sustainable overall by helping diversify diets and enabling consumption of more foods with lower environmental footprints. Insects can also be farmed in small spaces including in urban areas closer to consumers. They are being investigated for their potential to upcycle clean waste streams that are otherwise sent to landfill.[129]

There is a growing downstream demand for insect proteins, both from stockfeed industries and nearby Asian export markets. In 2020, around half of Australia's insect farming businesses were focused on producing feed for livestock and aquaculture industries,[130] with others focused on producing food, or on the associated production and manufacturing systems.[131]

126 AgriFutures Australia (2020) Catalysing a $10m Australian Insect Industry.

127 Halloran A, Roos N, Eilenberg J, Cerutti A and Bruun S (2016) Life cycle assessment of edible insects for food protein: A review. Agronomy for Sustainable Development 36(4), 1–13. DOI: 10.1007/S13593-016-0392-8/TABLES/3.; Alexander P, Brown C, Arneth A, Finnigan J, Moran D and Rounsevell M DA (2017) Losses, inefficiencies and waste in the global food system. Agricultural Systems 153, 190–200. DOI: 10.1016/J.AGSY.2017.01.014.

128 CSIRO (2021) Edible insects: A roadmap for the strategic growth of an emerging Australian industry. Canberra.

129 CSIRO (2021) Edible insects: A roadmap for the strategic growth of an emerging Australian industry. Canberra.

130 AgriFutures Australia (2020) Catalysing a $10m Australian Insect Industry.

131 Insect Protein Association of Australia (2021) Insects as food. Viewed 16 November 2021, <https://www.insectproteinassoc.com/insects-as-food>.

Australia's comparative advantages

Australia has many natural advantages and strengths in the development of an insect protein industry. These include traditional usage by First Nations Peoples, a unique biodiversity of insects, favourable climatic conditions for raising insects compared to other nations, an enviable biosecurity system that protects against exotic pests and diseases, and world class agricultural and food research capabilities.[132]

Regional opportunities

Building close to source is an important aspect of sustainably dealing with food waste and building insect supply chains. Insect industry development opportunities are suited to regional and metropolitan areas.

Implications for the Australian agricultural and food system

Satisfying insect demand from stockfeed industries (e.g., poultry, cattle and fish) may displace current demand that is satisfied by the grains industry. Greater utilisation of these crops for human consumption through the development of plant-based protein ingredients (Opportunity 3) could help address and complement this displacement. Insects for petfood may displace co-product streams from the animal protein industry. Insect inputs can include clean and mixed food waste, which could displace waste from landfill or low value uses.

Existing infrastructure and R&D underpinning opportunity

Research on insects as food and feed in Australia is presently minimal, with CSIRO and a few universities working in the space.[133] Despite this, Australia has strong agricultural, food and nutritional research capabilities that can be drawn upon in the development of this industry. CSIRO has research that spans across most insect groups, with focuses on taxonomy, biosecurity and innovations in genomics. Australia has a national entomological society, and the Australian National Insect Collection is recognised both nationally and internationally as a major research collection with over 12 million species.

Insect rearing is undertaken in a closed environment where ventilation, lighting, temperature and humidity can be controlled.[134] Technology and equipment for dedicated insect farming is an emerging industry with limited off-the-shelf solutions available.[135] Most technologies used are proprietary, with scale-up of production posing operational challenges.

132 CSIRO (2021) Edible insects: A roadmap for the strategic growth of an emerging Australian industry. Canberra.

133 AgriFutures Australia (2020) Catalysing a $10m Australian Insect Industry.; CSIRO (2021) Edible insects: A roadmap for the strategic growth of an emerging Australian industry. Canberra.

134 Insect Protein Association of Australia (2021) Insects as food. Viewed 16 November 2021, <https://www.insectproteinassoc.com/insects-as-food>.

135 AgriFutures Australia (2020) Catalysing a $10m Australian Insect Industry.; CSIRO (2021) Edible insects: A roadmap for the strategic growth of an emerging Australian industry. Canberra.

2022-2030 science, technology and infrastructure investment priorities

Investigate feasibility of co-location and sharing: Many producers lack access to capital, technology (especially automation), and infrastructure. The feasibility of a collaborative facility should be investigated. Such a facility could supply insect protein for animal feed that enables co-location of companies, with deliberate circularisation of supply chains, enabling companies to service each other. Other considerations could include shared feedstocks, access to local transport infrastructure, regional development, and recycling of waste.

Research to support insect waste management potential: There is interest in the potential for using insects to support the management of food waste, mixed waste and difficult waste. For example, Australian company Goterra has created modular waste management infrastructure to farm black soldier fly larvae. The larvae convert food waste to protein and fertiliser which can then be fed to animals and crops.[136] Research trials are needed to investigate insect-based waste management solutions for a variety of challenging wastes, as well as the efficacy of alternative uses for insects in other market applications. Provenance and traceability of wastes through to protein products also requires further research and development. This research could support the expansion of insect production and the circularity of agricultural production systems.

Research to understand the nutritional profile of insects: Significant knowledge gaps remain around the nutritional profile of insects, their digestibility, allergenicity, and bioaccumulation of pesticides and heavy metals. Pet and livestock feed trials are needed to assess performance, health, and nutrition, and help improve these parameters so insect-derived feed can compete with existing raw materials. Research trials are also required to investigate the nutritional and health benefits of insects for humans, helping support industry to make substantiated health claims. This research is required across many species of edible insects, for both human and animal consumption. Other important considerations include research into opportunities for Indigenous enterprises and communities and holding research trials to assess biosecurity risks of at-scale insect production.[137]

Support progressive insect infrastructure scale-up: It is still unclear how insects can be produced at scale in Australia and what production conditions are optimal (e.g., feed, temperature, space, etc).[138] Research is required to support process engineering, in particular, the integration of automation, sensing, machine learning and artificial intelligence technologies, which may help industry to optimise growing conditions for improved characteristics. Research is also needed to assess and learn from world best practice insect infrastructure – this involves studying learnings from international markets and adjusting to Australian conditions. For example, companies in other markets have invested in modular or vertical farms (Ynsect) and engineered circular economy and waste management principles. Further, lessons learnt from adjacent intensive animal and plant production industries should be investigated.

Support regulatory process development for insects: In addition to the development of industry guidelines (discussed above), many of the research trials discussed in this section (nutritional, biosecurity risk, waste management potential and other alternative uses etc.) can also inform regulatory decisions.

136 Goterra (2021) Goterra is building a circular economy to radically reduce the impact of food waste on our planet. Viewed 21 November 2021 <https://goterra.com.au/about/circular-economy/>.

137 CSIRO (2021) Edible insects: A roadmap for the strategic growth of an emerging Australian industry. Canberra.

138 AgriFutures Australia (2020) Catalysing a $10m Australian Insect Industry.; CSIRO (2021) Edible insects: A roadmap for the strategic growth of an emerging Australian industry. Canberra.

1.4 Enabling the scale-up of high growth sectors

Meeting future global and Australian demand for protein, through Australian grown and made products requires the identification of sectors that are currently relatively small in Australia but have high growth potential, and then supporting their scale-up. This will capture value and increase profitability, alongside more mature existing sectors. Although there are many examples of high growth sectors, two examples are presented in this roadmap, including local, sustainable **white flesh fish** and **plant-based products**.

This focus on scaling up high growth sectors is supported by several growth and support commitments across the protein and food industry. These include the agriculture industry's target to exceed $100 billion in farm gate output[139] or $200 billion in value-add by 2030;[140] and CSIRO's Future Protein Mission which aims to create new Australian protein products and ingredients that earn an additional $10 billion in revenue by 2030. Sovereign food manufacturing also has a renewed focus with the Australian Modern Manufacturing Strategy identifying food and beverage manufacturing as a national manufacturing priority that plays an important role in driving economic resilience.[141] In particular, the strategy encourages food manufacturers to capitalise on growing global demand for premium food offerings through development of innovative and high value products with diverse attributes.

Opportunity 7: Scaling up local, sustainable white flesh fish production

2030 opportunity

To scale up local, sustainable white flesh fish production to meet domestic demand and export products to nearby Asian markets.

Potential market size

Current state
- $300 million in product value

Conservative 2030 scenario
- $460 million in product value
- $230 million in manufacturing revenue
- 600 jobs

Ambitious 2030 scenario
- $1.5 billion in product value
- $770 million in manufacturing revenue
- 1,800 jobs

Difference between conservative and ambitious scenarios: **$1.04 billion** in retail value.
(See Appendix D for the economic methodology.)

Science, technology and infrastructure priorities

- Investment in cross-sector infrastructure and services
- Identify suitable white flesh fish species
- Understand consumer expectations for aquaculture
- Research to support aquaculture production enhancement
- Research to understand and address aquaculture-environmental interactions and climate impacts

139 National Farmers Federation (2020) 2030 Roadmap: Australian Agriculture's Plan for a $100 Billion Industry. Barton, ACT.
140 FIAL (2020) Capturing the prize- The A$200 billion opportunity in 2030 for the Australian food and agribusiness sector.
141 Australian Government (2020) Make It Happen: The Australian Government's Modern Manufacturing Strategy. Canberra.

What is driving the opportunity?

White flesh fish encompasses all edible finfish that are produced in aquaculture facilities, except for salmonids and tuna. Demand in Australia is driven by consumers wanting locally grown, inexpensive, boneless, skinless, white flesh fish. Demand for white flesh fish is also present in Asia, driven by a desire for a premium product like the Giant Groper, which is farmed and estimated to be a US$1 billion industry.[142]

Australia consumes more fish than it can supply locally, and this demand is continuing to grow as consumers increasingly view seafood as an important source of healthy, low-fat protein.[143] Between 2020 to 2025, Australia's fisheries and aquaculture production is expected to increase by 2.4% in value to $3.41 billion.[144] According to the OECD, in 2018 Australia's wild-catch fisheries comprised a large portion of this production value at 56% while aquaculture captured 44% of this value.[145] Australia's farmed white flesh fish industry currently produces 11,000 tonnes annually, however, has ambitions to reach 50,000 tonnes by 2030.[146]

Currently, Australia imports approximately 100,000 tonnes of low-cost white flesh fish annually to help meet demand.[147] However, imported fish supply chains face challenges that may threaten food integrity. This includes intentional seafood fraud such as mislabelling and adulteration of products. Demonstrating health standards are a challenge for Australian policy makers, particularly when environmental health and safety standards of many exporting countries are contrary to standards in place in Australia.[148]

While this roadmap only focuses on one aquaculture opportunity, there are many other technology-led growth opportunities worth exploring. For example, prawns are on a significant growth trajectory, with global prawn aquaculture increasing by around 6% per year.[149] New monitoring technology is being developed to increase prawn production in Australia and reduce the need for imports during peak demand periods.[150]

Australia's comparative advantages

Australia has many natural advantages in the development of aquaculture industries, including political stability, proximity to major Asian markets, considerable land and water resources and growing experience in farmed fish production. Further, there is significant interest and appetite for investment in aquaculture in Australia, particularly across Northern Australia which has advantages including large areas of suitable land and a prevailing climate characterised by high air temperatures—ideal for culturing most tropical aquatic species.[151]

142 EverBlu Capital (2018) Australian seafood is set to grow due to premium quality and growing domestic and global demand.

143 AgriFutures Australia (2020) The Changing Landscape of Protein Production: Opportunities and Challenges for Australian Agriculture. Wagga Wagga, NSW.; Burger J and Gochfeld M (2009) Perceptions of the risks and benefits of fish consumption: Individual choices to reduce risk and increase health benefits. Environmental research 109(3), 343. DOI: 10.1016/J.ENVRES.2008.12.002.

144 Mobsby D, Steven AH and Curtotti R (2020) Australian fisheries and aquaculture outlook 2020.

145 OECD (2021) Fisheries and Aquaculture in Australia.

146 CSIRO (2021) The quest for a new everyday supermarket fish. Viewed 29 October 2021, <https://ecos.csiro.au/new-everyday-supermarket-fish/>.

147 CSIRO (2021) The quest for a new everyday supermarket fish. Viewed 29 October 2021, <https://ecos.csiro.au/new-everyday-supermarket-fish/>.

148 Williams M, Hernandez-Jover M, Williams T and Shamsi S (2021) A risk scoring system for seafood supply chain breaches and examination of freshwater fish imported to Australia. Food Quality and Safety 5. DOI: 10.1093/FQSAFE/FYAB004.

149 FAO (2020) Towards sustainability in the shrimp industry. Viewed 23 January 2022, <https://www.fao.org/in-action/globefish/market-reports/resource-detail/en/c/1261310/>.

150 CSIROscope (2019) Prawn stars: Five facts about Aussie prawns. Viewed 23 January 2022, <https://blog.csiro.au/prawn-stars-five-facts-about-aussie-prawns/>.

151 CSIRO (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.

Regional opportunities in aquaculture

Aquaculture activity occurs throughout Australia, largely in regional areas, with Tasmania and South Australia producing three-quarters of Australia's aquaculture industry revenue.[152] Going forward, there are significant opportunities in Northern Australia, with all three governments across the region (Queensland, Northern Territory and Western Australia) identifying aquaculture as growth industries. For example, the Queensland Government has identified eight land-based marine aquaculture development areas (ADAs) to promote and grow a sustainable aquaculture industry in the state.[153] Each of these areas are in regional Queensland locations that fit specific physical, environmental and planning criteria. The Western Australian Government has similarly identified several regional areas to invest in through the development of Aquaculture Development Zones.[154] As the aquaculture industry grows, so too does the requirement for feed which may spur opportunities to expand crop production in regional Australia.

Implications for the Australian agricultural and food system

Increased domestic production of white flesh fish has mixed implications for associated national markets, particularly depending on the practices and resources used for industry expansion. In Australia, increased production would require greater domestic aquaculture capability and associated improvements to disease and waste management systems to avoid negative implications on surrounding ecosystems.[155] Impacts on the workforce may be beneficial, given significant opportunities for aquaculture employment including in regional areas and Aboriginal and Torres Strait Islander communities.[156] As production increases, so too could demand for feed inputs such as small fish, insects and some crops.[157] If using small fish as feed, this could disrupt supply to other industries that use small fish as inputs, such as livestock, commercial and recreational fisheries, baitfish or petfood.[158] The impact on agricultural crop supply may vary, as priority feed alternatives include a range of oilseeds and dehulled legumes.[159]

Existing infrastructure and R&D underpinning opportunity

Many organisations support aquaculture R&D in Australia, including the Fisheries Research and Development Corporation (FRDC), the Marine Bioproducts Cooperative Research Centre (CRC), the Blue Economy CRC, the CRC for Developing Northern Australia, CSIRO, plus universities, including James Cook University, and various state governments. Research includes process improvement, animal welfare, and new species development.

152 Dean R (2021) Aquaculture in Australia Industry Report A0200. IBISWorld.

153 Business Queensland (2019) Aquaculture development areas and investment. Viewed 23 January 2022, <https://www.business.qld.gov.au/industries/farms-fishing-forestry/fisheries/aquaculture/site-selection-production/development-areas/investment>.

154 WA Department of Primary Industries and Regional Development (2020) Aquaculture Development Plan for Western Australia Focusing on the key foundations for growth.

155 Department of Agriculture and Water Resources (2015) Australia's seafood trade. Canberra.

156 Department of Agriculture and Water Resources (2017) National Aquaculture Strategy. Canberra.

157 Department of Agriculture and Water Resources (2015) Australia's seafood trade. Canberra.; ABC News (2018) Fish feed study finds insects could improve aquaculture's environmental sustainability. Viewed 20 December 2021, <https://www.abc.net.au/news/2018-09-13/aquaculture-industry-expert-say-insect-fish-feed-more-efficient/>.; AEGIC and Grain Growers (2021) New opportunities for feed grains in Indonesia's growing livestock industry. Viewed 20 December 2021, <https://www.aegic.org.au/wp-content/uploads/2021/07/AEGIC-New-opportunities-for-feed-grains-in-Indonesias-growing-livestock-industry.pdf>.

158 NSW Government (2010) Status of Fisheries Resources in NSW | Australian Sardine.; Australian Bureau of Agricultural and Resource Economics and Sciences (2017) Australian fisheries and aquaculture statistics 2016. Canberra.

159 Turchini GM, Trushenski JT and Glencross BD (2019) Thoughts for the Future of Aquaculture Nutrition: Realigning Perspectives to Reflect Contemporary Issues Related to Judicious Use of Marine Resources in Aquafeeds. North American Journal of Aquaculture 81(1), 13–39. DOI: 10.1002/NAAQ.10067.

Common infrastructure for aquaculture farming systems range from sea cages (which are not commonly used for white flesh fish) and large earthen ponds to compact-land based tank systems – each with advantages and disadvantages, particularly from a geographic/regional perspective.[160] Essential underpinning infrastructure for the development of this opportunity includes (but is not limited to):

- Recirculating aquaculture systems (RAS) – Highly automated, capital and energy intensive equipment that enables significant productivity benefits; provides environmental control including water temperature, dissolved oxygen, and waste removal; allows for close monitoring, and reduces risk of mortality and disease. Can be located closer to markets, reducing cost of transport. However, skilled staff are required to operate these systems.
- Ponds – Generally less automated and lower technology than a RAS. Includes water and an aerator, is usually in an outside environment and is therefore location dependent.
- Larvae systems – systems to culture fish in the immature first stage of a life cycle after emerging from an egg (larvae).
- Broodstock tanks – tanks with filtration, temperate and photoperiod control, used for broodstock (mature animals used for breeding) rearing.
- Live feed – required to be continuously grown and harvested to ensure the nutritional profile of fish is met.

2022-2030 science, technology and infrastructure investment priorities

Investment in cross-sector infrastructure and services: Uncertainty regarding resource access is limiting investor participation and thus limiting the development of aquaculture infrastructure. Freight is also costly and logistically difficult, particularly in remote areas. The development of a national white flesh fish strategy could support more cross-sector collaboration. Similarly, large-scale aquaculture development hubs or facilities, such as those established by several state governments (e.g., QLD, WA and SA Governments) could increase production volumes, regulatory efficiency and supply chain connectivity.[161] Further considerations include shared feedstocks, access to local transport infrastructure, training and research facilities, regional infrastructure development, and recycling of waste.

Identify suitable white flesh fish species: It is important to identify white flesh fish species that suit Australian aquaculture conditions and meet consumer preferences. The identified species will need to be able to be bred and raised in nurseries, hatcheries and ponds so that wild fish stocks do not have to be used. For example, Aquna has targeted Murray cod as their target species for sustainable pond-grown white flesh fish production to meet local and international demands.[162] Murray Cod Australia is currently working on this opportunity by developing the profile of sustainable pond-grown Murray cod to meet local and international demands. The Queensland Government is also pursuing the opportunity, fostering collaboration with industry and researchers to support land-based aquaculture industry development. This includes investment in six ADAs for best practice land-based marine aquaculture management and a food pilot plant to reduce the risk of scaling production.[163] Candidate species identified include barramundi and cobia, with cobia showing strong retailer acceptance in the high-end food-service sector and recent advances in production efficiency.[164]

160 CSIRO (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.

161 Department of Agriculture and and Water Resources (2017) National Aquaculture Strategy. Canberra.

162 Aquna Sustainable Murray Cod (2021) Sustainability | Farming Practices. Viewed 13 December 2021, <https://aquna.com/sustainability/production/>.

163 Queensland Government (2019) Aquaculture development sites mean jobs for Rockhampton. Viewed 23 January 2022, <https://statements.qld.gov.au/statements/86485>.

164 FRDC (2018) Tasty results for Cobia in consumer trials. Viewed 23 January 2022, <https://www.frdc.com.au/fish-vol-26-3/tasty-results-cobia-consumer-trials>.

CSIRO is also assessing the potential for a white flesh fish species named Pompano to meet consumer demands, with a strategy to develop a Pompano industry in Northern Australia.[165] It is also concentrating on industry development through a multidisciplinary scientific approach with research addressing diet and nutritional requirements, genetics and selective breeding programs, animal health and welfare, and systems productivity.

Further, as fish feed accounts for more than 90% of the cumulative environmental impact of aquaculture supply chains,[166] there is an opportunity to reduce impact and cost through species selection. Herbivorous or omnivorous species such as catfish, carp and tilapia do not need animal protein to thrive, and their mainstay diets can comprise of inexpensive crop by-products and plankton.[167]

Understand consumer expectations for aquaculture: Marketing and social licence research trials into the sustainable production of white flesh fish.

Research to support sustainable aquaculture production enhancement: Understanding how to manage the implications of increased farmed white fish production on surrounding ecosystems, related supply chains and production costs will be necessary for the industry to meet production targets long term. To help address these issues, research priorities could include:

- Identifying opportunities to convert by-products into valuable co-products
- Management of fish health, diseases and pests
- Demonstrating growing out of identified fish species in nurseries, hatcheries and ponds so that wild fish fry stock does not have to be used
- Reducing production costs and improving price competitiveness
- Waste and environmental management
- Investigating and demonstrating innovative and sustainable farming production systems and techniques such as vertical farming
- Developing affordable, nutritionally balanced and sustainable feed.

Research to understand and address aquaculture-environmental interactions and climate impacts: Sustainability and environmental considerations are imperative for aquaculture, with climate change impacts increasingly experienced across the sector. Emerging environmental issues from aquaculture farms are a challenge to industry expansion; and there remain knowledge gaps regarding aquaculture-environment interactions, how future climate change may impact on the sector, and what adaptation practices may be required. While investment in research to support sustainable aquaculture management and development is already occurring, continued support is required to understand and address aquaculture environmental interactions and issues. For example, wastewater management, in particular nutrient release in discharge waters, is a critically important area for prioritisation. Lessons need to be identified from previous aquaculture developments (across Australia and globally), with learnings implemented in new developments. Addressing knowledge gaps and continuing industry engagement will be important for the sector to thrive while earning and maintaining its social licence to operate.

165 CSIRO (2021) The quest for a new everyday supermarket fish. Viewed 29 October 2021, <https://ecos.csiro.au/new-everyday-supermarket-fish/>.

166 Kok B, Malcorps W, Tlusty MF, Eltholth MM, Auchterlonie NA, Little DC, Harmsen R, Newton RW and Davies SJ (2020) Fish as feed: Using economic allocation to quantify the Fish In : Fish Out ratio of major fed aquaculture species. Aquaculture 528.

167 Belton B, Little D and Zhang W (2021) Farming fish in fresh water is more affordable and sustainable than in the ocean. Viewed 23 January 2022, <https://theconversation.com/farming-fish-in-fresh-water-is-more-affordable-and-sustainable-than-in-the-ocean-151904>.

Opportunity 8: Plant-based products

2030 opportunity

To scale up local production of plant-based products, enabling an end-to-end onshore supply chain.

Market Size

Current state

- $140 million in product value

Conservative 2030 scenario

- $3 billion in product value
- $1.5 billion in manufacturing revenue
- 2,110 jobs

Ambitious 2030 scenario

- $9 billion in product value
- $4.5 billion in manufacturing revenue
- 6,320 jobs

$5 billion in domestic retail expenditure in both scenarios

Difference between conservative and ambitious scenarios: **$6 billion** in retail value (See Appendix D for the economic methodology).

Science, technology and infrastructure priorities

- Scaling up processing infrastructure
- Services and skills to support food manufacturers and start-ups
- Investment in collaborative R&D and prototyping facilities
- Establish domestic ingredient supply chains
- Invest in plant-based product R&D

What is driving this opportunity?

Globally, there is rising demand for and market growth of value-added plant-based products. Advances in technology mean that plant-based products are increasingly comparable to animal products in taste and texture, and improving in nutritional content. The global plant-based alternatives to meat market is expected to reach US$8.3 billion by 2025.[168] Demand drivers differ by major demand regions; in North America, healthy and sustainable meat alternative products that effectively mimic meat are in demand; in Europe, greater awareness of food product carbon footprints is expected to drive demand for local plant protein sources; in the Asia Pacific, consumer aversion toward meat products, heightened during the ongoing pandemic, and government initiatives to reduce meat consumption (e.g., China) are key drivers.[169] The global non-dairy cheese alternative market is expected to reach US$3.3 billion by 2026,[170] and the Australian soy and almond milk industry revenue is expected to grow to A$554.3 million by 2026-27.[171]

The industry is still small in Australia, however, it is ramping up rapidly. Over the last year, the plant-based alternative to meat industry grew from 10 to 19 brands, retail sales rose 32% to $185 million and manufacturing revenue doubled from $35 million to nearly $70 million.[172] Total products on grocery shelves doubled to over 200, with 42% produced locally in 2019-20. The most common Australian-made products include crumbed products (nuggets and schnitzels), ready meals, sausages and burgers.[173] Australia currently exports only a very small amount of plant-based meat alternative products;[174] approximately half of all products sold domestically via retail are imported.[175] While some brands have reached price parity with animal meats, in 2020 plant-based meat alternative products were, on average, 49% more expensive than animal meats.[176]

168 MarketsandMarkets (2020) Plant-based meat market. Viewed 2 Feb 2021, <https://www.marketsandmarkets.com/Market-Reports/plant-based-meat-market-44922705.html>.

169 Frost & Sullivan (2021) Global meat analogs protein ingredients growth opportunities

170 Business Wire (2021) Global Vegan Cheese Market (2020 to 2026) - by End-use, Source, Product and Region - ResearchAndMarkets.com. Viewed 9 November 2021, <https://www.businesswire.com/news/home/20210122005252/en/Global-Vegan-Cheese-Market>.

171 IBISWorld (2021) Soy and Almond Milk Production in Australia.

172 Food Frontier (2021) 2020 State of the Industry Australia's Plant-Based Meat Sector.

173 Food Frontier (2021) Plant-Based Meat Alternatives Sold in Australia: An Analysis of Product Labels.

174 v2food to New Zealand, Japan, Korea, Thailand, the Philippines and now China. Future Food Systems (2021) Australia's v2 'alt-meat' product range cracks world's largest market. Viewed 9 November 2021, <https://www.futurefoodsystems.com.au/byte/australian-made-plant-based-meat-goes-on-sale-in-china/>.

175 Food Frontier (2019) Meat the Alternative: Australia's $3 Billion Opportunity.

176 Food Frontier (2021) 2020 State of the Industry Australia's Plant-Based Meat Sector.

Australia's comparative advantages

Australia has significant food engineering research expertise and manufacturing capabilities to support the development of plant-based products. Australia's significant agricultural industry, in particular its cropping industry, provides the basis for locally grown ingredients, including wholegrain, minimally and semi-processed. Momentum is already building, with several businesses looking to convert raw crop materials into concentrated plant-based protein ingredients (see section 1.2). This will enable Australian manufacturers to locally source ingredients for plant-based products.

Regional opportunities

Plant-based product manufacturing plants could be located close to ingredient production facilities and crop growing areas. Locations for regional manufacturing and innovation centres could be selected for construction across the next decade to 2030. Crop production areas are discussed in Section 1.2. The NSW Special Activation Precincts, for example, provide the auxiliary infrastructure and commercial support required for new agribusiness operations to be established efficiently. It has been suggested that a long-term commitment in the order of 25 years to food manufacturing infrastructure could provide the necessary certainty for companies to make investments.

Implications for the Australian agricultural and food system

As consumer buying habits change and there is a growing demand for diverse plant-based products, it will be important to ensure that Australian-made products meet these needs instead of customers only being able to access imported products. Moreover, Australian-made products will have a growing contribution to Australia's protein exports. These products will likely initially assume a small proportion of the growing protein market demand.

Products made in Australia could meet domestic demand at lower prices than imported products, as is currently the case for consumer offerings,[177] and could be exported overseas to new markets to grow the Australian agriculture industry's revenue. Manufacturing plant-based food products creates opportunity across the value chain, including the crop production and ingredient extraction stages.

Scaling the plant-based product industry will increase demand for input crops. This may necessitate land use change from traditional production systems to plant-based food production systems.

The viability of Australian-made products for export will depend on various factors including manufacturing costs, supply chain costs, and price and quality competitiveness with other products on the market internationally. The complexity of export viability should be considered and may require further analysis.

Existing infrastructure and R&D underpinning opportunity

Plant-based products are made via the processing of various plant material and ingredients. They are typically made using such crops as wheat, soy, pea and rice, however others such as pulse crops are being considered as high protein sources. Depending on the end-product, manufacturing can involve formulation of various processed crops and plant-based ingredients, and texturisation to create the desired food structure and behaviour.

Food engineering and innovation research is conducted extensively across Australian research organisations, including at CSIRO through its Food Innovation Centre, through universities, CRCs, State Governments, and private research organisations. Underpinning research themes relevant to this opportunity include meat sciences, consumer science, food manufacturing and food safety. Table 4 describes select Australian food innovation facilities.

Underpinning infrastructure required for this type of food innovation includes technology to produce texturised vegetable protein (TVP) as well as to produce plant-based products, either using TVP to produce burgers, sausage and mince or high moisture extrusion processing of the isolate to directly produce fibrous plant-based products such as strips, and chunks. Extrusion technology is a versatile processing technology that combines multiple unit operations such as mixing, heating, cooking, shaping and forming into one integrated process to produce TVP. For simpler products which make use of minimally processed or semi-processed grains and flours, texturisation and extrusion processes may not be required.

177 Food Frontier (2021) 2020 State of the Industry Australia's Plant-Based Meat Sector.

Table 4: Australian food innovation facilities

FACILITY/PROGRAM	DESCRIPTION	LOCATION
Australian Export Grains Innovation Centre (AEGIC)[178]	AEGIC provides a range of services relating to grains and grain products, including grain quality and property testing, flour quality and dough rheology analysis, and end product testing.	Sydney, NSW and South Perth, WA
CSIRO Food Innovation Centre[179]	CSIRO's Food Innovation Centre provides facilities and expertise to support companies to develop, test and commercialise new food IP and products. Services include food processing facilities, consumer science, food safety and protein advisory expertise.	Werribee, VIC
Health and Food Sciences Precinct[180]	The precinct host scientists from the Queensland Department of Agriculture and Fisheries (DAF), CSIRO and UQ through the Queensland Alliance for Agriculture and Food Innovation (QAAFI). It provides infrastructure and expertise for researchers and businesses to develop and test new food products. Facilities include equipment for processing seafood, meat, dairy and horticultural products; laboratories and workspaces; and biosecurity diagnostic equipment.	Brisbane, QLD
International Flavour Research Centre[181]	A $2.5m facility at the University of Adelaide's Waite campus, funded by v2food, the University of Adelaide, University of Nottingham and the Biotechnology and Biological Sciences Research Council. The aim of the centre is to understand the role of food ingredients in flavour and support development of plant-based food and ingredients. This includes the MS-Nose tool, which measures aromas while eating in real-time.	Adelaide, SA
WA Food Innovation Precinct	The precinct, set to be complete mid-2022, is valued at $21.75 million.[182] Its purpose is to scale-up agribusinesses, create new products through R&D, and capture a greater food and beverage market share for WA.[183] It will contain agri-food experts, business services and a shared food technology facility. The precinct will be the home for the X-Protein Lab; an innovation centre for alternative proteins, with a focus on Singapore.	Nambeelup, WA
Waite Research Precinct plant-based food incubator	In November 2021 the South Australian Government invested $2m into this plant-based food incubator based at the University of Adelaide's Waite campus. Its purpose is to support innovation and pilot projects between industry and the research sector and attract international investment.[184]	Adelaide, SA

178 AEGIC (2020) Grain and food quality testing. Viewed 21 January 2022, <https://www.aegic.org.au/domestic-services/all-testing-services/>.

179 CSIRO (2021) CSIRO's food innovation centre for industry. Viewed 20 December 2021, <https://www.csiro.au/en/work-with-us/industries/food>.

180 Queensland Government DAF (2021) Health and food sciences precinct. Viewed 21 January 2022, <https://www.daf.qld.gov.au/contact/offices/stations-facilities/health-food-science>.

181 Brown K (2021) Serving up healthy plant-based food research with new flavour facility. Viewed 20 December 2021, <https://www.adelaide.edu.au/newsroom/news/list/2021/11/02/serving-up-healthy-plant-based-food-research-with-new-flavour-facility>.

182 Shire of Murray (2021) Western Australian Food Innovation Precinct. Viewed 20 December 2021, <https://www.murray.wa.gov.au/Shire-and-Council/Projects/Western-Australian-Food-Innovation-Precinct>.

183 Future Food Systems (2021) WA Food Innovation Precinct to drive growth in premium value-added foods. Viewed 20 December 2021, <https://www.futurefoodsystems.com.au/new-wa-food-innovation-precinct-to-help-produce-premium-value-added-food-products-in-australias-west/>.

184 Government of South Australia (2021) $2 million investment to grow SA plant-based food sector. Viewed 22 Oct 2021, <https://pir.sa.gov.au/alerts_news_events/news/ministerial_releases/$2_million_investment_to_grow_sa_plant-based_food_sector>

2022-2030 science, technology and infrastructure investment priorities

Scaling up processing infrastructure: Scaling up plant-based product facilities will be necessary to capture a greater share of the growing demand domestically and globally. This includes scaling extrusion capacity for creating TVP. The industry could benefit from economies of scale in production and distribution.[185] Multi-faceted plant-based ingredient facilities for plant-based isolates, concentrates and fibres could be established.

Services and skills to support food manufacturers and start-ups: Food manufacturers and start-ups should be supported with access to capability and expertise. Expertise may be required in the realms of food technology, regulation, or commercialisation. Programs could take the form of accelerators, incubators and support teams; and could support branding, marketing, and relationship building with companies with established supply networks. The AgTech and Logistics Hub, funded by the Queensland Government, the FKG Group, Toowoomba and Surat Basin Enterprise, University of Southern Queensland and the University of Queensland, is an example of an initiative to connect stakeholders and support innovation. The WA Agri-Business Grant is an initiative of the Western Australian Food Innovation Precinct for WA-based agribusiness and enterprises to support the scale-up of food and beverage manufacturing.[186] Venture capital has been cited as a useful sector to connect start-ups with commercial and regulatory expertise, capital, and connections to supermarkets. More broadly, CSIRO's Kick-Start program is an initiative that offers funding and research expertise to start-ups and SMEs to research new ideas, test products and develop their business.[187]

Investment in collaborative R&D and prototyping facilities: Food manufacturers and start-ups need facilities to test and prototype new products. This could take the form of a shared R&D facility for various food start-ups to hire and use, with links to universities and research institutes to access talent and R&D expertise. Such a pilot facility could take the form of a Centre of Excellence dedicated to plant proteins, where plant-based product development and protein ingredient R&D can be conducted together. This pilot facility could be located adjacent to planned plant processing industry, or embedded within research institutions to enable greater collaboration with the research sector.

185 Food Frontier (2021) 2020 State of the Industry Australia's Plant-Based Meat Sector.

186 Shire of Murray (2021) $3.8M Grant Open for WA Agri-Businesses. Viewed 20 December 2021, <https://www.murray.wa.gov.au/Shire-and-Council/News-and-Media/Media-Releases/3.8M-Grant-Open-for-WA-Agri-Businesses>.

187 CSIRO (2021) CSIRO Kick-Start. Viewed 21 January 2022, <https://www.csiro.au/en/work-with-us/funding-programs/programs/csiro-kick-start/about>.

Facilities required cut across the plant protein value chain, from plant-based ingredients and fibres to plant-based products. Systems at various scales are required, from laboratory to pilot plant and small scale manufacturing facilities. Technologies needed include decanting, separation, extrusion and extraction technologies. Plug and play modules would allow start-ups to test and develop products confidentially. Collaboration between manufacturers, research and industry could accelerate new technology development and uptake. Collaborations should consider models for ownership stake conditions between involved parties. Some existing and planned food innovation centres are described in Table 4.

Establish domestic ingredient supply chains: One of the most frequently cited priorities by consulted stakeholders was the establishment of local production capabilities for plant-based ingredients. Currently, plant proteins and many other ingredients used in plant-based foods (such as soy protein) are produced offshore and imported by Australian food manufacturers. This can present risks associated with quality, lead times, and logistics of offshore purchasing. Establishing domestic ingredient supply chains could secure more reliable supply for growing ingredient demand, potentially reduce costs, reduce environmental footprint, and provide a high-value revenue stream to Australian farmers and plant processors. Local value chains can also have benefits associated with Australian Made labelling and improved country-of-origin claims. It could also allow closer collaboration between ingredient producers and food product manufacturers. To meet protein growing protein ingredient needs, increasing targeted crop production or imports may be required. Reaching economies of scale for both plant-based products and protein ingredients will be important for reaching competitive prices.

Invest in plant-based product R&D: There is opportunity to develop higher quality plant-based products with improved taste, texture, function, nutritional profile and in some cases allergenicity. Additionally, production costs could be reduced to draw closer to price parity with conventional animal meat offerings. R&D priorities vary based on the desired outputs and the crop inputs used. Broadly, priorities include:

- Product flavour, odour, texture, appearance and tribology (mouthfeel) of products. Improved taste including reduction of beany notes and flavours (or minimising bitter or metallic aftertaste)**.** Improved texturisation for plant-based products, e.g., extrusion technologies, shear, low moisture and high moisture extrusion cooking, strip alignment technologies for creating fibrous structures.
- Nutrition, composition and functionality of ingredients. This includes fortification, for example with minerals and vitamins that are typically only found in high quantities in meat, dairy and egg products. Reduction of antinutritional components, e.g., alkaloids and glucosinolates. Reduction in cost and complexity of additives, including sodium. Food safety and risk assessment testing including shelf-life evaluation alongside microbiological, chemical or physical hazards.
- Optimising crops to remove unwanted elements and improve desirable elements; and improving crop processing technology to allow whole grain utilisation of macro and micronutrients.
- Industry 4.0 principles and technologies across the supply chain and in factories, such as automation, robotics, IoT, deep learning and analytics.

Aside from texturisation, the priorities for plant-based dairy and egg products are similar to those of plant-based alternatives to meats. Despite being an established industry, product innovation for plant-based milks continues. In February 2021, for example, Sanitarium collaborated with UNSW to develop oat and almond milks with improved silkiness and foaminess.[188]

188 Cooperative Research Australia (2021) Using science to make better vegan café lattes. Viewed 10 November 2021, <https://crca.asn.au/using-science-to-make-better-vegan-cafe-lattes/>.

CASE STUDY

Plant-based protein ingredients and crop inputs

This case study seeks to estimate the volume of raw plant-based protein ingredients and crop inputs required to produce the finished plant-based products outlined in Opportunity 2.

Assuming plant-based proteins make up, on average, 20% of finished plant-based products by weight,[189] then **60,000 tonnes** of raw plant-based proteins will be needed in the conservative scenario, and **180,000 tonnes** will be needed in the ambitious scenario.

These plant-based proteins will require plant-based protein ingredients, such as texturised plant protein (TPP), as well as isolates, concentrates and flours. These ingredients will, in turn, be derived from crop inputs. Both ingredients and crop inputs are sourced from domestic or imported sources.

Types of plant-based protein ingredients required

Globally plant-based protein products retail market by four major ingredient types: soy protein, wheat protein, pea protein, and other.[190] In 2020, soy accounted for nearly 58% of the market share by value, while wheat protein accounted for nearly 37%, pea protein and others over 5%. By 2030, soy is likely to grow to 60% of the market, wheat 33%, and pea and other 7% (Figure 4).

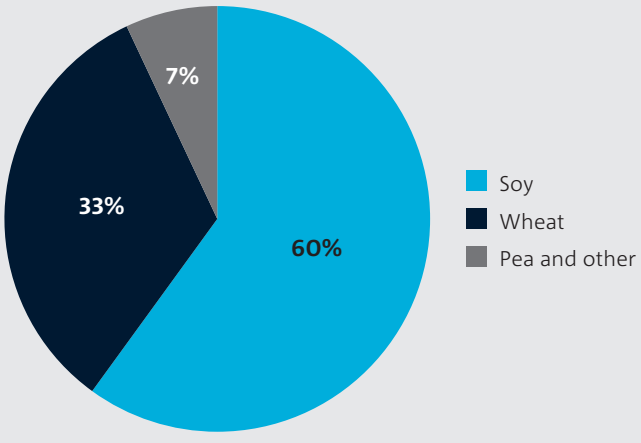


Figure 4: 2030 Global market share of major plant-based protein alternatives by protein type

Source: Technavio (2021) Global Plant-based Protein Products Market 2021-2025, own calculations.

Global market shares for these crop ingredients have been applied to Australia's 2030 manufacturing share by tonnage in the conservative and ambitious scenarios, producing a breakdown of types of plant-based protein ingredients required. It is assumed here that international usage splits apply for the Australian sector and that Australia pulse proteins can address forecast demand in the 'pea and other' category.

Under the conservative and ambitious scenarios, if domestic manufacturers were to produce plant-based finished products using ingredients from local sources, they would need the following amounts of pure protein by weight as noted in Table 5. For instance, for Australian domestic manufacturers under the conservative scenario to produce 60% of their finished plant-based products from soy protein, they will require 36 kt of pure soy protein.

Table 5: Amount of plant-based protein required in ambitious and conservative scenarios

PURE PLANT-BASED PROTEIN	CONSERVATIVE SCENARIO (60,000 TONNES OF PROTEIN IN TOTAL)	AMBITIOUS SCENARIO (180,000 TONNES OF PROTEIN IN TOTAL)
Soy protein	36 kt	108 kt
Wheat protein	19.8 kt	59.4 kt
Pulse protein	4.2 kt	12.6 kt

189 Benchmarked from desktop research into protein percentages by weight for retail meat products.

190 Technavio (2021) Global Plant-based Protein Products Market 2021-2025.

Crops/products required

Based on these pure protein amounts described above, it is possible to estimate the actual crop/product amounts that would be needed. Table 6 describes average protein proportions that were used to model and estimate this.

Table 6: Nutritional composition of crop/product types

CROP/PRODUCT TYPE	PROTEIN (%) BY WEIGHT	SOURCE
Raw soybean seeds	37%	Based on USDA data[191]
Wheat grain	10%	Conservative benchmark from protein content in Australian wheat grades[192]
Raw pulse seeds	24%	Average from nutritional composition data in Fernando (2021)[193]

Based on these protein proportions, this translates to the following amounts of the raw product/crop in Table 7. For example, to create 36 kt of soy protein under the conservative scenario (see Table 5 above), this will require nearly 99 kt of raw soybean seeds.

Table 7: Amount of raw product required in ambitious and conservative scenarios

CROP/PRODUCT TYPE	CONSERVATIVE SCENARIO	AMBITIOUS SCENARIO
Raw soybean seeds	98.6 kt	295.9 kt
Wheat grain	198 kt	594 kt
Raw pulse seeds	17.2 kt	51.5 kt

For context, Australia produced only 31 kt of soybeans per year on average for the five years to 2019-20.[194] If Australia were to derive all its soy protein from domestic sources, current production is insufficient for both the conservative and ambitious scenarios.

A significant scale-up of domestic soybean cropping, imports of soy protein ingredients, alternative protein crops, or a mixture of these options would be required to meet the manufacturing needs by 2030. The potential for significant and effective scale-up of domestic soybean crops could be explored. Further investigation could be conducted into soybean import sources (e.g., from sustainable and/or non-GM sources to address consumer concerns), as well as further investigation into plant-based alternatives to soy protein that are still comparable to soybeans in terms of features such as taste, texture, and functionality.

Similarly, for context, domestic production of wheat in Australia was 21,559 kt per year on average for the five years to 2019-20,[195] and domestic production of all pulses was 2,780 kt per year on average for the five years to 2019-20.[196] Further, Australia currently has capacity to commercially process at least 10,000 tonnes of faba beans per year and produce at least 2,500 tonnes of pulse protein isolate, with capacity expected to double soon.[197] As such, the domestic pulse protein requirements under the conservative scenario will likely be easily met.

Given Australia's major role in the production of both of these crop types, in a hypothetical scenario where Australia derives a significant amount of its wheat and pulse protein domestically for food manufacturing purposes, there would be sufficient supply currently to meet 2030 domestic manufacturing needs.

191 United States Department of Agriculture (2019) FoodData Central – Soybeans, Mature Seeds, Raw. Viewed 20 December 2021, <https://fdc.nal.usda.gov/fdc-app.html#/food-details/174270/nutrients>.

192 GRDC (2009) Understanding Australian Wheat Quality: A Basic Introduction to Australian Wheat Quality.

193 Fernando, S (2021) Production of protein-rich pulse ingredients through dry fractionation: A review. LWT 141.

194 United States Department of Agriculture (2021) Production, Supply and Distribution data.

195 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data: Rural commodities – wheat.

196 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data: Rural commodities – pulses.

197 GRDC (2019) New $20m facility set to deliver value-adding alternative to traditional pulse markets. Viewed 20 December 2021, < https://groundcover.grdc.com.au/crops/pulses/plant-based-protein-start-up-provides-new-pulse-market-option>; Food & Drink Business (2021) Australian Plant Proteins secures $45.7m investment. Viewed 20 December 2021, < https://www.foodanddrinkbusiness.com.au/news/australian-plant-proteins-secures-45-7m-investment>.

1.5 Developing novel protein production systems

Identifying new methods for producing protein through targeted investments in R&D and infrastructure will continue to be important in capturing value, optimising resources, and leveraging Australia's comparative advantages. Innovative R&D is currently underway to enable the scale-up and commercial development of many new protein production systems, from traditional fermentation and large-scale biomass fermentation through to cultivated meats, microalgae and using new and different feedstocks, such as CO_2 (see Appendix E for other emerging protein opportunities).

These novel production systems will become more important as greater pressure is placed on global food systems to feed more people with less resources. Food security solutions need to address both accessibility and affordability of new products. Looking out to 2030, Australia has the reputation, skills, and most importantly, the primary resources (e.g., agricultural waste from sugar, wine, fruit, etc.) to catalyse novel protein production systems to service domestic and export markets.

This roadmap focuses on two of the key opportunities for novel protein production systems in Australia, identified through literature review and industry consultation. These opportunities involve the creation of new Australian value chains for protein from **precision fermentation** and, over the long term, from **cultivated meats**.

Synthetic biology (the application of engineered biological solutions to industrial, health and environmental challenges) is an area of strategic focus in Australia, which encompasses precision fermentation and cultured meat techniques. CSIRO's Synthetic Biology Roadmap (2021) describes many actions and investments that are necessary for Australia to capture economic growth by positioning synthetic biology as a critical national capability that underpins a thriving domestic bioeconomy.[198] The actions described in this report, particularly the short-term actions around building capability and demonstrating commercial feasibility, will support the realisation of synthetic biology opportunities.

Opportunity 9: Precision fermentation

2030 opportunity

To expand the volume and variety of protein ingredients and products commercially produced via precision fermentation for both domestic and export markets.

Potential market size

Current state
- Negligible

Conservative 2030 scenario
- $750 million in product value
- $374 million in manufacturing revenue
- 670 jobs

Ambitious 2030 scenario
- $2.2 billion in product value
- $1.1 billion in manufacturing revenue
- 2,020 jobs

*Difference between conservative and ambitious scenarios: **$1.45 billion** in retail value*
(See Appendix D for the economic methodology.)

Science, technology and infrastructure priorities

- Investigate and support pilot scale facilities
- Support collaboration with adjacent sectors and infrastructure for precision fermentation scale-up
- Services for precision fermentation scale-up
- Research to support microorganism engineering and strain development and optimisation
- Research to support feedstock selection, optimisation, and process improvement
- Research to understand manufacturer and consumer needs
- Life Cycle Analysis to understand impact
- Research to understand nutritional profile of precision fermentation products
- Precision fermentation product development

198 CSIRO Futures (2021) Australia's Synthetic Biology Roadmap. CSIRO, Canberra.

What is driving this opportunity?

Precision fermentation has the potential to supply diversified protein into the global food system. There are three categories of fermentation: traditional fermentation transforms food through the metabolic activities of microorganisms; biomass fermentation cultivates microorganisms as the primary protein source (e.g., Quorn™ made from filamentous fungi via fermentation); and precision fermentation which uses customised microorganism strains (e.g., bacteria and yeast) to produce specific functional ingredients. The stated advantages of precision fermentation are that specific proteins possessing desirable attributes, novel and complex ingredients can be produced fast and in large volumes, using significantly less water and land resources.[199] As an example, animal proteins can be produced that offer the full nutritional profile without undesirable substances, such as cholesterol and allergens.

While precision fermentation processes are not new, cost efficient production at scale is a key barrier and it is not yet commercially viable to produce commodity ingredients as the costs are not competitive with incumbent production methods. [200] It is estimated that the cost of precision fermentation is at least two to three times more than that of conventional proteins.[201] Despite this, it is currently used for niche high-value food ingredients and pharmaceutical products, such as chymosin (the key ingredient in rennet), used in the cheese industry which traditionally came from the rumen of calves, and the pharmaceutical protein insulin, which traditionally came from the pancreas of cows or pigs.

Key cost factors for precision fermentation include appropriately sized fermentation equipment to produce protein at scale.[202] Following this, energy, staff, facilities, feedstock, and downstream processing all need to be considered. As the costs of precision fermentation are driven down, through advancements in technology, market demand and large-scale developments, it is expected that protein (and other functional ingredients) created through this method will reach price parity with animal proteins.[203]

Globally, there is significant momentum in the sector, with increasing venture capital investments in protein fermentation companies,[204] and numerous companies working towards commercialising products. Investors see opportunities for fermentation to revolutionise modern protein production while building a healthier, more efficient, and sustainable global food system.[205] Examples of international companies include (non-exhaustive):

- Every Company (formerly Clara Foods) using precision fermentation to create egg proteins[206]
- Impossible Foods making plant-based heme via fermentation of genetically engineered yeast[207]
- Motif FoodWorks using precision fermentation to create HEMAMI, a yeast-derived heme protein that provides umami flavour and meaty aroma to plant-based meat products[208]
- Perfect Day using precision fermentation to make whey proteins that have been commercialised through three ice cream brands in the US.[209]

199 Tubb C and Seba T (2021) Rethinking Food and Agriculture 2020-2030: The Second Domestication of Plants and Animals, the Disruption of the Cow, and the Collapse of Industrial Livestock Farming. Industrial Biotechnology 17(2), 57–72.

200 Wood P and Tavan M (2021) Feed Our Future: A New Zealand Sustainable Food Systems Dialogue. Official Journal of the New Zealand Association of Scientists 77(3–4).

201 Boston Consulting Group and Blue Horizon (2021) Food for Thought: The Protein Transformation.

202 Wood P and Tavan M (2021) Feed Our Future: A New Zealand Sustainable Food Systems Dialogue. Official Journal of the New Zealand Association of Scientists 77(3–4).

203 World Economic Forum (2020) Fermentation can help build a more efficient and sustainable food system – here's how. Viewed 16 November 2021, <https://www.weforum.org/agenda/2020/11/fermentation-can-help-build-a-more-efficient-and-sustainable-food-system-here-s-how/>.

204 World Economic Forum (2020) Fermentation can help build a more efficient and sustainable food system – here's how. Viewed 16 November 2021, <https://www.weforum.org/agenda/2020/11/fermentation-can-help-build-a-more-efficient-and-sustainable-food-system-here-s-how/>.

205 World Economic Forum (2020) Fermentation can help build a more efficient and sustainable food system – here's how. Viewed 16 November 2021, <https://www.weforum.org/agenda/2020/11/fermentation-can-help-build-a-more-efficient-and-sustainable-food-system-here-s-how/>.

206 The EVERY Company (n.d.) Home. Viewed 16 November 2021, <https://theeverycompany.com/>.

207 Impossible Foods (n.d.) Heme + The Science Behind Impossible. Viewed 30 November 2021, <https://impossiblefoods.com/au-en/heme>.

208 Dacri J (2021) Motif FoodWorks Announces the Commercial Launch of HEMAMI™, Food-Tech earns Generally Recognized as Safe (GRAS) Status from FDA. Viewed 21 January 2022, <https://madewithmotif.com/2021/12/08/motif-foodworks-announces-the-commercial-launch-of-hemami-food-tech-earns-generally-recognized-as-safe-gras-status-from-fda/>.

209 Perfect Day (2021) Find Us. Viewed 16 November 2021, <https://perfectday.com/find-us/>.

A commercially sponsored Life Cycle Analysis (LCA) on Perfect Day's whey protein found that compared to the total protein in milk, its product is 91% to 97% lower in greenhouse gas emissions, 29% to 60% lower energy demand, and 96% to 99% lower in blue water consumption.[210]

Precision fermentation supports the global ambition to sustainably meet protein demand and will result in an augmented food production system. There is increasing momentum in the development of this technology with unique applications. Australia is already investing in this area. Several companies have recently been established in Australia with the goal of scaling up precision fermentation to create novel ingredients. Supporting these companies and nurturing new opportunities in this space is essential to ensure Australia keeps pace with international counterparts and does not become reliant on imports of these products. Dedicated industry development leveraging Australia's comparative advantages could even see Australia set the pace.

Critical to precision fermentation-derived proteins reaching price, texture and taste parity with animal proteins is R&D and strategic investment towards achieving necessary scale. Cost will be reduced from increased efficiency in how microorganisms convert feedstock into protein, and the adoption of low-cost feedstocks.[211] Developing pilot, demonstration, and commercial-scale biomanufacturing facilities certified to work with GMOs in food grade facilities is an expected bottleneck, and a key requirement for the scale-up of precision fermentation (and other synthetic biology applications) in Australia, as identified in CSIRO's Synthetic Biology Roadmap.[212]

Australia's comparative advantages

Australia has strong comparative advantages with its large agricultural industry that provides a readily available source of feedstock. Agricultural waste from wine, fruit and sugar industries can be valuable inputs into fermentation. Australia's strong agricultural reputation and proximity to Asian export markets will also be an advantage in the development of new exports.

Regional opportunities

Industry consultation for this project highlighted distinct development opportunities for Australia's industry. This includes strategically developing the industry in a way that deliberately incorporates greater circularity of fermented products, either by co-fermenting products in a single fermentation tank or using by-products of one process as the feedstock for another. Further, co-location at existing fermentation businesses (e.g., wineries, breweries) could be a useful step in the scale-up of the industry, helping further utilise existing assets that may be idle during the year.

Implications for the Australian agricultural and food system

Developing Australia's precision fermentation capability and industry will support the creation of new skilled jobs. Further, it offers value-adding opportunities for utilisation of agricultural biomass and waste products as feedstocks,[213] with resulting products (generally ingredients) feeding into and diversifying Australia's current food manufacturing industry.

As precision fermentation theoretically allows for the manufacture of any complex ingredient, including proteins traditionally sourced from animals, it is possible that once parity in price and composition is achieved, the precision fermentation industry could help meet demand for traditional animal proteins. Alternatively, precision fermentation can also be deployed to produce specific ingredients that are harder to source in nature, or where extraction yields a high volume of side stream and thus renders isolation and purification resource-inefficient. Such developments will allow Australian food manufacturers access to Australian-made ingredients beneficial for manufacturing processes (processing aids) or as desirable ingredients for new product development. Nature-equivalent molecules will be the initial precision fermentation targets, but it is anticipated that in the future machine learning/ artificial intelligence (ML/AI) combined with precision fermentation will likely start to deliver novel ingredients.

210 Perfect Day Inc (2021) ISO-Conformant Report: Comparative Life Cycle Assessment of Perfect Day Whey Protein Production to Dairy Protein.

211 Boston Consulting Group and Blue Horizon (2021) Food for Thought: The Protein Transformation.

212 CSIRO Futures (2021) Australia's Synthetic Biology Roadmap. CSIRO, Canberra.

213 Good Food Institute (2020) State of the Industry Report: Fermentation.

Existing infrastructure and R&D underpinning opportunity

Precision fermentation is an emerging industry, supported by food, biotechnology and synthetic biology research themes across various research organisations, including CSIRO and universities.

Current infrastructure for precision fermentation is mainly for use in pharmaceutical applications. Generally, these are over-engineered for food production, and are limited in capacity and quantity. There is currently limited infrastructure available in Australia at any scale. Lab and pilot scale infrastructure is important to enabling growth of the industry. Large scale production infrastructure is a major issue worldwide, with some estimates that existing fermentation infrastructure will be at capacity during 2022.[214]

Infrastructure requirements for precision fermentation include:

- Pilot (<1,500L), demonstration (<100K L) and commercial (>100K L) scale food grade PC2 fermentation facilities. These facilities are generally stainless-steel fermentation tanks with precise control systems for processing conditions. They may be self-contained to avoid contamination and require precise control over parameters such as oxygenation, temperature and pH.
- Downstream processing equipment for separation and purification includes continuous centrifugation, spray and freeze dryers, separation units, chromatography, etc. These are all available technologies.
- Supply chain infrastructure for transport and logistics (e.g., rail, road and ports), in particular to enable efficient delivery of feedstock.

2022-2030 science, technology and infrastructure investment priorities

Investigate and support pilot scale facilities: Suitable pilot scale food grade fermentation infrastructure is very limited in Australia, especially food grade facilities that can handle genetically modified organisms (GMO), such as modified yeast strains. Opportunities exist for the development of commercial pilot scale food fermentation facilities at strategic locations across the nation (close to feedstock sources), e.g., as a Bio-incubator – this might be through public investment via universities, publicly funded research agencies or public private partnerships.

Support collaboration with adjacent sectors and infrastructure for precision fermentation scale-up: Suitable large-scale food grade fermentation infrastructure that is compatible with GMOs does not exist in Australia. Building and operating these large-scale facilities will have significant associated costs and depreciation costs will also need to be considered. There are opportunities to support and facilitate collaboration with adjacent fermentation industries (e.g., wineries, breweries) to investigate opportunities for collaboration and asset sharing. Further, investigation should be undertaken to assess the feasibility of collaborative large-scale precision fermentation infrastructure (fermentation complexes) that enables co-location of multiple food companies, with deliberate circularisation of supply chains enabling companies to service each other. Considerations include shared feedstocks, access to local transport infrastructure, regional development, and recycling of waste including spent biomass into other industries. These activities could be facilitated by a dedicated industry development organisation or as part of an industry sponsored research, development and demonstration project.

214 Werner M (2021) Commercial fermentation: Opportunities and bottlenecks – webinar via The Good Food Institute.

Services for precision fermentation scale-up: Scale-up from lab scale to commercial scale is a huge challenge for start-ups. As an emerging industry, pioneering companies are each overcoming similar issues with little ability to learn from each other. The industry would benefit from the establishment of collaboration/service hubs and Bio-incubators (which may be co-located with the pilot scale facilities mentioned above) that provide business services to companies to help them sustainably scale-up. This includes bringing in experts who understand scale-up, such as supply chain facilitation, product development, operations, downstream processing, regulation and access to research expertise. These collaboration hubs could also host and run precision fermentation focused innovation accelerators.

Research to support microorganism engineering and strain development and optimisation: High-value ingredients are possible through the innovative engineering of microorganisms. Research is required to develop these microorganisms for optimised yield and efficient protein production at both small and large scale. Strains that use alternative feedstocks to refined sugars are also important. New microorganisms could be developed as platform strains.

Research to support feedstock selection, optimisation, and process improvement: Australia has an opportunity to lead in the development of precision fermentation that deliberately incorporates reuse and circularity principles. An investigation of the feasibility of co-fermentation candidates could occur with the goal of enabling two or more products to be fermented at the same time. Feedstock could be further optimised, with research into options for low-cost feedstocks, including functionality of uniquely Australian or regional feedstocks (e.g., sugarcane regions in Queensland offering unique advantages), low-cost industrial (e.g., food waste) or agricultural side streams or waste streams. Fermenter design and downstream processing are also important research areas to improve efficiency, enable real time process control and improve protein extraction. The feasibility of continuous processing should be investigated, alongside the functionalisation of waste biomass with the goal of engineering waste for new uses (e.g., inputs for other precision fermentation activities and higher value secondary uses).

Research to understand manufacturer and consumer needs: Understanding desired ingredients, functionality and market differentiation required by food manufacturers is important for ensuring the right proteins are targeted for development by this emerging industry. Having these conversations upfront is important. Further, consumer acceptance is not guaranteed, requiring research into the factors that impact social licence to operate alongside sensory evaluation and taste preferences of novel foods.

Life Cycle Analysis to understand impact: As technologies mature and reach commercially readiness, Life Cycle Analyses will be important to accurately assess any commercial, environmental and social benefits of the technology.

Research to understand nutritional profile of precision fermentation products: Knowledge gaps remain for precision fermentation outputs. Nutritional evaluation on products and ingredients is needed including bioavailability, allergenicity, digestibility, and bioequivalence of products. This is an important consideration should consumers move from obtaining nutrition from wholefoods wherein other micronutrients are included, to the inclusion of specific proteins in a reconstructed product. Milk is a clear example that could be assessed with nutritional and sustainability lenses applied. Research is required to support and demonstrate nutritional claims.

Precision fermentation product development: Development of consumer products and ingredients requires industry-led research to develop low-cost functional additives that improve the taste, texture, and nutritional value. Machine learning and artificial intelligence can be used to develop and deliver novel ingredients. Establishing precision fermentation locally will provide food manufacturers access to a stable supply of Australian-made ingredients that allow the creation of products that possess market differentiated attributes that can compete in domestic and export markets.

CASE STUDY

Precision Fermentation feedstock and infrastructure requirements by 2030

This case study seeks to estimate the feedstock and infrastructure required to produce protein via precision fermentation outlined in Opportunity 9.

Feedstock

Assuming that a protein product is 20% protein by weight, this implies that precision fermentation facilities will produce 15,000 tonnes of actual raw protein in the conservative scenario, and 45,000 tonnes of raw protein in the ambitious scenario.

In terms of inputs, precision fermentation efficiency is trending from 3kg of feedstock per 1kg of protein to a conversion ratio of less than 2:1 by 2030.[215]

Taking a mid-point of 2.5:1 for the purposes of this modelling, over **37,000 tonnes** of sugar are needed to reach the roughly 15,000 tonnes of protein for Australia in the conservative scenario. For the ambitious scenario, over **112,000 tonnes** of sugar are needed.

For context, Australian sugar production was 4,283 kt.[216] Therefore, the conservative scenario represents approximately 1% and the ambitious scenario represents approximately 3% of current domestic sugar production.

Infrastructure

Assuming a benchmark yield of 10 grams of protein per litre and a fortnightly production run per fermenter (26 cycles per year),[217] the calculations suggest that approximately 58 million litres of bioreactor capacity will be required for the conservative scenario. Assuming that the fermentation tanks are in the 500,000 L range,[218] this means that around **115 large-scale fermentation tanks** will be necessary. It should be noted that each individual commercial facility could contain a number of these commercial fermenters in the 500,000 L range.

For the ambitious scenario, total bioreactor capacity required increases to nearly 173 million litres of bioreactor capacity and, again assuming fermentation tanks in the 500,000 L scale, this would mean the need for around **350 large-scale tanks**.

It should be noted that the benchmark of 10 grams of protein per litre is an uncertain variable. Should precision fermentation performance of, for instance, 20 grams of protein per litre be realised in 2030, this would halve the bioreactor and fermentation tank requirements listed above.

It should also be noted that aside from the fermentation tanks themselves, a number of other pieces of capital are required in a commercial precision fermentation facility, including:

- measuring devices
- cooling systems
- cleaning and sterilisation systems
- equipment for introducing sterile air, inoculum, feedstock, and other inputs
- centrifuges for removing waste material
- micro- and ultra-filtration systems to isolate molecules and media
- spray dryers to produce the target protein.

Many of these pieces of equipment are energy intensive and the bioreactor process is likely to be highly energy intensive as a whole. Therefore, in order for precision fermentation to align with sustainability principles and to engender social acceptance, the sector may need to integrate renewable energy sources into its processes.

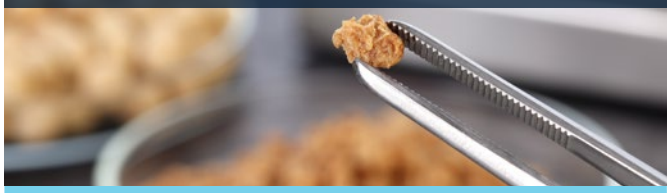
215 RethinkX (2020) Rethinking Food and Agriculture 2020-2030

216 Australian Bureau of Agricultural and Resource Economics and Sciences (2020), Agricultural commodity statistics 2020, Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra, December.

217 As suggested in Wood P and Tavan M (2021) Feed Our Future: A New Zealand Sustainable Food Systems Dialogue. Official Journal of the New Zealand Association of Scientists 77(3–4).

218 Upper limit on fermenter size informed by Werner M (2021) Industrial Biotechnology Commercialization Handbook.

Opportunity 10: Cultivated meats



2030 opportunity

To progress Australian R&D on cultivated meat products, with clear regulatory pathways for domestically produced cultivated protein products.

Potential market size

*The global opportunity for cultivated meats has been estimated at **$26 billion** by 2030. It is currently unclear to what degree Australia will be able to capture this global opportunity. (See Appendix D for data sources).*

Science, technology and infrastructure priorities

- Optimise cell culture media
- Identify cell sources for cultivated meat
- Cultivated meat product development
- Research to support food safety
- Research to inform bioprocess development
- Research to understand consumer preferences

What is driving this opportunity?

Cultivated meat is a frontier in food technology – an emerging source of protein enabled by innovative research and development. Australia is very much at the beginning of its venture into cultivated meats, with four companies working on various aspects of the supply chain. Given its early-stage nature, the Australian opportunity out to 2030 is unlikely to be mass market products, but rather improved technology readiness through R&D, with select niche, high-value commercial applications. High-end restaurants are likely to be the first channel to market, with mass market availability further away.[219] Developing Australia's capability to produce cultivated meat can support the creation of a new industry, new skilled jobs, and attraction of overseas investment. Failing to develop Australian expertise and capability in this area will result in the nation importing knowledge and products over the long term.

Known by many names, including cell-based meat, cell cultured meat, *in vitro* meat, lab grown meat, clean meat, etc., the concept involves the creation of animal cell-based proteins using tissue engineering concepts. Cultivated meat from any animal can theoretically be created, including high value seafoods like eel or products where sustainable sourcing is challenging.

Driving this opportunity is consumer concerns about the environment, animal welfare, food security and food safety. The prerequisite of this technology is the harvest of cells from an animal to start the culture. Cultivated meat is attractive to consumers wanting a product biologically identical to meat but who have concerns about animal welfare or environmental impacts. Cultivated meats may also be safer than traditional meats as they avoid potential contamination that can happen at slaughter by intestinal pathogens such as *Salmonella* and *Campylobacter*, and the controlled lab environment and close monitoring can easily address signs of infection.[220] Cultivated meat may also have health benefits as its nutritional content can be controlled during its production, but it should be noted that this represents a reformulated product and nutrition should be considered from a wholistic perspective including energy density, presence of macro- and micronutrients, and nutrient availability. For example, saturated fats can be replaced by omega-3 fats, and other nutritious micronutrients such as iron can be added.[221]

Much work is required to see cultivated meats on shelves, both from a technology perspective as well as industry development. This includes understanding elements that impact the social acceptance of these products and generation of trusted data about the environmental impacts of cultivated meat. High energy usage may detract from social acceptance, driving the need for cultivated meat production to integrate renewable energy sources.[222] Final product form and nutritional equivalence are also perceived barriers to adoption, with consumers largely attached to traditional cuts of meat.

219 Warner R (2019) Review: Analysis of the process and drivers for cellular meat production. Animal 13(12), 3041–3058.

220 Chriki S and Hocquette JF (2020) The Myth of Cultured Meat: A Review. Frontiers in Nutrition 7, 7.

221 Chriki S and Hocquette JF (2020) The Myth of Cultured Meat: A Review. Frontiers in Nutrition 7, 7.

222 Lynch J and Pierrehumbert R (2019) Climate Impacts of Cultured Meat and Beef Cattle. Frontiers in Sustainable Food Systems 3, 5. DOI: 10.3389/FSUFS.2019.00005/BIBTEX.

Cultivated meat products are beginning to be commercially available but scale-up, production cost and getting the texture right are still considerable challenges. In December 2020, the Singapore Food Agency approved Eat Just's cultivated chicken nugget product enabling the company to start selling commercially.[223] Eat Just's facility is currently 1,000L and needs to scale to more than 50,000L to make a profit, which is likely to take several years. Currently its chicken nugget product is priced on par with organic chicken and sold in limited restaurants (for approximately SGD $23[224]), resulting in the company taking a loss.[225] Singapore-based Shoik Meats is another company planning to commercialise cultured meat products, with plans to sell cell-based shrimp in 2023 at a cost of SGD $50/kg. As the company grows and scales, it anticipates a price point of between SGD $5 to $10 per kilogram over the next five to seven years.[226] There are at least 80 companies working on cultivated meat and seafood globally. Some of these companies are working on the full cultivated meat production process, while others are specialising in a part of the process, such as optimising the culture media or developing scaffolds.[227]

Australia's comparative advantages

Australia has significant research expertise to call upon for this opportunity, including food engineers, meat scientists and stem cell research groups across various universities and publicly funded research agencies (see below). Networks are forming in Australia that demonstrate support towards the opportunities presented by cultivated meat (e.g., Cellular Agriculture Australia).

Regional opportunities

R&D to support this opportunity can be carried out at any research agency or university, including rural laboratories. Commercial development of this opportunity is mostly location-agnostic.

Implications for the Australian agricultural and food system

Cultivated meat is not expected to measurably displace global conventional meat consumption[228] before 2030.

Existing infrastructure and R&D underpinning opportunity

Biologically equivalent cultivated meat products are created by taking a starting cell from a living animal and then producing subsequent cell lines without further need for animal involvement.[229] The cells are added to a bioreactor and fed cell culture media to proliferate into potentially thousands of kilograms of resulting muscle and/or fat cells which are then structured in 3D scaffolding materials into cultivated meat products.[230]

Stem cell research is a key underpinning research theme for cultured meats, alongside synthetic biology and traditional food engineering and meat science. Induced pluripotent stem cells (iPSC), culture techniques and associated media, and scaffolds and product form are some key areas of underpinning research. A few select universities have relevant research themes and labs, such as the University of Melbourne through its Future Food Hallmark Research Initiative and the University of New South Wales.

Infrastructure requirements for scale-up need to be anticipated based on the expected final product form, associated R&D and manufacturing techniques. Bioreactors that generate controlled environments suitable for culture will likely be used at high densities and volumes. Supporting this will be infrastructure for cell culture media, including media storage tanks and media heat exchangers, alongside scaffold development, which should use materials that are sustainable, consistently available, and have minimal batch to batch variation.[231]

223 Singapore Food Agency Safety of Alternative Protein. Viewed 16 November 2021, <https://www.sfa.gov.sg/food-information/risk-at-a-glance/safety-of-alternative-protein>.

224 New Food Magazine (2021) Lab-grown meat officially on the menu. Viewed 14 December 2021, <https://www.newfoodmagazine.com/news/131310/lab-grown-meat-restaurant/>.

225 Waltz E (2021) Club-goers take first bites of lab-made chicken. Nature biotechnology 39(3), 257–258.

226 Ng J and Amin H (2022) Lab-Grown Shrimp's Price Tag Shows Long Way Ahead to Mass Market. Viewed 21 January 2022, <https://www.bloomberg.com/news/articles/2022-01-03/lab-grown-shrimp-s-price-tag-shows-long-way-ahead-to-mass-market>.

227 Waltz E (2021) Club-goers take first bites of lab-made chicken. Nature biotechnology 39(3), 257–258.

228 Humbird D (2021) Scale-up economics for cultured meat. Biotechnology and Bioengineering 118(8), 3239–3250. DOI: 10.1002/BIT.27848.

229 Stephens N, Di Silvio L, Dunsford I, Ellis M, Glencross A and Sexton A (2018) Bringing cultured meat to market: Technical, socio-political, and regulatory challenges in cellular agriculture. Trends in Food Science and Technology 78, 155–166. DOI: 10.1016/j.tifs.2018.04.010.

230 Gerhardt C, Suhlmann G, Ziemßen F, Donnan D, Warschun M and Kühnle HJ (2020) How will cultured meat and meat alternatives disrupt the agricultural and food industry? Industrial Biotechnology 16(5), 262–270.

231 Allan SJ, De Bank PA and Ellis MJ (2019) Bioprocess Design Considerations for Cultured Meat Production With a Focus on the Expansion Bioreactor. Frontiers in Sustainable Food Systems 3, 44.

2022-2030 science, technology and infrastructure investment priorities

There are numerous technical challenges associated with growing and developing cultivated meat products that must be overcome.

Optimise cell culture media: The cell culture used to grow the products can contain amino acids, salts, sugars, foetal bovine serum (FBS) and signalling molecules, the latter of which is currently very expensive. The use of FBS is also controversial and directly opposed to some of the benefits of cultivated meat to consumer groups (such as reducing animal welfare concerns). For this reason, almost all companies working on cultivated meat are exploring ways to produce their products using FBS-free/animal-free serum. R&D priorities include food grade cell culture media enhancements such as optimisation for improved sustainability, scale-up and cost reduction. Ingredients need to be optimised to reduce the cost of growth factors, reduce carbon footprint of media, and negate reliance on animal-derived products, such as FBS.

Identify cell sources for cultivated meat: Research is required to identify tissue that can provide a sufficiently large number of homogeneous starter cells to conduct effective proliferation and differentiation.

Cultivated meat product development: An important challenge facing the cultivated meat industry is finding scaffolds that mimic the texture of complex meat products such as beef steak or chicken breast. Currently, most products being developed are in basic mince-like forms[232] or hybrid plant and cultivated meat products like meatballs. Development of consumer products requires significant research into perfecting this final form. This includes the development of affordable scaffold biomaterials to enable development of complex tissues and meat structures across different product streams (e.g., seafood, steak, etc). Technology solutions like 3D printing may assist in reaching this final product form but present challenges at scale. R&D is required to improve sensory properties including taste, texture, and mouthfeel to reach parity with traditional proteins. Parity with nutritional attributes, product stability, and digestibility is also required.

Research to support food safety: Although traditional food contamination issues are avoided, there is potential for different foodborne pathogens to be introduced during the production process and subsequent food chain which can introduce different food safety challenges than those associated with animal-based meats. Research is required ensure relevant guidance is provided to inform safe development.

Research to inform bioprocess development: Commercial scale-up of lab-based processes poses unique engineering challenges, requiring research to inform bioprocess development including engineering for metabolic efficiency, bioreactor engineering for commercial scale with adequate microbial contamination safeguards, alongside process automation.

Research to understand consumer preferences: Consumer and social research is required to inform product development including sensory evaluation and taste preferences of novel foods, and research into the factors that impact social licence to operate for cultivated meats. Early adopters of cultivated meat products are likely to be high-end consumers and food services – research can also support industry in understanding what is needed to move from high-end to mainstream segments.

232 Waltz E (2021) Club-goers take first bites of lab-made chicken. Nature biotechnology 39(3), 257–258.

Learnings from Singapore

Singapore is building a reputation as a world leader in the development of non-traditional protein industries and has attracted significant attention and investment in recent years. Spurring this is the Singapore Food Agency's (SFA) '30 by 30', a plan to build the nation's agri-food industry capability and capacity to produce 30% of its nutritional needs locally and sustainably by 2030.[233]

Singapore has a supportive government policy environment focused on sovereign and sustainable food production. Industry development, R&D, innovation and investment are all actively supported, alongside a supportive food safety and regulatory environment. Together with increasing consumer demand, this supportive government environment has attracted widespread investor interest in the protein industry, in particular, for non-traditional proteins.[234] To scale potential growth opportunities, Singapore's business environment includes accelerators and government investment. For example, Singapore's government investment company, Temasek, has invested in alternative protein companies such as CSIRO venture v2food.[235]

While the '30 by 30' plan was developed to increase Singapore's food security and overcome unique conditions, such as land and resource constraints and a high reliance on food imports, the environment that has been nurtured in the country can provide learnings relevant to the Australian context.

- **Investing in R&D for non-traditional protein –** A key theme in Singapore's Food Story R&D Programme is funding the development and scale-up of advanced biotechnology-based proteins such as microbial proteins, plant-based proteins and cell-based meat.[236] The Agency for Science, Technology and Research (A*STAR) plays a key role in food and consumer related R&D.
- **Supporting industry access to new technology –** Singapore established a science and innovation fund to help farmers gain access to new farming system technologies.
- **Developing more efficient on-land aquaculture systems –** Singapore has invested into multi-story Recirculating Aquaculture Systems (RAS) which can be more resource efficient than traditional farming methods.[237]
- **Facilitating start-up growth –** Singapore's multinational food solutions company, SATS, plans to become a one-stop go-to-market platform in Asia for alternative protein start-ups. This includes support for marketing, distribution and potentially co-manufacturing.[238]
- **Supportive regulatory environment –** To balance food safety with innovation, the SFA engages internationally to share novel food management practices, has developed a novel food regulatory framework to guide science-based risk management, and helped establish the Future Ready Food Safety Hub (FRESH) to guide research on food safety and build capabilities locally.[239]

233 Singapore Food Agency (2021) 30 by 30. Viewed 6 December 2021, <https://www.ourfoodfuture.gov.sg/30by30>.

234 Channel News Asia (2021) IN FOCUS: No roaming cattle but with high-tech labs, could Singapore be a 'meat' exporter? Viewed 7 December 2021, <https://www.channelnewsasia.com/singapore/alternative-proteins-plant-based-singapore-companies-in-focus-349626>.

235 Asian Investor (2021) Singapore's Temasek posts strongest returns in 11 years. Viewed 7 December 2021, <https://www.asianinvestor.net/article/singapores-temasek-posts-strongest-returns-in-11-years/471038>.; CSIRO (2019) What's made of legumes but sizzles on the barbie like beef? Australia's new meat alternative. Viewed 24 December 2021, <https://blog.csiro.au/australias-new-meat-alternative/>.

236 Agency for Science Technology and Research (2021) Nationwide Programmes. Viewed 2 December 2021, <https://www.a-star.edu.sg/Research/research-focus/food-nutrition-consumer-care/nationwide-programmes>.

237 Singapore Food Agency (n.d.) Our Singapore Food Story – The 3 Food Baskets. Viewed 22 November 2021, <https://www.sfa.gov.sg/food-farming/sgfoodstory>.

238 Khiu C (2019) Media Release: SATS develops market for sustainable food products in Asia. Singapore.

239 Singapore Food Agency (2021) Balancing Innovation with Safety: Novel Food. Viewed 6 December 2021, <https://www.sfa.gov.sg/food-for-thought/article/detail/balancing-innovation-with-safety-novel-food>.

2 Ecosystem priorities

The broader ecosystem supporting the protein industry is pivotal to its growth objectives over the next decade. Five priorities are identified to guide activities for whole of ecosystem benefit and to monitor progress.

2.1 Producers, communities and regions

Ecosystem objective: Producers, communities and regions recognise the role that the protein industry plays in food production and economic prosperity; and see being part of the Australian protein industry as attractive now and into the future.

Roadmap considerations

Support primary producers with technology adoption, data and insights: Primary producers (farmers) from across each of the focus areas identified need to be supported in the adoption of new advanced technologies to ensure Australia can maintain and grow its position as a global protein provider.

Producers need to be supported in the trial and adoption of new advanced technologies, in particular digital technologies, for greater productivity, efficiency, sustainability, and traceability. Adoption of some of these technologies can help to enable value-based payments for farmers, for example red meat grading can enable justified higher prices for cattle; likewise, technologies that enable segregation of high protein crops will help farmers to earn more.

Data and insights around consumer demand also need to be made readily accessible and useful for farmers, to allow them to meaningfully respond to changing markets and adjust animal or farm management practices accordingly. Examples include seafood demand for aquaculture producers, downstream plant-based protein demand for crop producers, and consumer preferences for red meat derived products. Farmers should be provided with appropriate insights to support their strategic decisions to diversify, for example, into new crops. This could be facilitated by appropriate industry bodies.

Agronomists play a key role in supporting primary producers, especially crop farmers. Ensuring that Australian agronomists are themselves upskilled on appropriate technologies and have an understanding of new production systems across the supply chain is important. This could be facilitated by state governments and tertiary education providers.

Develop an appropriately skilled workforce: Accessing skilled staff is a significant challenge across many parts of the food system, particularly in regional and remote areas of Australia. Developing an appropriately skilled workforce is a priority for many of the opportunities identified, in particular, white flesh fish aquaculture and precision fermentation. The University Research Commercialisation Action Plan that includes Australia's Economic Accelerator, introduction of a National Industry PhD Program, expanding CSIRO's Main Sequence Ventures, and establishment of the Trailblazer Universities Program may provide an avenue forward for universities to help build world-leading industry-ready capability.[240]

- For aquaculture, an investigation into potential changes to the visa system might allow for longer terms and more specialised aquaculture skill categories. Potential changes to semi- and unskilled worker regional migration programs and training and mentoring schemes designed specifically for aquaculture could also be used to support the sector.
- For precision fermentation, finding workers highly skilled in both food and precision fermentation is difficult, with staff either coming from adjacent industries (e.g., pharmaceuticals) with precision fermentation experience but not food experience, or from the food industry with no experience in precision fermentation. Tertiary education providers (universities and TAFE) can help by developing training pathways for new protein industries, including modules on fermentation (traditional, biomass and precision) as well as food-focused synthetic biology. Traditional courses, short courses and micro-credentials are all options that should be explored to build skilled capacity for the industry. Further, the development of mentoring networks that bring together experts from across various relevant fields (science domains, operations, scale-up, product development, safety, business, etc.) can help precision fermentation start-ups access timely expertise needed to grow.

240 DESE (2022) University Research Commercialisation Package. Viewed 28 February 2022, <https://www.dese.gov.au/university-research-commercialisation-package>.

Engage and co-develop with Australian First Nations Peoples: Growth and development of Australia's protein industry, in particular red meat and livestock, aquaculture and insects, represents significant economic opportunities for Indigenous Australians. As Australia's protein industries continue to develop, businesses and industry organisations across all sectors should seek to engage with Australian First Nations Peoples. This may include working with the Indigenous Land and Sea Corporation (ILSC), a Commonwealth entity that assists Aboriginal and Torres Strait Islander people to realise economic, social, cultural and environmental benefits that the ownership and management of land, water and water related rights can bring.[241]

- Australia's red meat and livestock sector is a significant provider of Indigenous employment. In 2016, 1.8% of people directly employed in specialist beef farms identified as Indigenous, with farms in the Northern Territory and north-west Western Australia providing significant employment opportunities.[242] Continuing to explore opportunities for First Nations People beyond employment opportunities will be important for the red meat and livestock industry going forward.
- The development of Australia's insect industry should prioritise Australia's native species, especially those with demonstrated previous use. There are approximately 62,000 native insects, 60 of which have been recorded as a traditional food source for Indigenous Australian People.[243] The emerging industry should be at the forefront of protecting First Nations culture and ensuring that First Nations Peoples have tangible opportunities to lead business enterprises in a way that benefits communities and protects insect species with cultural significance.[244]
- Similarly, Australia's aquaculture industry can provide economic, environmental and social benefits to First Nations Peoples. First Nations peoples have managed Australia's aquatic resources and practised aquaculture for thousands of years.[245] Aquaculture requires a stronger level of recognition of the rights and interests of First Nations Peoples in the management and development of aquaculture in Australia.

241 The Indigenous Land And Sea Corporation (2021) About: The Indigenous Land And Sea Corporation. Viewed 21 January 2022, <https://www.ilsc.gov.au/about/>.

242 Meat & Livestock Australia (2021) State of the Industry Report: The Australian red meat and livestock industry 2021.

243 CSIRO (2021) Edible insects: A roadmap for the strategic growth of an emerging Australian industry. Canberra.

244 CSIRO (2021) Edible insects: A roadmap for the strategic growth of an emerging Australian industry. Canberra.

245 Department of Agriculture and Water Resources (2017) National Aquaculture Strategy. Canberra.

Support the development of regional communities to support agriculture: Most of Australia's current protein industry originates from rural areas of Australia. For example, 90% of the meat and livestock industry's employees and nearly 80% of meat processing employees live in rural and regional areas.[246] Farms and processors support regional communities, and regional communities support the industry. This interdependency can be supported through government and industry supported community development activities.

The Australian Farm Institute notes five key investment, incentivisation and intervention priorities (all of which were supported by industry consultation): (1) regional jobs, education and training to help build and attract an appropriately skilled workforce; (2) uptake of digital technology including acceleration of digital infrastructure which is a barrier in regional Australia; (3) physical access to markets such as essential supply chain infrastructure and deliberate co-location of complementary businesses; (4) energy efficiency including regionally targeted renewable projects; (5) better liveability, such as housing availability, health services, schools and cultural activities to encourage people to not only move but stay in regions.[247] The National Farmers Federation is also advocating for regional community development through its Regionalisation Agenda, recommending that regionalisation is elevated to a National Cabinet issue and that 20 new regional development precincts are identified and established with the development of a list of 'shovel-ready' regional infrastructure projects.[248]

Stabilise high-protein crop price and demand: Profitability and price stability of protein crops, relative to other crop options, are critical factors for farmers looking to grow high-protein crop varieties that will help catalyse the ongoing development of Australia's plant-based protein industry. This can be achieved through the development of predictable offtake streams in domestic and export markets. To take up new crops, farmers require information regarding the demand and expected increased value from producing such crops with desired traits. Consulted stakeholders noted that there is currently limited information going to farmers regarding the opportunities for certain crop varieties and characteristics. Industry bodies can engage farmers with market demand information to demonstrate potential price stabilisation and additional value for farming enterprises.

246 Meat & Livestock Australia (2021) State of the Industry Report: The Australian red meat and livestock industry 2021.

247 McRobert K and Fox T (2021) Stronger ag sector, stronger regions.

248 National Farmers Federation (2021) Regionalisation Agenda.

2.2 Customers and consumers

Ecosystem objective: Customers and consumers are engaged and seek high value, high quality, and trustworthy Australian products.

Roadmap considerations

Conduct consumer sentiment and sensory research: Consumer interests are changing; understanding what consumers want and how they want to buy it is imperative to informing protein product development and associated industry growth. For example, health has been a bigger concern for global consumers since the COVID-19 pandemic, and increased health consciousness and interest in illness prevention impacts on purchasing decisions. For the red meat industry, understanding whether consumer perceptions about red meat are changing is critical to the industry's future growth, with the industry conducting market research since 2010 to understand trends in trust, attitudes, consumption and purchasing habits of red meat in Australian metropolitan areas.[249] Some of these attitudes are highlighted in Figure 5.

Consumers are increasingly interested in convenience products, spurring demand for added-value ready-to-eat and ready-to-cook meals.[250] Also growing is consumer interest in non-meat-based protein options.[251] Large scale consumer and sensory research could be supported to help businesses build deeper and more effective knowledge of key target markets. Export markets could also be investigated with partners. These insights will inform new product development across all protein sectors and allow businesses to develop, maintain and increase market share by satisfying consumer demand. During the development of new products, focus groups and consumer taste panels can be used to determine consumer preferences and optimise products.

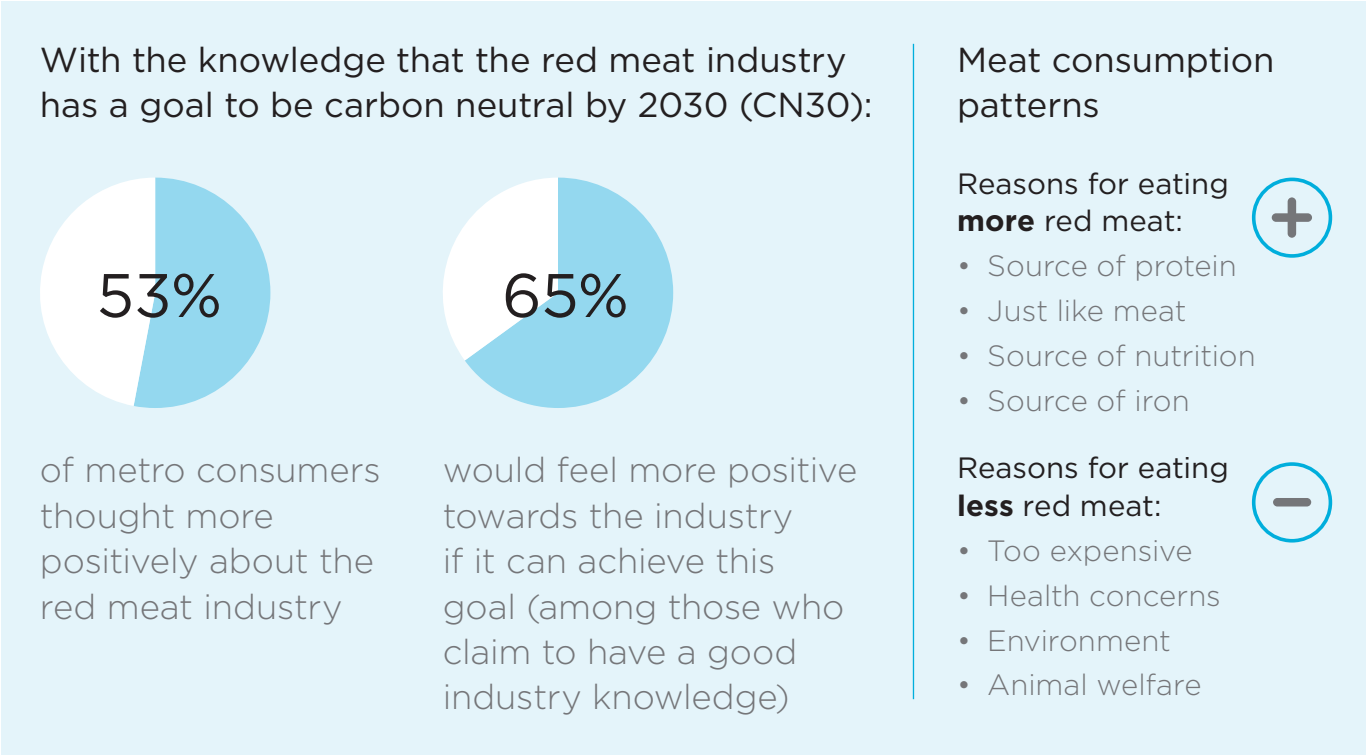


Figure 5: Australian perceptions about the red meat industry

Source: MLA

249 Meat & Livestock Australia (2021) Consumer sentiment research: Australian perceptions about the red meat industry. Viewed 17 November 2021, <https://www.mla.com.au/marketing-beef-and-lamb/consumer-sentiment-research/>.

250 Meat & Livestock Australia (2021) 2021 MLA global market snapshots released. Viewed 21 January 2022, <https://www.mla.com.au/news-and-events/industry-news/2021-mla-global-market-snapshots-released/#>.

251 Bashi Z, McCullough R and Ong L (2019) Alternative proteins: The race for market share is on. Viewed 21 January 2022, <https://www.mckinsey.com/industries/agriculture/our-insights/alternative-proteins-the-race-for-market-share-is-on>.

Develop consumer communication and engagement plans for non-traditional proteins: Consumer trust and acceptance of non-traditional protein sources, such as precision fermentation, cultivated meats, insects and some plant-based products is not guaranteed. The perception of reduced reliance on traditional farming industries may negatively impact or challenge these emerging industries. Ongoing industry development would benefit from the creation of industry-led communication and engagement plans. Taking the precision fermentation industry as an example, the communication and engagement plan would aim to: (a) educate consumers and build awareness and transparency about the precision fermentation process and its benefits, in order to reduce fear, uncertainty and doubt; (b) use evidence-based research to define the nutritional value and sustainability metrics of fermentation-derived foods benchmarked against other high-value proteins; (c) engage organisations from across the value chain to ensure consistent messaging to reduce consumer confusion; and (d) position precision fermentation as a new platform to provide additional proteins, complementing traditional industries. Suggested communication tools from consultations with stakeholders include likening precision fermentation to insulin and chymotrypsin (also produced using precision fermentation), and bread and beer (also fermented).

Early community engagement for cultivated meat: While cultivated meat is very early in its development, there are many challenges that will impact 'willingness to buy', including technology regulation, implications of shifting power in the food system from traditional sources,[252] and product form and parity with traditional meat products. Consumer acceptance of cultivated meat is not guaranteed and research is required to understand best practice in enabling a social licence to operate for the emerging industry, alongside best practice for community engagement. It is important that the community is positively engaged and educated on the potential benefits of the products. Early activities should be planned to educate and engage other research fields and the public on the emerging opportunity. Approaches could include community research webinars, engagement at public science forums, and collaborating with high profile media spokespeople.

Support consumer acceptance of insect proteins: While studies have found that a growing number of Australians are open to the possibility of future insect consumption (56% in a 2021 study[253]), remaining hesitancy about eating insects and consumer acceptance remains a challenge for the industry's growth. Although farming close to consumers can help to reduce the environmental footprint of production, concerns have also been raised about whether communities will resist the idea of having insect production at scale located near them.[254] Industry could provide increased opportunity for consumers to try products, and increased accessibility and education on insect-based foods.[255] Further consumer acceptance research into insects for human food (as well as producer acceptance research into insects for feed) is also needed to encourage willingness to try new products. Marketing for insects may also be useful, such as the recent use of crickets in a recipe on MasterChef.[256]

252 Post MJ, Levenberg S, Kaplan DL, Genovese N, Fu J, Bryant CJ, Negowetti N, Verzijden K and Moutsatsou P (2020) Scientific, sustainability and regulatory challenges of cultured meat. Nature Food 1(7), 403–415.

253 Hopkins I, Farahnaky A, Gill H, Newman LP and Danaher J (2022) Australians' experience, barriers and willingness towards consuming edible insects as an emerging protein source. Appetite 169, 105832.

254 AgriFutures Australia (2020) Catalysing a $10m Australian Insect Industry.; CSIRO (2021) Edible insects: A roadmap for the strategic growth of an emerging Australian industry. Canberra.

255 Hopkins I, Farahnaky A, Gill H, Newman LP and Danaher J (2022) Australians' experience, barriers and willingness towards consuming edible insects as an emerging protein source. Appetite 169, 105832.

256 MasterChef (2021) Cricket caramel semifreddo with lime curd and betel leaf crumb. Viewed 21 November 2021 < https://10play.com.au/masterchef/recipes/cricket-caramel-semifreddo-with-lime-curd-and-betel-leaf-crumb/r190614rslew>.

2.3 Environment

Ecosystem objective: Australian protein production increases while also protecting ecosystem health and biodiversity, and meeting consumer and market expectations for sustainability and biosecurity.

Roadmap considerations

Sustainability considerations for red meat production: For the red meat and livestock industry, sustainability represents the best business case for success. All R&D investments are focused on clearly demonstrating that sustainability goes hand in hand with profitability. The industry has set some ambitious aspirations to guide these future investments including its commitment to carbon neutrality by 2030 (CN30) across the supply chain,[257] and the goals set out by the Australian Beef Sustainability Framework.[258] Continued progression along this path with increased industry engagement is essential, alongside continued investment in science and technology to enable further advances in productivity and sustainability practices.

Whole-of-food-system view of healthy sustainable diets: Research shows that energy-dense, nutrient-poor discretionary foods are the largest food-related contributors to environmental impact. The need to increase the volume and productivity of food and agricultural production, provide affordable and nutritious food, and operate within planetary boundaries for resource use and emissions is widely viewed as a challenge requiring the transformation of food systems.[259] There is a need for systems thinking and analysis that simultaneously considers potential competing interests and trade-offs, and feeds into coordination and collaboration activities as well as policy and regulatory activities.

Consumer access to lower environmental impact food products and knowledge: In addition to the system view of healthy and sustainable diets discussed above, Australians also need access to a wider range of lower environmental impact food products.[260] Alongside access, Australians also need to be better enabled to identify such lower environmental impact food products through tools that might include clear product labelling, with stronger encouragement towards reduced consumption of energy-dense, nutrient poor discretionary foods.

Understand impact through Life Cycle Analysis: As different sources of protein become viable, independent Life Cycle Analyses will be important to accurately assess commercial, environmental and social benefits compared to incumbent protein sources.

257 Red Meat Advisory Council (2021) Red Meat 2030.

258 Annual Beef Sustainability Framework (2021) Annual Update 2021.

259 Ridoutt, B.G., Baird, D., Hendrie, G.A. (2021) Diets within planetary boundaries: What is the potential of dietary change alone? Sustainable Production and Consumption 28: 802-810.

260 Ridoutt, B.G., Baird, D., Hendrie, G.A. (2021) Diets within planetary boundaries: What is the potential of dietary change alone? Sustainable Production and Consumption 28: 802-810.

2.4 Coordination and collaboration

Ecosystem objective: The Australian protein industry sees the significant global opportunity for all types of protein and is coordinated and collaborative in pursuing this opportunity.

Roadmap considerations

Establish dedicated industry development to support novel protein production:

- **Precision fermentation** is a new and emerging industry, with very limited coordinated industry development activities. As technologies mature and more companies enter, both through start-ups and overseas investments, there is a need for a dedicated industry development organisation or team within a broader organisation. This organisation could be responsible for facilitating industry development activities, fostering start-ups, connecting key players (including established food manufacturers with start-ups), and establishing mutually beneficial research programs.
- **Cultivated meat**, while very early in its development, would benefit from a dedicated industry development organisation or team within a broader organisation (e.g., Cellular Agriculture Australia). This organisation could help to ensure transparent and coordinated development of the cultivated meat industry by facilitating industry development activities, advocacy and coordinated industry engagement.
- **Insect** based businesses operating in Australia are starting to emerge. Most of these businesses are either start-ups or are still scaling up and the industry is not yet large enough to meet demand from livestock farmers and consumers seeking insect products. Providing support for a dedicated industry development team could help to establish a prioritised research agenda and deliver industry-led projects and initiatives to help build scale. This could be done either directly through the Insect Protein Association of Australia or through a third-party contractor or consultant.

Learn from international protein industry development (policy and scale-up): Plant-based and non-traditional protein industries (e.g., precision fermentation, cultivated meats, insect proteins) are newly emerging in Australia with a limited number of commercially advanced examples in other countries. In Australia, many companies are forging their own path (such as Australian Plant Proteins, Eden Brew, Change Foods, All G Foods, Vow, Nourish Ingredients, etc.).

An important activity to help these companies is an examination of world's best practice for development and efficient operation of large-scale infrastructure in their given field. For example, for precision fermentation, a dedicated industry development organisation or industry sponsored R&D project could examine the business models and operations of international food grade precision fermentation facilities (e.g., the Protein Brewery, the Every Company), particularly those that incorporate sustainability principles (e.g., the use of renewable energy), advanced fermentation and processing technologies, and GMO handing protocols. Importantly, findings from any such activity need to be communicated to industry.

Further, detailed analysis of other countries with strong protein industries could help to identify further learnings for the development and growth of Australia's protein industry, both by understanding effective policy levers and the lessons learnt from failures of international counterparts. For example, lessons could be taken from Canada's supercluster initiative which has led to the development of Protein Industries Canada (PIC), an industry-led, not-for-profit organisation that aims to position the nation as a global source of high-quality plant protein and plant-based co-products.[261] Other countries and initiatives are detailed in Appendix F.

Engage with industry incumbents: Acceptance of emerging protein industries, like precision fermentation, by the existing protein industry will be vital to enabling growth of this nascent industry. While many protein companies see the benefit of integrating non-traditional protein sources into their portfolio (e.g., Norco, Australia's oldest dairy cooperative, has invested in Eden Brew, a precision fermentation start-up[262]) to meet consumer's needs, others may not view the industry and technology as positively, which will impact social licence to operate. Emerging, non-traditional protein industries could meaningfully engage with and learn from Australia's traditional protein industries.

261 Government of Canada (2021) Canada's Protein Industries Supercluster. Viewed 21 January 2022, <https://www.ic.gc.ca/eic/site/093.nsf/eng/00012.html>.
262 CSIRO (2021) Animal-free dairy. Viewed 8 November 2021, <https://www.csiro.au/en/research/production/food/eden-brew>.

Share knowledge across industry: Sharing of knowledge across different industries is important to the uptake of new technologies and the development of new industries. For example, uptake of systems for improved product integrity will benefit from sharing of lessons learned between cattle farmers. Emerging industries, like insect proteins, have minimal insect farming experience, with each business overcoming similar issues with little ability to learn from each other. Providing support for industry events to be run (e.g., conferences) could attract overseas experts to Australia. Providing support for industry members to attend global insect conferences (e.g., the Insects to Feed the World Conference) or other relevant international events on insect farming could build capacity, help the industry stay informed and up-to-date, and generate collaboration, education, and research project opportunities.

Develop new business models and supply chains: Some of the industry opportunities identified will involve establishing new businesses (e.g., precision fermentation), while others will require established businesses to pivot and develop new business models with new supply chains. Developing value-added products from red meat by-products, for example, is a paradigm shift for established businesses, requiring business model innovation and investment in new partnerships, infrastructure and capability development. This process could be supported by government and industry organisations.

Coordinate and collaborate for animal protein product integrity: End-to-end traceability and credentialling is currently hampered because data is not shared across supply chain systems or actors for two key reasons. Stakeholders noted that there is a lack of trust that confidentiality will be preserved, causing industry participants to keep information to themselves and act in silos. Further, there is currently no industry agreed criteria for verifiable credentials and standards which means interoperability is severely compromised. Developing data sharing protocols and legislation that provide transparency and protection for owners of commercial and personal information would help to build trust in privacy preservation. Further, Deakin University and GS1 are currently in the process of developing standards, but the challenge is ensuring wider industry adoption. Costs associated with the implementation and management of verification systems may be a barrier to widespread adoption, especially for small companies facing resource and capability limitations. Further, there is little incentive for brand owners to enhance product integrity beyond standards required by customers and government regulators, given the pre-existing trust international consumers have for the Australian meat industry.[263] As such, supporting continued development and industry-wide adoption of standards for credentials and data will be critical. Government can support this by building awareness, helping industry realise benefits and economic return.

Support cross-sector collaboration: Protein providers, new and emerging, have much to gain through collaboration with other protein providers and adjacent sectors. Realising these opportunities will require strong industry leadership and coordination.

Examples include the development of new products from red meat or aquaculture co-products, which is an opportunity that would gain significant value from partnering with other nutraceutical companies for product development. Similarly, precision fermentation companies could collaborate with other Australian companies that own or use brewing and fermenting infrastructure to gain learnings on scale-up. Within the protein industry, plant protein innovators could work with animal protein providers to develop hybrid products that add value to each business or use co-product streams from protein fractionation as feed ingredients. Further, animal, plant and non-traditional industries could work together to develop common systems for supply chain provenance and other important verified credentials so as not to each be starting from scratch.

263 Mckinna D and Wall C (2020) Final report: Commercial application of supply chain integrity and shelf life systems. North Sydney.

Facilitate the development of protein innovation clusters and accelerators: Investments in new protein businesses and innovation reflects a growing desire for diversification and novel products. The number of international accelerators and venture capital funds dedicated to the creation of innovative food technology and protein businesses are growing, with an increased investor focus on environmental, social, and governance (ESG) elements. To stimulate innovation and growth in the Australian protein industry, support and facilitation assistance should be provided to establish co-located clusters (across all protein types) to allow improved transfer of knowledge and centralised specialised support services. FIAL's cluster grant program is an example – helping bring business, government and research together to tackle food related challenges and take advantage of market opportunities (see Box on FIAL supported Food & Agribusiness Network for an example). Accelerator programs will also be invaluable to emerging protein businesses or technology service providers, such as the CSIRO ON Prime program, of which the 2022 cohort will focus on protein opportunities.

Food & Agribusiness Network[264]

The Food & Agribusiness Network (FAN) is a not-for-profit food industry cluster that was established in 2015. FAN aims to grow the industry by creating an ecosystem that supports collaboration, accelerates innovation and drives trade locally and globally. The network helps members build capability, increase knowledge, grow networks and profile their businesses. Operating across the Greater Sunshine Coast in Queensland, the network has more than 320 members from across the food value chain and is recognised nationally and internationally as a leading Australian food cluster. FAN is Australia's fastest growing industry-led cluster and has received support from FIAL's cluster grant program.

264 Food & Agribusiness Network (2020) Food & Agribusiness Network. Viewed 21 January 2022, <https://foodagribusiness.org.au/>.

2.5 Policy and regulation

Ecosystem objective: The Australian protein industry is well supported by policy and regulations that enable the industry to compete globally and deliver high quality products to local and export markets.

Roadmap considerations

Deliver streamlined compliance for protein exporters: The cost, complexity and duplicity of meeting compliance obligations mean that Australia's export competitiveness is reduced through financial cost, time delays and missing opportunities to build additional trust. Regulation and compliance costs for Australian agrifood exporters are among the highest in the world, costing up to 0.8% of the farm-gate value of production.[265] The current system of inspections and certifications is challenging for government as it is largely manual, causing bottlenecks and costing approximately $130 million a year.[266] The redevelopment of government IT systems to provide seamless digital interfaces between industry and government platforms and to streamline data flows will be necessary to deliver 'tell-one-once' compliance. As such, the Australian Government's $328.4 million Busting Congestion for Agricultural Exporters package aims to improve the regulatory burden on exporters by transitioning the country's agricultural systems to a single online portal.[267] Establishing a platform that maintains an up-to-date set of codified export regulations and protocols that can be embedded into digital platforms will allow the assessment of compliance in real time across supply chains, and concurrently provide better market intelligence. Technologies such as blockchain could also be considered to track products across the supply chain and demonstrate provenance.

Provide regulatory clarity for new and novel foods: Industry stakeholders noted that Food Standards Australia and New Zealand (FSANZ) and the Food Standards Code have resulted in strong food safety in Australia; however, it was also noted that the regulatory process for new foods can often slow the time taken for a product to reach the market, particularly if it is considered novel. Food regulatory processes are generally poorly understood by industry and research, and regulations vary between countries, which may have implications for where a given product can be exported. Many potential standards are applicable to novel foods and matching a new product with current standards can be complex.

Consulted stakeholders have indicated that: (a) more clarity is required around product definitions with mapping to show how this does and does not harmonise with definitions from other key jurisdictions (e.g., USA, Europe); (b) clarity is required around regulatory and labelling obligations if a food includes or has been manufactured using genetic modification; and (c) the development of process maps to help manufacturers of novel or non-traditional foods understand the regulatory pathway and their obligations for commercialising new food products could help provide more clarity and compliance.

To provide further clarity, a recent senate enquiry into the definitions of meat and other animal products has put forth recommendations around the sector's product labelling freedoms. Relevant recommendations include delivery of: a mandatory regulatory framework for plant-based product labelling; a review into the placement of products in stores and online; a national standard to define and restrict the use of meat category brands to animal proteins; and changes to the definition and compositional requirements of plant-based protein products. The plant-based protein industry will need to comply with the resulting changes in addition to existing Australian Consumer Laws and the Food Standards Code. To assist with these changes, the report also recommended measures to support industry growth.[268]

Review process for aquaculture farm licences: Australia's aquaculture industry is managed by several agencies at all levels of government including local council, state and federal government. The regulatory environment for aquaculture is overly complex and subject to many interstate inconsistences.[269] If the aquaculture sector is to expand, then so too will the required number of aquaculture licences. Reviewing the process for obtaining these licenses to ensure they are robust but consistent could support industry growth.

265 CSIRO (2020) Delivering trusted Australian agrifood exports and boosting value: The role of research and development. Brisbane.
266 CSIRO (2020) Delivering trusted Australian agrifood exports and boosting value: The role of research and development. Brisbane.
267 Australian Government (2020) Budget 2020-21: Busting Congestion for Agricultural Exporters.
268 Parliament of Australia (2022) Don't mince words: definitions of meat and other animal products.
269 Department of Agriculture and and Water Resources (2017) National Aquaculture Strategy. Canberra.

Enable a safe but proactive regulatory environment for precision fermentation: Under FSANZ, some proteins manufactured via precision fermentation will be considered novel foods as well as potentially a GMO, both of which present challenges for regulatory approval. To help address this, FSANZ are updating the Food Code definitions for 'food produced using gene technology' and 'gene technology' for improved clarity and to reflect existing and emerging genetic technologies including new breeding techniques[270]). However, significant timeframes are required for regulatory approval, which are sometimes at odds with commercial timeframes. To help expedite and streamline future submissions to enable rapid industry innovation, the feasibility of running simulation precision fermented protein products through FSANZ protocols to develop frameworks and tolerances should be investigated. This might also help determine platform organisms that could be used as generally safe production systems.

Develop science-informed food safety standards for cultivated meats: Being an emerging field with no commercial food products, there are currently no permissions or requirements in the Australian Food Standards Code for cultivated meats. While FSANZ has been aware of cultivated or cell-based meats for some time, the agency has not yet been approached by a food business seeking regulatory approval.[271] Regulatory requirements in relation to the Food Standards Code within Australia and any potential market access issues if planning to export will need to be considered. There is an opportunity in the development of this area to ensure the right science is performed and the relevant evidence collected to inform development of regulations.

Ongoing conversations between research, start-ups, FSANZ and state and territory compliance authorities will be important to inform both product development pathways and new regulatory pathways. Additionally, opportunities for FSANZ to benefit from the expertise in countries that have already given regulatory approval should continue, through mechanisms like the FSANZ MOU with the Singapore Food Agency.[272] These mechanisms should aim to allow collaborative sharing of knowledge to expedite the process to market, to help ensure Australia remains in a leading position globally in this new area of food.

Develop insect industry guidelines: Currently there is a lack of regulatory clarity for the Australian insect industry as there is no national standard for the industry to follow. Internationally, the Food and Agriculture Organisation recently published a comprehensive manual on sustainable cricket farming to address knowledge gaps among cricket farmers and government agencies responsible for food safety.[273] There is also a lack of consistency across the Australian states as the regulations vary between states and between the various livestock sectors that use insects as feed. The pet food industry is self-regulated, and while this does not pose a problem currently, AgriFutures suggests that improved regulatory clarity would support the industry's growth.[274] Developing industry guidelines could inform industry and regulators on how to farm, process, slaughter, and render insects, leveraging frameworks and best practices from other industries where possible (e.g., poultry, livestock, mushrooms).

Continue policy and government support for infrastructure and market access: Many opportunities identified will necessitate the development of new manufacturing infrastructure, often in regional areas. Establishing and continuing policy measures that support and facilitate the development of new infrastructure, such as the Modern Manufacturing Initiative, alongside providing support for regional development will be important for the continued development of Australia's domestic protein industry. Further, continued support to access export markets and investment attraction, such as that provided by Austrade is pivotal to growing Australia's protein exports.

270 Food Standards Australia New Zealand (2021) Food standards development Work Plan. Viewed 16 November 2021, <https://www.foodstandards.gov.au/code/changes/workplan/Documents/Food standards development Work Plan October 2021.pdf>.

271 FSANZ (2021) Cell based meats, https://www.foodstandards.gov.au/consumer/generalissues/Pages/Cell-based-meat.aspx

272 FSANZ (2020) Annual Report 2019-20.

273 FAO (2020) FAO releases a comprehensive guide to sustainable cricket farming. Viewed 21 November 2021, < https://www.fao.org/asiapacific/news/detail-events/en/c/1365143/>.

274 Insect Protein Association of Australia (2021) Insects as food. Viewed 16 November 2021, <https://www.insectproteinassoc.com/insects-as-food>.

3 Roadmap synthesis

Australia is not alone in recognising the protein opportunity. Other countries, including Canada and Singapore, are actively growing their protein production through targeted initiatives and R&D (see Appendix F for more detail on other countries). If Australia is to remain a global protein leader, action must be taken. Now is the time to focus on building a sustainable and resilient Australian food system that delivers nutritious protein for discerning local and global consumers.

Figure 6 below highlights the maturity of technological solutions alongside the requirement for new infrastructure for the identified growth opportunities. It highlights opportunities that will require strong infrastructure and R&D commitments to reach ambitious growth targets by 2030. These opportunities require targeted R&D investments to mature key enabling technologies and infrastructure through to higher levels of technology readiness and commercial readiness (Appendix C) required for industry creation, growth and impact.

Australia can leverage the momentum created by increasing global protein demand to invest in and build its protein industries, cementing its international position as a protein leader while minimising the environmental impact of protein production. If Australia can capitalise on the opportunities available, some of which have been identified within this report, both the nation's existing and emerging protein industries can develop in unison to complement each other in expanding Australia's protein output.

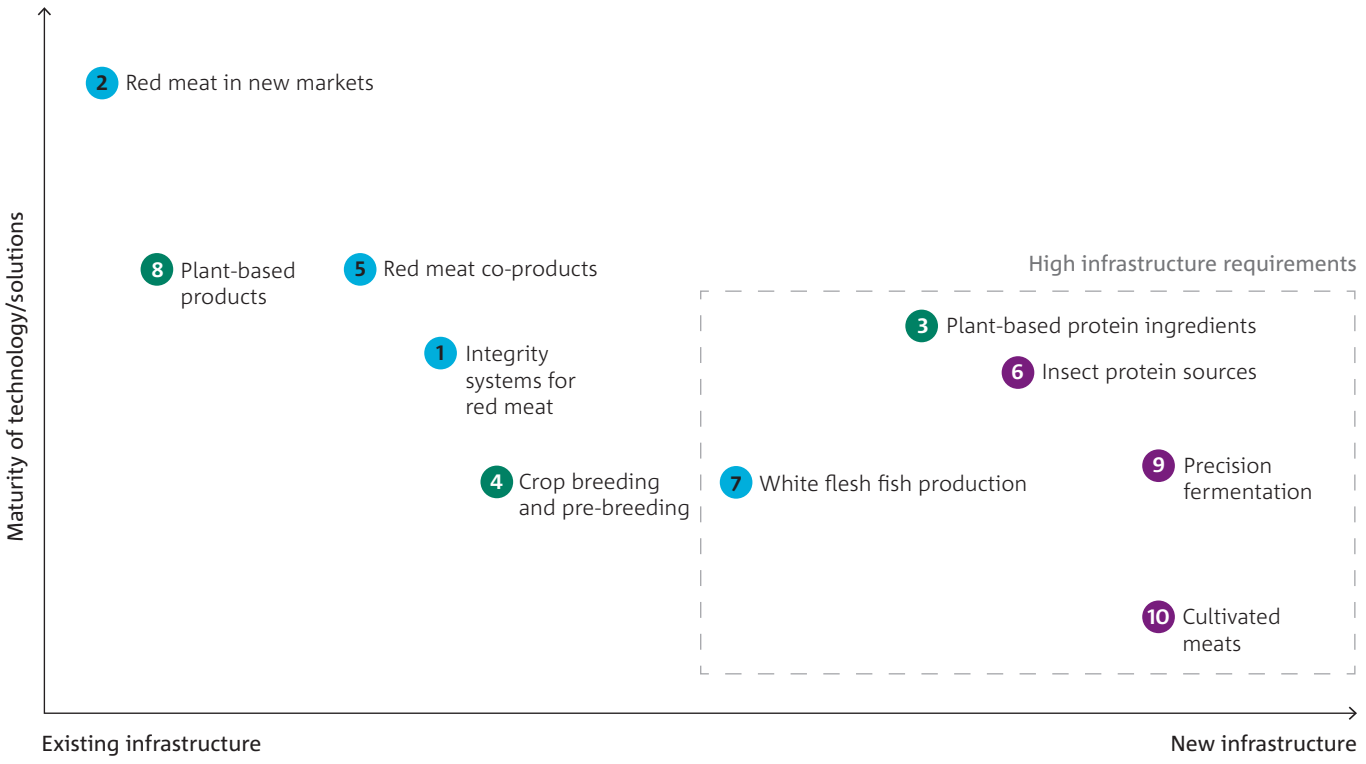


Figure 6: Protein opportunities

Note: placement is approximate

Appendix A – Consulted stakeholders

CSIRO would like to thank all consulted organisations for their contributions to this project through interview and reviews. Listed below are those organisations that consented to being named.

Note: the insights expressed throughout this report were developed by considering the collective views obtained alongside independent economic and qualitative research and may not always align with the specific views of one of the consulted individuals or organisations.

- AgriFutures Australia
- Agritechnology
- Dr Angeline Achariya
- All G Foods
- Australian Department of Agriculture, Water and Environment (DAWE)
- Australian Department of Industry, Science, Energy and Resources (DISER)
- Australian Export Grains Innovation Centre (AEGIC)
- Australian Farm Institute
- Australian Food and Grocery Council
- Australian Meat Processor Corporation (AMPC)
- Australian Plant Proteins
- Australian Trade and Investment Commission (Austrade)
- Bardee (Beyond Ag)
- Bayer LEAPS
- Bega Cheese
- Big Idea Ventures
- BioBrew (ZX Ventures)
- Coles
- Eden Brew
- Fisheries Research and Development Corporation (FRDC)
- Food Frontier
- Food Innovation Australia Ltd (FIAL)
- Food Standards Australia New Zealand
- Goterra
- GrainCorp
- Grains & Legumes Nutrition Council (GLNC)
- Grains Australia
- Grains Research and Development Corporation (GRDC)
- Ingredion
- JBS Australia
- Main Sequence Ventures (MSV)
- Meat and Livestock Australia (MLA)
- National Farmers Federation (NFF)
- Noumi (formerly Freedom Foods)
- New South Wales Government
- Nourish Ingredients
- Queensland Government
- South Australian Research and Development Institute (SARDI)
- South Australia Government
- Tassal
- Teys
- Unigrain
- Unilever
- University of Adelaide
- v2food
- Victorian Government – Department of Jobs, Precincts and Regions (DJPR)
- Western Australia Government – Department of Primary Industries and Regional Development (DPIRD)

Appendix B – Protein snapshots

Snapshot: Australian animal protein

Table 8: Value and volume of animal protein exports (2019-20)[275]

PROTEIN	$M	VOLUME	AVERAGE EXPORT (FOB) PRICE
Beef and veal	11,258	1,290 kt (sw)	$8.7 per kg
Lamb and mutton	4,056	462 kt (sw)	$8.8 per kg
Live cattle	1,565	1.3 million (head)	$1,246 per head
Edible fisheries (both aquaculture and wild catch)	1,331	56 kt	$23.8 per kg
Live sheep	154	1.7 million (head)	$144 per head
Pork[276]	130	44 kt (cw)	Limited data
Chicken meat[277]	87	49 kt (cw)	Limited data
OTHER			
Goat meat (2020 estimate)[278]	146	14 kt (sw)	$10.3 per kg
Kangaroo meat (2017-18 estimate)[279]	16 (fresh and processed)	3 kt (fresh and processed)	$5.3 per kg

Red meat (beef and sheep)

- In 2019, the **national cattle herd** (including dairy and beef cattle) was 23.4 million.[280]
- Beef and veal production was 2,372 kt (carcase weight or cw) in 2019-20, of which 78% was exported. These exports were valued at approximately $11.3 billion. Further, a total of 1.3 million live slaughter cattle were exported, valued at $1.6 billion. [281]

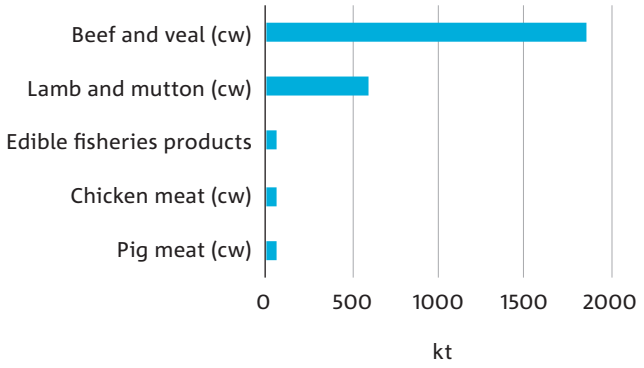


Figure 7: Five largest animal protein exports by volume (2019-20)[282]

275 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data.

276 Export value figure from: Australian Pork Limited (2020) Inquiry into Diversifying Australia's Trade & Investment Profile Submission.

277 Export value figure from: Australian Chicken Meat Federation (2021) Facts & Figures. Viewed December 10 2021, <https://www.chicken.org.au/facts-and-figures/#Exports>

278 Export value and volume figures from: Meat & Livestock Australia (2021) Global Snapshot: Goatmeat.

279 Export value and volume figures from: AgriFutures (2021) AgriFutures Kangaroo Program Strategic RD&E Plan (2021-2026).

280 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data: Rural Commodities - meat - beef and veal.

281 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data: Rural Commodities - meat - beef and veal.

282 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data: Rural Commodities - meat - beef and veal.

- In 2020, Australia was the world's **second largest exporter** of beef after Brazil.[283] China, Japan and the US were the **most valuable beef and veal export markets**.

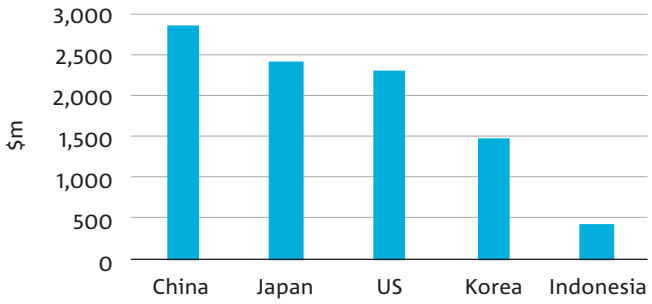


Figure 8: Five largest beef and veal export markets (2019-20)

- **Sheepmeat production** in 2019, including lamb and mutton, was 731 kt (cw), of which 79% was exported.[284] **Lamb exports** were worth $2.7 billion, nearly twice as much as **mutton exports** at under $1.4 billion. Additionally, 1.7 million **live sheep** were exported, valued at $154 million.

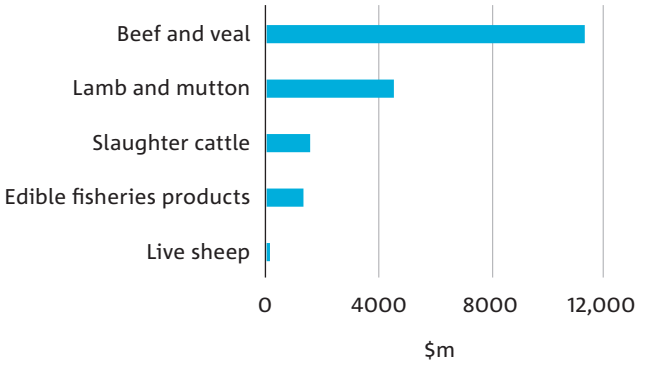


Figure 9: Five largest animal protein exports by value (2019-20)

Aquaculture

- For general fisheries production, including both aquaculture and wild catch, in 2018-19 Australia produced 258 kt (including fish, crustaceans and molluscs), valued at $3.2 billion.[285] In 2019-20, 56 kt was exported and was valued at $1.3 billion.[286]
- **Aquaculture exports** on their own have only been estimated to represent 2% of this total Australian export figure, accounting for under $30 million in 2019.[287]
- Australian aquaculture had a **gross value product** (GVP) in 2019-20 of $1.6 billion, which was half the GVP of total fisheries operations.[288]
- Aquaculture **volume produced** was 106 kt, which accounted for 38% of total fisheries volume.[289]
- Australia's top aquaculture species in terms of production value are salmonids, tuna, edible oysters, pearl oysters and prawns.[290] Other species groups grown in Australia include abalone, freshwater finfish (e.g., barramundi, silver perch), brackish water or marine finfish (e.g., snapper, yellowtail kingfish, groupers), mussels, ornamental fish, marine sponges, mud crab and sea cucumber.
- The **most valuable aquaculture products** were finfish ($1.2 billion), followed by molluscs ($234 million) and crustaceans ($139 million). Similarly, finfish accounted for 78% of **total quantity produced**, followed by molluscs (13%) and crustaceans (6%).[291]

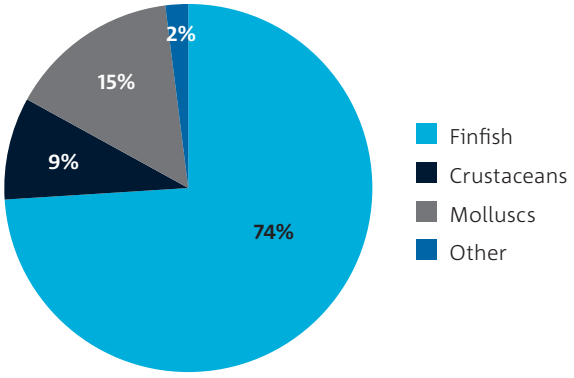


Figure 10: Value of aquaculture products (2019-20) (%)

283 Meat & Livestock Australia (2021) Value of Australian beef exports falls in 2020. Viewed 9 November 2021, <https://www.mla.com.au/prices-markets/market-news/2021/value-of-australian-beef-exports-falls-in-2020/>.

284 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data: Rural Commodities - meat - sheep.

285 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data: Rural commodities - fisheries.

286 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data: Rural commodities - fisheries.

287 IBISWorld (2021) Australia Industry (ANZSIC) Report A0200: Aquaculture in Australia.

288 Department of Agriculture Water and the Environment (2020) Aquaculture industry in Australia. Viewed 8 November 2021, <https://www.awe.gov.au/agriculture-land/fisheries/aquaculture/aquaculture-industry-in-australia>.; Australian Bureau of Agricultural and Resource Economics and Sciences (2021) Australian fisheries and aquaculture production. Viewed 9 November 2021, <https://www.awe.gov.au/abares/research-topics/fisheries/fisheries-and-aquaculture-statistics/production>.

289 Australian Bureau of Agricultural and Resource Economics and Sciences (2020) Fisheries and aquaculture statistics 2020 - Report.

290 Department of Agriculture Water and the Environment (n.d.) Aquaculture industry in Australia. Viewed 8 November 2021, <https://www.awe.gov.au/agriculture-land/fisheries/aquaculture/aquaculture-industry-in-australia>.

291 Department of Agriculture Water and the Environment (n.d.) Aquaculture industry in Australia. Viewed 8 November 2021, <https://www.awe.gov.au/agriculture-land/fisheries/aquaculture/aquaculture-industry-in-australia>.

Pigs and poultry

- Pig and chicken meat production represents a **smaller part** of the traditional protein export market, with production largely serving the domestic market.
- Total **pig meat production** in 2019 was 398 kt (cw), of which 44 kt was exported.[292] Overall, Australia is a net pork importing country, importing 403 kt (cw) in 2019.
- Total **chicken meat production** was 1,227 kt (cw), of which 49 kt was exported, indicating that nearly all chicken consumed in Australia was produced domestically.[293]
- In Australia, poultry is the most consumed meat (at 44 kg per person in 2020), followed by pork (20 kg), beef and veal (19 kg), and sheep (6 kg).[294]
- Australian meat consumption growth per person is forecast to be minimal, driven by moderate increases in poultry meat (which will offset red meat per person declines).[295]

Eggs and dairy

- In 2019-20, Australia produced around 359 million dozen **eggs**.[296] Almost all this is consumed domestically due to the perishable nature of eggs and the relatively low value to weight ratios.
- Australia produced nearly 8.8 billion L of **milk** in 2019-20. From this production, Australia produced 65 kt of **butter and butterfat** and 390 kt of **cheese**.
- Of this 2019-20 production, 18% (or around 12 kt) of the butter and butterfat and 40% (or 158 kt) of the cheese was exported. Further, 139 kt of skim and whole milk powder was exported.
- In terms of dairy exports value, Australia exports nearly $1 billion in cheese, and over $700 million in skim and whole milk powders in 2019-20.[297]

Table 9: Summary of Australian dairy exports (2019-20)[298]

PRODUCT	EXPORT VALUE ($M)
Cheese and curd	985.4
Butter and butterfat	90.2
Whey	80.6
Buttermilk, curdled milk and cream, other fermented/acidified dairy products	55.5
Milk and cream (unconcentrated)	318.3
Concentrated milk and cream	344.6
Milk and cream solids (including powder for infant formula)	568.4
Sweetened milk and cream	42.9
Total	**2,486.1**

292 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data: Rural commodities – pigs and poultry.

293 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data: Rural commodities – meat – pigs and poultry.

294 OECD (2021) OECD-FAO Agricultural Outlook: Meat consumption. Viewed 19 November 2021, <https://data.oecd.org/agroutput/meat-consumption.htm>

295 Australian Bureau of Agricultural and Resource Economics and Sciences (2019) Global trends in meat consumption. Viewed 19 November 2021, <https://www.awe.gov.au/abares/research-topics/agricultural-outlook/meat-consumption>

296 ABS (2021) Agricultural Commodities, Australia, 2019-20 financial year. Viewed 17 November 2021, <https://www.abs.gov.au/statistics/industry/agriculture/agricultural-commodities-australia/latest-release>.

297 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data: Rural commodities – meat – dairy products.

298 DFAT (2021) Australia AHECC export pivot table 2006-07 to 2020-21. Viewed 20 November 2021, <https://www.dfat.gov.au/about-us/publications/trade-statistical-pivot-tables>.

Snapshot: Australian plant-based proteins

As of September 2021, there are 19 companies in Australia using plant-based technologies to produce protein products with the main protein ingredients used being wheat, soy and pea.[299]

In 2019-20, the Australian plant-based protein sector generated $185 million in sales, of which $154 million went to retail (with the rest to food services).

There has been significant investment activity for Australian plant-based protein start-ups, including:

- v2food securing $72 million in its latest Series B funding round in the latter half of 2021, bringing the company's total raise to $185 million.[300]
- Fenn Foods launching a carbon-neutral beef alternative called 'vEEF' in 2020.[301]
- All G Foods raising $15.5 million in seed funding to develop its plant-based meat alternative brand, as well as its precision fermentation brand.[302]
- Harvest B raising $3.5 million seed funding from Aura Ventures and Woolworths' venture capital arm W23 in July 2021.[303]

While exports were only $2.7 million in 2019-20,[304] there have recently been significant movements towards greater exports – such as v2food's expansion into the Asian market, specifically into China.[305]

Wheat

- **Wheat and soy products** are among the dominant ingredients used in Australian plant-based proteins.
- According to one analysis, for locally manufactured plant-based proteins, the **majority of wheat protein is locally sourced**. Nevertheless, **most of the proteins are imported** as concentrates, isolates, textured proteins or partially transformed ingredients.[306] This is due to the small scale of Australian soybean production, as well as limited capacity to commercially process pulses.
- **Global production of wheat** was estimated to be nearly 753 Mt in 2020 and is forecast to reach 840 Mt in 2030.[307] In 2030, China, the EU, India, Russia, and the US are expected to produce over 60% of wheat globally; with US, Ukraine, Canada, the EU and Russia accounting for 73% of exports.
- **Domestic production of wheat** in Australia was 21,559 kt per year on average for the five years to 2019-20 (with a corresponding five-year price average of $293 per tonne).[308] It is used in a wide range of products for human consumption world-wide (e.g., noodles, breads, confectionary, pasta, cous cous) as well as in animal feed formulations.
- In terms of **global trade**, Australia represented 5% of wheat exports in 2019-20 (9.4 Mt of 191 Mt). In contrast, Australia only exported 0.7 kt of soybeans in 2019-20, a mere fraction of total world exports that year (165 Mt).[309]

299 Food Frontier (2021) Alternative Proteins Company Directory – Australia and New Zealand Published 3 September 2021. Lacy-Nichols J, Scrinis G and Moodie R (2020) The Australian Alternative Protein Industry.

300 Berry K (2021) v2food readies for China push. Viewed 17 November 2021, <https://www.foodanddrinkbusiness.com.au/news/v2food-readies-for-china-push>.

301 Green Queen Media (2021) The APAC Alternative Protein Industry Report 2021.

302 Simmons D (2021) Alternative protein startup All G Foods flexes $15.5m seed raise. Viewed 17 November 2021, <https://www.businessnewsaustralia.com/articles/alternative-protein-startup-all-g-foods-flexes--15-5m-seed-raise.html>.

303 Green Queen Media (20210) APAC Report 2021

304 Food Frontier (2021) 2020 State of the Industry Australia's Plant-Based Meat Sector.

305 Ho S (2021) Australian Vegan Meat Leader v2food Eyes Asian Expansion After $54M Series B. Viewed 17 November 2021, <https://www.greenqueen.com.hk/v2food-funding-vegan-meat/>.

306 Food Processing (2020) Australia's grain sector to tap into plant-based meat substitutes. What's New in Food Technology & Manufacturing .

307 OECD/FAO (2021), OECD-FAO Agricultural Outlook 2021-2030, OECD Publishing, Paris.

308 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data: Rural commodities – wheat.

309 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data: Rural commodities – oilseeds.

Soy

- Soybean is the most economically important grain legume crop grown globally, providing an affordable and dense source of vegetable protein for millions of people, as well as an input for hundreds of chemical industrial applications.[310]
- **Global production of soy** was estimated to be 356 Mt in 2020. The vast majority of soybeans (90%) are processed into vegetable oils for a variety of purposes and used for animal feed. By 2030, soybean production is expected to reach 411 Mt, more than double the output of other oilseeds. Exports are expected to be dominated by Brazil and the United States, with China accounting for about two-thirds of soybean imports.[311]
- **Domestic production of soybeans** is limited. Australia produced only 31 kt per year on average for the five years to 2019-20.[312]
- In 2020-21, China was the world's largest producer of **soybean meal**, producing nearly 30% (73.7 Mt) of global supply, followed by the US (18% or 45.9 Mt) and Brazil (15% or 36.2 Mt).[313]

Table 10: Summary of Australian statistics for wheat and soy crops (five-year average to 2019-20)[314]

WHEAT	
Production	21,559 kt
Exports	14,187 kt
SOY	
Production	31 kt
Exports	3 kt

Pulses

- **Global production of pulses** was estimated to be 89 Mt in 2020 and is expected to grow to 111 Mt in 2030. Pulses are expected to grow in importance in diets in many regions of the world, moving up from 7.9 kg per capita currently to 9.1 kg per capita by 2030. Canada is expected to be the main exporter of pulses in 2030 at 8 Mt, followed by Australia with 2.4 Mt of exports.[315]
- In terms of overall **global pulse trade**, and according to the most recent available data, Australia represented 14% of pulse exports in 2017 (2,730 kt of 19,628 kt).[316]
- In terms of Australia's global performance on the trade and production of specific pulses:[317]
  - **Chickpeas:** Although representing around 6% of world production, Australia is the largest exporter of chickpeas (40% of world exports). Around 95% of its chickpeas are exported.
  - **Lentils:** Australia represents around 8% of global lentil production, and 14% of world exports. Over 80% of its lentils are exported.
  - **Field peas:** Australia is a minor player. It represents under 3% of world production, 5% of world exports. Over 60% of its field peas are exported.
  - **Faba beans**: Australia produces under 8% of the world's faba beans and exports around 80% of it. Australia is currently the world's largest exporter, at around a third.
  - **Lupins:** Australia is the largest exporters of lupins in the world, primarily as feed and fodder.[318] In 2019-20, Australia exported 48% of its lupin production.[319]
- Pulses represent a much smaller part of the current Australian plant-based protein market, in part due to limited capacity to commercially process pulses.
- There is currently only one commercial plant-protein fractionation plant owned and operated in Australia – Australian Plant Proteins (APP), capable of producing protein isolates from pulses such as lentils and faba beans. Recently, APP secured a $45.7 million investment to allow the company to double its protein output by early 2022.[320]

310 Britannica (2021), Soybean. Viewed 14 December 2021, < https://www.britannica.com/plant/soybean>.

311 OECD/FAO (2021), OECD-FAO Agricultural Outlook 2021-2030, OECD Publishing, Paris.

312 United States Department of Agriculture (2021) Production, Supply and Distribution data.

313 United States Department of Agriculture (2021) Oilseeds: World Markets and Trade – November 2021 report.

314 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data: Rural Commodities - meat – wheat; United States Department of Agriculture (2021) Production, Supply and Distribution data.

315 OECD/FAO (2021), OECD-FAO Agricultural Outlook 2021-2030, OECD Publishing, Paris.

316 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data: Rural commodities – pulses.

317 FAO (2019) The Global Economy of Pulses.

318 Australian Trade and Investment Commission (2017) Grains, Pulses and Oilseeds.

319 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data: Rural commodities – pulses.

320 Berry K (2021) Australian Plant Proteins secures $45.7m investment. Viewed 17 November 2021, <https://www.foodanddrinkbusiness.com.au/news/australian-plant-proteins-secures-45-7m-investment>.

- Unigrain, an Australian oat and pulse processor, has also recently announced plans to build its first pulse fractionation facility in Victoria.[321]

Table 11: Summary of Australian statistics for major pulse crops (five-year average to 2019-20) [322]

LUPINS	
Production	734 kt
Exports	318 kt
Value of exports	$124 million
Gross value of production	$194 million
FIELD PEAS	
Production	263 kt
Exports	136 kt
Value of exports	$70 million
Gross value of production	$100 million
CHICKPEAS	
Production	873 kt
Exports	990 kt [323]
Value of exports	$914 million
Gross value of production	$700 million
FABA BEANS	
Production	349 kt
Exports	312 kt
Value of exports	$181 million
Gross value of production	Not estimated
TOTAL PULSES [a]	
Production	2,780 kt
Exports	2,382 kt
Value of exports	$1,811 million
Gross value of production	$1,787 million

a Total pulses includes lupins, field peas, chickpeas, faba beans, mung beans, navy beans, lentils and some other minor pulses.

Other (fungi, root vegetables, fruit)

- Other plant-based protein sources – namely, those using fungi, root vegetable (e.g., konjac), and fruit (e.g., jackfruit) – are a niche industry in Australia.
- Nevertheless, protein from other plant-based sources is an emerging industry. For instance, one domestic mushroom-based protein producer, Fable Food Co, secured $6.5 million seed funding in August 2021 to globally expand production of its meat alternatives.[324]

321 Grain Central (2021) Unigrain to build pulse fractionation plant. Viewed 17 November 2021, <https://www.graincentral.com/news/unigrain-to-build-pulse-fractionation-plant-at-smeaton/>.

322 Australian Bureau of Agricultural and Resource Economics (2020) Agricultural commodities and trade data: Rural commodities – pulses.

323 In many years, Australia chickpea exports exceed production figures. This is likely reflective of the fact that the vast majority of chickpeas (over 90%) in Australia are exported and Australia has significant capacity for maintaining chickpea stocks to handle price fluctuations. For further commentary, see FAO (2019) The Global Economy of Pulses.

324 Green Queen Media (2021) The APAC Alternative Protein Industry Report 2021.

Snapshot: Australian non-traditional proteins

Microorganism-based

- **Microorganism-based protein alternatives** (which can include proteins produced using bacteria, yeasts, single-celled algae, or fungi) using fermentation technology are an emerging Australian industry.
- In **Australia**, companies such as Agritechnology provide manufacturing capabilities to assist in the commercial development of fermentation and industrial microbiology processes.[325]
- Further, several **precision fermentation** companies have been founded with a focus on protein production, including:
  - **Nourish Ingredients**, using precision fermentation to derive fats for use with meat, dairy, and fish alternatives.[326]
  - **Change Foods**, a joint US-Australia start-up, using precision fermentation to derive proteins and fats for cheese alternatives.[327]
  - **Eden Brew** and **All G Foods**, using precision fermentation to derive proteins for milk alternatives.[328]

Table 12: Recent investments in Australian precision fermentation companies

COMPANY	RECENT INVESTMENT NEWS
Nourish Ingredients	Raised around $15 m in seed funding from venture capital in early 2021.[329]
Change Foods	Raised around $2.9 m in new seed funding (for expansion in its US location) in mid-2021.[330]
Eden Brew	Launched with a $4 m investment, backed by CSIRO and Australian diary company Norco in mid-2021.[331]
All G Foods	Raised $16 m in new seed funding in late 2021.[332]

325 Credit Suisse (2021) Sustainable food as an investment opportunity.; Agritechnology (2021) Expertise. Viewed 17 November 2021, <https://agritechnology.com.au/expertise/>.

326 Nourish Ingredients (2021) About Us. Viewed 17 November 2021, <https://nourishing.io/about-us/>

327 Neo P (2020) Cow-free bio-engineered cheese: New tech will reduce costs and aid customisation - Change Foods. Viewed 17 November 2021, <https://www.foodnavigator-asia.com/Article/2020/09/08/Cow-free-bio-engineered-cheese-New-tech-will-reduce-costs-and-aid-customisation-Change-Foods>.

328 CSIRO (2021) Animal-free dairy. Viewed 8 November 2021, <https://www.csiro.au/en/research/production/food/eden-brew>.; Berry K (2021) It's all good, Australia's newest alt protein player. Viewed 17 November 2021, <https://www.foodanddrinkbusiness.com.au/news/it-s-all-good-australia-s-newest-alt-protein-player>.

329 Nourish Ingredients (2021) Nourish Ingredients raises $11M USD to create sustainable, better-tasting animal-free fats. Viewed 17 November 2021, <https://nourishing.io/nourish-ingredients-raises-11m-usd-to-create-sustainable-better-tasting-animal-free-fats/>.

330 Ho S (2021) Change Foods Raises US$2.1M Seed Funding To Fuel Bay Area Expansion & Animal-Free Cheese R&D.

331 Food Frontier (2021) CSIRO backs Eden Brew. Viewed 17 November 2021, <https://www.foodfrontier.org/csiro-eden-brew/>.

332 Macdonald A and Redrup Y (2021) Plant-based meat producer All G Foods scores $16m. Viewed 17 November 2021, <https://www.afr.com/street-talk/plant-based-meat-producer-all-g-foods-scores-16m-20210905-p58oxq>.

Insect-based

- The **edible insect protein** industry, including insects for human food, animal feed and upcycling of waste streams, is still considered an emerging Australian industry.
- In **Australia**, there are currently 14 insect-based businesses. Ten are producing insects for animal feed and 4 are producing insects for human consumption.[333]
- In terms of products produced:
  - **Crickets and mealworms** are currently the only insect types being commercially produced in Australia for human consumption.[334]
  - Additionally, **crickets, mealworms and black soldier flies** are commercially sold for pet food (including for dogs).[335] **Black soldier fly** is the only species currently being investigated for livestock feed.[336]
  - Insects for livestock feed or pet food must meet product regulation requirements which vary by state.[337] Current state and federal government restrictions prevent use of insects as feed for ruminant animals.[338]

Cultivated meat

- The potential for commercially available cultivated meat products in the future is an area of active research in Australia.
- In **Australia,** since 2017, companies have been founded in the four cultivated meat space: Heuros, Vow, Cass Materials and Magic Valley focused on different components of cellular protein production.[339]

Table 13: Cultured protein companies in Australia

COMPANY	FOCUS	ADDITIONAL NOTES
Heuros	Serum-free cell culture media	-
Vow	Cell lines	Secured $7.7 m in new investment funding in early 2021.[340]
Cass Materials	3D scaffolds	-
Magic Valley	Cell lines	-

- **Australian R&D activity** within the cultivated meat space has been quickly expanding in recent years. Examples include:
  - Research funded through the Future Food Hallmark Research Initiative at the University of Melbourne.[341]
  - Seed grant funding for the University of the Sunshine Coast from US-based research institute New Harvest to develop cell-based crayfish meat.[342]
  - UNSW's research into cellular agriculture through its collaborative ChallENG Program and Future Food Systems Cooperative Research Centre (CRC).[343]
  - Promotion of research, collaboration and innovation in this space done by Cellular Agriculture Australia, a non-profit organisation.[344]

333 AgriFutures Australia (2020) Catalysing a $10m Australian Insect Industry.

334 CSIRO (2021) Edible insects: A roadmap for the strategic growth of an emerging Australian industry. Canberra.

335 See for instance: Buggybix (2021) Products. Viewed 17 November 2021, <https://www.buggybix.com.au/collections/all>

336 Insect Protein Association of Australia (2021) Insects as feed.Insect Protein Association of Australia (2021) Insects as feed.

337 AgriFutures Australia (2020) Catalysing a $10m Australian Insect Industry.

338 CSIRO (2021) Edible insects: A roadmap for the strategic growth of an emerging Australian industry. Canberra.

339 Protein Report (2021) Directory. Viewed 17 November 2021, < https://www.proteinreport.org/directory>

340 Keating E (2021) Cell-based meat startup Vow raises $7.7 million from big-name investors. Viewed 17 November 2021, <https://www.smartcompany.com.au/startupsmart/news/vow-cell-based-meat-raises-7-7-million/>.

341 University of Melbourne (2021) Future Food. Viewed 17 November 2021, <https://research.unimelb.edu.au/research-at-melbourne/multidisciplinary-research/hallmark-research-initiatives/future-food>.

342 Le B (2020) New Harvest Funds Australian Research on Cell-Based Crayfish Meat. Viewed 17 November 2021, <https://www.proteinreport.org/new-harvest-funds-australian-research-cell-based-crayfish-meat>.

343 UNSW (2021) The ChallENG Program: Cellular Agriculture. Viewed 17 November 2021, <https://www.challeng.unsw.edu.au/challeng-projects/cellular-agriculture>.; Future Food Systems (2021) Home. Viewed 17 November 2021, <https://www.futurefoodsystems.com.au/>.

344 Cellular Agriculture Australia (2021) Home. Viewed 17 November 2021, <https://cellularagricultureaustralia.org/>.

Appendix C – Technology Readiness Levels[345]

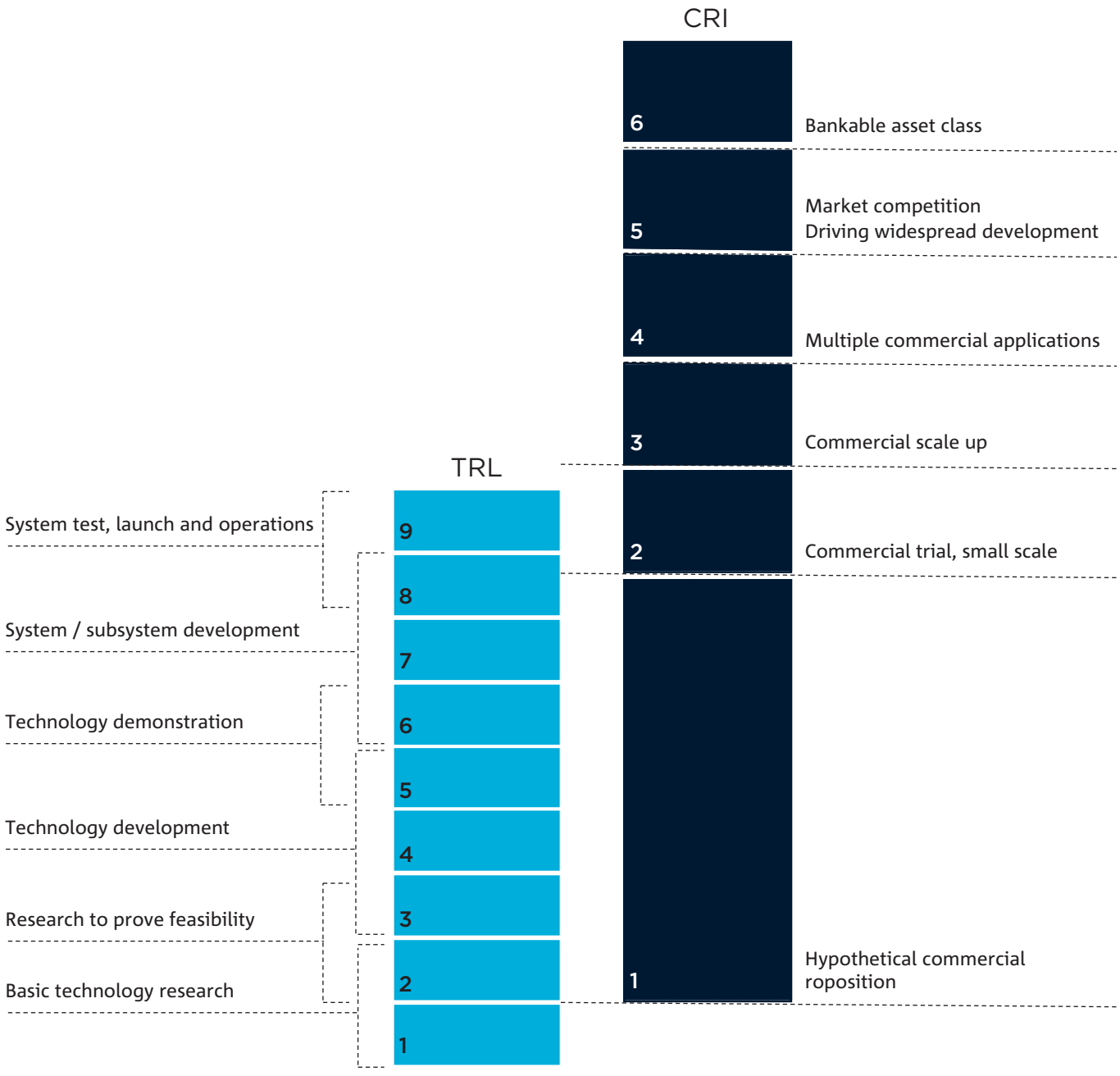


Figure 11: Technology Readiness Levels and Commercial Readiness Index

345 ARENA (2014) Technology Readiness Levels for Renewable Energy Sectors.

Appendix D – Economic analysis

A.1 Integrity systems in the red meat sector

Conservative opportunity: Approximately A$16.5 billion in export revenue in 2030 beef, veal and sheepmeat exports in a conservative scenario where there is a low price premium and it applies to a low proportion of exports.

Ambitious opportunity: Approximately $17.1 billion in export revenue in 2030 beef, veal and sheepmeat exports in an ambitious scenario where there is a high price premium and it applies to a high proportion of exports.

Price premiums

The method for benchmarking price premiums is by comparing the price Australian products receives per unit against the per-unit prices from the country that receives the highest price on international markets. The assumption is that red meat with verifiable credentials could enable Australian exports to shift into the highest price category. For example, in 2020, the average Australian beef export price was US$5.86 per kg, whereas the highest was 20% higher at US$7.06 per kg (for US beef exports).[346]

An extensive meta-analysis of studies on consumers' willingness-to-pay for sustainable food products conducted by Li and Kallas (2021) found that the overall willingness-to-pay premium is 29.5% on average.[347] However, only 15 of the 80 worldwide studies used were directly related to meat products.

Based on guidance from MLA, a premium of **3%** is taken as the price premium for Australian red meat with verifiable credentials for conservative modelling and, for ambitious modelling, a premium of **7.5%** is used.

Exports in 2030

According to the OECD-FAO forecasts, Australia's beef and veal exports are forecast to increase in volume by 26% in 2030 from its 2018-20 average.[348] Likewise, its sheepmeat exports are forecast to increase in volume by 15% in 2030 from its 2018-20 average.

Using these growth rates, red meat export data provided by ABARES can be grown to 2030.[349] It is calculated that beef and veal exports will increase from a 2018-20 average of 1,188 kt shipped weight (sw) to 1,492 kt (sw) in 2030. Likewise, it is calculated that sheepmeat exports will increase from a 2018-20 average of 464 kt (sw) to 534 kt (sw) in 2030. In total, 2030 red meat exports will equal 2,026 kt (sw).

For conservative modelling, it is assumed that the price premium will apply to **10%** of the 2030 exports (203 kt, sw). For the ambitious modelling, it is assumed that the premium will apply **50%** of the exports (1,013 kt, sw).

Prices in 2030

Due to the difficulty of determining a price for Australian red meat exports out to 2030, the three year average of 2018 to 2020 beef, veal and sheepmeat of Australian export prices was conservatively used. Over those three years, beef and veal sold on average at around A$8.11 million per kt (sw) and, similarly, sheepmeat sold at around A$8.15 million per kt (sw).[350]

Applying the 3% price premium gives a higher price of A$8.35 million per kt (sw) for beef and veal exports and A$8.39 million per kt (sw) for sheepmeat.

Similarly, applying the 7.5% price premium gives a price of A$8.72 million per kt (sw) of beef and veal and a price of $8.76 million per kt (sw) for sheepmeat sold.

346 MLA (2021) Global beef industry and trade report.

347 Li, S and Kallas, Z (2021) Meta-analysis of consumers' willingness to pay for sustainable food products. Appetite 163(3).

348 OCED-FAO (2021), OECD-FAO Agricultural Outlook 2021-2030, OECD Publishing.

349 Australian Bureau of Agricultural and Resource Economics and Sciences (2021) Agricultural commodities and trade data: Rural commodities - meat - beef and veal; Australian Bureau of Agricultural and Resource Economics and Sciences (2021) Agricultural commodities and trade data: Rural commodities - meat – sheep.

350 Australian Bureau of Agricultural and Resource Economics and Sciences (2021) Agricultural commodities and trade data: Rural commodities - meat - beef and veal; Australian Bureau of Agricultural and Resource Economics and Sciences (2021) Agricultural commodities and trade data: Rural commodities - meat – sheep.

Export revenue estimation

Based on this approach, a conservative scenario can be constructed where the low price premium (of 3%) from verifiable credentials is applied to 10% of 2030 red meat export volumes. This would result in a total of A$16.5 billion in export revenue.

Alternatively, an ambitious scenario can be constructed where a high price premium (of 7.5%) is applied to 50% of these export volumes. This would have resulted in a total of A$17.1 billion in export revenue.

The difference between the conservative and ambitious scenario is nearly A$570 million in export revenue. Figure 12 below shows additional estimates for a high premium, low export proportion scenario, as well as a low premium, high export proportion scenario.

	3% price premium	7.5% price premium
10% of exports (145 kt, sw)	Low premium, low export proportion **$16.5 billion in revenue**	High premium, low export proportion **$16.6 billion in revenue**
50% of exports (727 kt, sw)	Low premium, high export proportion **$16.7 billion in revenue**	High premium, high export proportion **$17.1 billion in revenue**

Figure 12: Matrix of export revenue with different verifiable credentials price premiums and 2030 export proportions affected

A.2 Red meat co-products for health and wellness markets

Conservative opportunity: A$1.4 billion in annual retail product value from cattle-derived collagen, blood plasma co-products, meat snacks and red meat protein powder by 2030. A$675 million in annual revenue for manufacturers and 1,070 jobs by 2030.

Ambitious opportunity: Over A$5.1 billion in annual retail product value from cattle-derived collagen, blood plasma co-products, meat snacks and red meat protein powder by 2030. Over A$2.6 billion in annual revenue for manufacturers and 4,070 jobs by 2030.

Global opportunity

The four red meat protein co-products that are focused on for economic analysis are collagen products (from bovine sources), bovine blood plasma derivatives, meat snacks made from red meat and red meat protein powder derivatives. Due to data limitations, other product categories such as offal and fat co-products were not estimated.

Grand View Research estimates that the global collagen market will grow to US$16.7 billion by 2028, with an average Compound Annual Growth Rate (CAGR) of 9.0%.[351] Collagen from bovine sources currently accounts for around a third of the market.[352] Taking this bovine share of the collagen market as fixed across time and projecting this forward to 2030 gives global bovine collagen product market of A$8.5 billion.[353]

Verified Market Research estimates that the global bovine blood plasma derivatives market will grow to US$2.46 billion by 2028, with an average CAGR of 4.3%.[354] Projecting this forward to 2030 gives global bovine collagen product market of A$3.4 billion.

Technavio estimates that the global meat snacks market will grow to US$12.8 billion by 2025, with an average CAGR of 8.2%.[355] It is assumed that snacks from red meat sources will conservatively comprise at least half of this market in 2030 based on existing evidence (for instance, jerky is expected to be over half the meat snacks market by 2025 and beef jerky accounted for more than 80% of jerky sales in 2020). Taking this red meat share and projecting this forward to 2030 gives a red meat snacks market of A$12.1 billion.

351 Grand View Research (2021) Collagen Market. Viewed 29 November 2021, <https://www.grandviewresearch.com/industry-analysis/collagen-market>.

352 Technavio (2018) Global Collagen Market 2018-2022.

353 1 USD = 1.29 AUD based on the 2000 to 2020 exchange rate average.

354 Verified Market Research (2021) Bovine Blood Derivatives. Viewed 29 November 2021, <https://www.verifiedmarketresearch.com/product/bovine-blood-plasma-derivatives-market/>.

355 Technavio (2021) Global Meat Snacks Market 2021-2025.

There is limited information about the red meat protein powder derivatives market. As such, the meat extract market was taken as a proxy. According to Grand View Research, by 2028 the meat extract market could reach US$21.7 billion with a CAGR of 5.2% over the forecast period.[356] Assuming that (as with how the beef collagen opportunity was modelled), red meat conservatively accounts for a third of this opportunity, then by projecting forecast growth forward, the total 2030 addressable market could reach A$10.3 billion.

Australia's share of the opportunity (conservative)

Due to data limitations on current domestic co-product production, in the conservative scenario, Australia's share of 2030 red meat production is used as a proxy to represent the country following the world trend in red meat co-product production as well.

According to forecasts by the OECD-FAO,[357] Australia will represent around 3.9% of world beef and veal production in 2030 (by kt, carcase weight equivalent). Applying this proportion to the global bovine collagen product market opportunity gives a potential market share in collagen for Australia worth A$337 million in product value in 2030. Likewise, by applying Australia's world beef and veal production share to the bovine blood plasma market, this yields a product value opportunity for Australia worth A$133 million in 2030.

Similarly, according to OECD-FAO forecasts, Australia will represent around 3.9% of world beef, veal and sheepmeat production in 2030. Applying this to the global red meat snacks market yields a product value for Australia worth A$479 million in 2030. Applying this to the global red meat protein powder market estimate yields a product value for Australia of A$410 million in 2030.

Combined, this yields a conservative red meat co-product opportunity of A$1.4 billion in product value in 2030.

Australia's share of the opportunity (ambitious)

In the ambitious scenario, Australia's share of 2030 red meat exports is used as a proxy to represent a case where Australia leans into its co-product manufacturing to the same intensity, if not more so, as its high-value red meat export performance.

According to the OECD-FAO, Australia will represent around 12.9% of global beef and veal exports in 2030. Applying this proportion to the global bovine collagen product market opportunity gives a potential market share in collagen for Australia worth A$1.1 billion in product value in 2030. Applying this share to the bovine blood plasma market yields a product value opportunity worth A$441 million in 2030.

Similarly, OECD-FAO forecasts indicate that Australia will represent around 16% of world beef, veal and sheepmeat trade in 2030. Applying this to the global red meat snacks market yields a product value for Australia worth A$1.9 billion in 2030. Applying this to the global red meat protein powder market estimate yields a product value for Australia of A$1.7 billion in 2030.

In total, this yields an ambitious red meat co-product opportunity of A$5.1 billion in product value in 2030.

Manufacturer revenue

It is assumed that the average price difference between the retail sales price and what co-product manufacturers receive will be 100%, as with the plant-based products methodology (see Section A5).

In this case, in the conservative scenario, co-product manufacturers are expected to earn A$675 million in annual revenue from the three co-product categories modelled for this report by 2030. In the ambitious scenario, this rises to over A$2.6 billion in annual revenue.

Jobs

IBISWorld's estimates for the vitamin and supplement manufacturing sector in Australia is used as a proxy to calculate the potential jobs of the co-products sector.[358] It estimates that, on average, from 2018 to 2027, wages will constitute 13% of revenue. Therefore, this 13% figure is applied to the aggregate 2030 revenue estimate to derive total wages in 2030.

IBISWorld also predicts that wages will grow 0.7% per year on average from 2018 to 2027. By projecting this growth figure forward, it is found that average wages will be around A$81,200 per employee by 2030.

Dividing the 2030 sector wages by 2030 wage per employee, a total of 1,070 jobs is estimated in the conservative scenario. In the ambitious scenario, this rises to 4,070 jobs.

356 Grand View Research (2021) Meat Extract Market Size. Viewed 29 November 2021, < https://www.grandviewresearch.com/industry-analysis/meat-extract-market>.
357 OCED-FAO (2021), OECD-FAO Agricultural Outlook 2021-2030, OECD Publishing.
358 IBISWorld (2021) Vitamin and Supplement Manufacturing in Australia.

A.3 Insect protein sources for food and feed

Conservative opportunity: A$12 million in annual revenue for insect protein producers and 40 jobs by 2030.

Ambitious opportunity: A$44 million in annual revenue for insect protein producers and 140 jobs by 2030.

Global opportunity

Technavio provides a forecast for the global edible insect market through to 2026.[359] In particular, they provide estimates for the animal nutrition (which includes livestock feed) segment of the market. For the purposes of the modelling, this is assumed to be a reasonable proxy for the insect-based livestock feed market in particular.

Technavio estimates this segment to be worth over A$1.9 billion by 2026, with an average CAGR of 28.5% over the 2018 to 2026 period.[360] Projecting this growth rate for the insect-derived animal nutrition market forward to 2030 gives a global opportunity of **A$5.3 billion**.

Australia's share of the opportunity (conservative)

Technavio estimates that in 2025, the global edible insect market will be worth A$4.3 billion. Agrifutures is aiming for a A$10 million insect protein market in Australia by 2025.[361] Using these benchmarks, Australian insect protein could represent around **0.2%** of the global insect market by around 2025, if not more, in a conservative scenario.

Australia's share of the opportunity (ambitious)

A more ambitious scenario is to view Australia's insect protein for livestock feed industry reaching a level of relative global performance akin to that of traditional feed production for the country.

According to the Alltech 2020 Global Feed Survey, global estimated feed production in 2019 was approximately 1,126 million tonnes.[362] According to the survey, Australia, in contrast, produced 9.3 million tonnes of feed (0.8% of the global). Using this share as a benchmark, the ambitious scenario sees Australia's insect protein for livestock feed industry reaching **0.8%** of the global sector.

Revenue and volume

Supposing that by 2030, in a conservative scenario, 0.2% of the global insect-based animal nutrition is captured by domestic insect feed producers, then Australia will reach **A$12.5 million** in revenue. Agrifutures identifies **A$2,000 per tonne** as the industry benchmark for insect feed.[363] It is assumed that these will be, in many cases, direct sales to livestock producers with minimal difference between retail/wholesale prices and the prices that insect feed producers receive.

Applying this price benchmark implies that around **6,200 tonnes** of insect feed could be produced in the conservative scenario. In an ambitious scenario, where 0.8% of the addressable insect-based feed market in Australia is captured, this then amounts to around **22,000 tonnes** of insect feed being produced domestically, with a revenue of **A$43.9 million**.

Jobs

Since insect protein farming is an emerging industry with little data related to its potential wage structure and average wage growth, this report has used IBISWorld's industry data for Australia's poultry meat farming sector as a proxy.

IBISWorld estimates that, on average, from 2018 to 2027, wages will constitute 10% of revenue. It also predicts that wages will grow 1.2% per year on average over the same ten-year period. By projecting this forward, average wages in Australian poultry meat farming will be around A$30,900 per employee by 2030.[364]

In the conservative scenario, by multiplying the 2030 revenue by the wage share and then dividing it by the average wage per employee, it is found that by 2030, **40 jobs** will be created for insect-based feed producers in Australia. In the ambitious scenario, this instead rises to **142 jobs.**

359 Technavio (2021) Global Edible Insect Market 2022-2026.

360 1 USD = 1.29 AUD based on the 2000 to 2020 exchange rate average.

361 Agrifutures (2020) Catalysing a $10M Australian Insect Industry: an industry-led RD&E plan.

362 Alltech (2020) 2020 Global Feed Survey. Viewed 10 December 2021, < https://www.alltech.com/feed-survey-interactive-map>.

363 Agrifutures (2020) Catalysing a $10M Australian Insect Industry: an industry-led RD&E plan.

364 IBISWorld (2021) Poultry Meat Farming in Australia.

A.4 Scaling up local, sustainable white flesh fish production

Conservative opportunity: A total retail value of around A$460 million by 2030. Approximately A$230 million in revenue for aquaculture producers with around 600 jobs by 2030.

Ambitious opportunity: A total retail value of over A$1.5 billion by 2030. Nearly A$770 million in revenue for aquaculture producers with around 1,800 jobs by 2030.

Revenue (conservative)

IBISWorld provides industry forecasts for the aquaculture sector in Australia through to 2028.[365] Based on its forecasts, revenue growth from the ten years of 2019 to 2028 is predicted to average 1.4% per year. By taking this average growth figure, the 2028 revenue forecast can be projected for an additional two years to yield a 2030 total aquaculture revenue figure of **A$2.2 billion** in Australia.

For the modelling, white flesh fish has been defined as all edible finfish that is produced in aquaculture facilities, except for salmonids and tuna. According to data from ABARES, white flesh fish provided 10.3% of the value of aquaculture production in Australia in 2019-20.[366]

By taking this market share from 2019-20 and applying it to the forecast total 2030 revenue for aquaculture producers, it can be estimated that white flesh fish products from aquaculture will conservatively generate **A$229 million** of revenue by 2030 for Australian producers.

Revenue (ambitious)

According to data from ABARES, the total commodity value of white flesh fish from aquaculture was approximately A$150 million in the 2019 calendar year.[367] Ten-year (2010-11 to 2019-20) average annual commodity value growth for the sector was 12.7%. In contrast, five-year (2015-16 to 2019-20) average annual commodity value growth was a significantly higher 19.9%.

Assuming that the white flesh fish aquaculture sector is able to sustain a reasonably high growth rate and that growth in commodity value reflects growth in revenues received by aquaculture producers, the ambitious scenario sees the sector experiencing a 'mid-point' average commodity value growth of 16%.

Projecting this forward gives white flesh fish a total revenue of **A$768.5 million** by 2030 for aquaculture producers.

Retail value

Unfortunately, there is limited industry data available on pricing of seafood through the various supply chains that operate in the sector.[368] As with plant-based products and microorganism-based protein products (see Sections A5 and A6), it is assumed there is a 100% price difference between the price received by aquaculture producers and the retail price, after transport and logistics, warehousing and wholesaling, seafood processing and packaging, and other value-chain activities.

In this case, the retail price for white flesh fish from Australian aquaculture producers in the conservative scenario is **A$459 million**. It is **A$1.5 billion** in the ambitious scenario.

Jobs

IBISWorld also provides industry wage forecasts for the Australian aquaculture sector. It estimates that, on average, from 2019 to 2028, wages will constitute 20% of revenue.

IBISWorld also predicts that wages will grow 2.9% per year on average over the same ten-year period of 2019 to 2028. By projecting this growth figure forward, it is found that average wages in Australian aquaculture will be around A$78,200 per employee by 2030.

Under the conservative scenario, dividing the 2030 sector wages by 2030 wage per employee, a total of **589 jobs** is estimated for white flesh fish aquaculture in Australia. Under the ambitious scenario, this approach yields **1,793 jobs**. For context, the total aquaculture sector in Australia only employs 7,000 people as of 2019-20.[369]

365 IBISWorld (2021) Aquaculture in Australia.

366 Australian Bureau of Agricultural and Resource Economics and Sciences (2021) Agricultural commodities and trade data: Rural commodities – fisheries.

367 Australian Bureau of Agricultural and Resource Economics and Sciences (2021) Agricultural commodities and trade data: Rural commodities – fisheries. Average taken across 2018-19 and 2019-20.

368 Rural Industries Research and Development Corporation (2016) From farm to retail – how food prices are determined in Australia.

369 Australian Bureau of Agricultural and Resource Economics and Sciences (2021) Employment in Australian fisheries and aquaculture 2019-20. Viewed 29 November 2021. <https://www.awe.gov.au/abares/research-topics/fisheries/fisheries-and-aquaculture-statistics/employment>.

A.5 Plant-based products

It is estimated that Australian domestic retail expenditure (of both locally produced and imported) finished plant-based products will reach A$5 billion in 2030.

Conservative opportunity: 300,000 tonnes of finished product could be produced (sold domestically and exported) and worth A$3 billion at retail.

Domestic manufacturing revenue could reach A$1.5 billion in annual revenue and 2,110 jobs by 2030.

Ambitious opportunity: 900,000 tonnes of finished product could be produced, driven by greater international export market penetration, and worth over A$9 billion at retail.

Domestic manufacturers could experience A$4.5 billion in annual revenue and 6,320 jobs by 2030.

Global and Asian-Pacific consumption by volume in 2030

BCG forecasts in their base-case scenario that global consumption of finished plant-based products could be 69 million metric tonnes globally by 2035 and that CAGR from 2030-2035 will average 7%.[370] Working backwards from 2035, it is possible to estimate the 2030 global consumption volume at **49 million tonnes**. Plant-based products will make up approximately 75% of global alternative protein consumption in 2030.

Again, working backwards from the 2035 BCG forecasts, it is estimated that nearly 42 million tonnes of finished alternative protein products will be consumed in the Asia-Pacific region in 2030. Assuming that plant-based products make up 75% of this consumption at the regional level as well, it can be calculated that the consumption of finished plant-based products in the Asia-Pacific region in 2030 will be equivalent to approximately **31 million tonnes** of products.

Australia's share of the global retail market

Technavio estimates that the global plant-based products retail market (including meat alternatives, milk alternatives, among other plant-based products) was A$14.9 billion in 2020.[371]

Food Frontier estimates Australian expenditure for plant-based meat alternative products (both domestically produced and imported) through retail and foodservice channels was A$154 million in 2019-20.[372] Further, Australian domestic meat alternatives manufacturing revenue was A$69.9 million in 2019-20.

Using the Technavio global retail estimate of A$14.9 billion and the Food Frontier Australian retail estimate of A$154 million as a proxy for domestic expenditure on plant-based protein alternatives more generally, Australia's share of the global plant-based protein retail market is currently approximately **1%**.

For the market sizing calculations, it is assumed that Australia maintains its current share of the global plant-based retail market at 1%.

Australia's retail consumption by volume in 2030

With the BCG estimate of global consumption volume at 49 million tonnes and assuming Australia maintains a 1% share of the global plant-based protein retail market, Australian consumers are expected to purchase around **492,000 tonnes** of finished plant-based products in 2030.

Taking an average selling point of approximately A$10 per kg, which would be a conservative retail price benchmark for high-end plant-based products to be cost competitive with traditional proteins,[373] this means that Australian retail expenditure will reach nearly **A$5 billion** by 2030 (for both domestically produced and imported products).

For context, domestic expenditure on beef was approximately A$7.8 billion in 2019, and domestic expenditure on lamb was approximately A$2 billion.[374] In terms of volume, total domestic beef and veal consumption was estimated at approximately 709,200 tonnes and sheep consumption at 177,000 tonnes in 2019.[375]

370 BCG (2021) Food for Thought.

371 Technavio (2021) Global Plant-based Protein Products Market 2021-2025.

372 Food Frontier (2020) State of the Industry: Australia's Plant-Based Meat Sector.

373 As is the case with conventional proteins, average revenue per kg is likely higher for high-quality meat alternatives but significantly less for high-volume plant-based protein products such as milk alternatives.

374 MLA (2020) 2020 Industry Fast Facts. Viewed 13 December 2021, <https://www.mla.com.au/prices-markets/market-news/2020/2020-industry-fast-facts-released/>.

375 OECD (2021) Agricultural output – meat consumption data. Viewed 13 December 2021, < https://data.oecd.org/agroutput/meat-consumption.htm>.

Australia's opportunity for local manufacturers (conservative)

It is assumed that the average price difference between the retail sales price and what food manufacturers receive will be 100% once branding, shipping and logistics, retail and warehousing, and other value-added activities (in both domestic and export supply chains) are added.[376] In other words, manufacturers receive A$5,000 per tonne of finished plant-based protein product sold.

Following guidance from stakeholders, it is assumed in the conservative scenario that Australia's plant-based products manufacturing sector will produce **300,000 tonnes** (equivalent to approximately 60% of the amount sold in Australia), with proportions sold domestically and exported to overseas markets.

Under this conservative scenario, the Australian plant-based product manufacturers will generate **A$3 billion** worth of retail products for domestic and international consumers. Of this value, **A$1.5 billion** will be received by the manufacturers.

Australia's opportunity for local manufacturers (ambitious)

In the ambitious scenario, it is assumed that Australian domestic manufacturers will triple their production volume from the conservative scenario's assumption. That is to say, Australia's production expands due to greater international market penetration, with the volume of Australian national plant-based protein consumption remaining the same.

Following guidance from stakeholders, in the ambitious scenario it is assumed Australian manufacturers produce **900,000 tonnes** of finished plant-based products – a significant amount of which is exported to the Asia-Pacific region – and earn a total retail revenue of over **A$9 billion** (of which **A$4.5 billion** is manufacturer revenue).

Jobs

Few data sources exist for Australia's plant-based meat manufacturing wages, so data was sourced from overseas industry indicators. IBISWorld's estimates for meat alternatives production in the United States indicate that wages will be 9% of revenue (2018 to 2027 average), that wages per employee will be US$52,200 in 2027, and that they will grow on average 0.2% per year (2018 to 2027 average).[377] Projecting these wages forward yields a per employee wage in 2030 of approximately A$67,600.

Applying the 9% wage to revenue ratio to the 2030 Australian plant-based products sector revenue and dividing it by the per employee wage yields a job count of approximately **2,110 jobs** in the conservative scenario. In the ambitious scenario, these calculations yield a job count of approximately **6,320 jobs**.

For context, the Australian plant-based meat industry directly employed 246 FTE jobs in 2019-20.[378]

376 This has been confirmed as an appropriate benchmark through stakeholder consultation and is supported by distribution margins calculated from the ABS Input-Output tables: ABS (2021) Australian National Accounts: Input-Output Tables, 2018-19 financial year.

377 IBISWorld (2021) Meat Alternatives Production in the US Industry Report.

378 Food Frontier (2019) Meat the Alternatives: Australia's $3 Billion Opportunity.

A.6 Precision fermentation

Conservative opportunity: Australia will produce 75,000 tonnes of finished microorganism-based protein products, worth A$750 million at retail.

This equates to A$374 million in annual revenue for protein manufacturers and 670 jobs in 2030.

Ambitious opportunity: Australia will produce 225,000 tonnes of finished microorganism-based protein products, worth A$2.2 billion at retail.

This equates to A$1.1 billion in annual revenue for protein manufacturers and 2,020 jobs by 2030.

Global opportunity

BCG forecasts in their base-case scenario that global consumption of microorganism-based alternative protein products could be 22 million metric tonnes by 2035 and that CAGR from 2030-2035 will average 8%. Based on this, it is possible to estimate that just under **15 million tonnes** of microorganism-based finished protein products might be globally produced and consumed in 2030.[379]

Australia's share of the opportunity (conservative)

The lower bound for the market share range for food and agriculture opportunities in synthetic biology was estimated to be 0.5% for Australia by 2040 in CSIRO's National Synthetic Biology Roadmap.[380]

As with the plant-based products modelling (see Section A5), it is assumed that Australian precision fermentation-derived finished protein products will retail on average for A$10 per kg.

For the conservative opportunity, the lower-bound of **0.5%** was used. Applying 0.5% to the global 2030 production figure implies that Australia could be conservatively supplying around **75,000 tonnes** of microorganism-based finished protein products through fermentation that year to both domestic and overseas markets, valued at around **A$750 million** at retail.

Australia's share of the opportunity (ambitious)

According to the Good Foods Institute (GFI), there are at least 51 companies focused primarily on fermentation for alternative protein applications. This lists companies using biomass, traditional and precision fermentation methods with microorganisms (bacteria, microalgae, protists, and fungi). They identify only one Australian company (Nourish Ingredients).[381]

However, the GFI report is non-exhaustive for Australia. Additionally, there are a number of other recent fermentation-derived protein companies have been founded in Australia (e.g., Change Foods, Eden Brew, All G Foods), focused on precision fermentation and have raised significant amounts of investment capital. Australia has a strong presence in the precision fermentation emerging industry, beyond merely one or two key companies, along with readily available access to sugar and biomass feedstock, a strong IP regime, and geographic proximity to the Asia-Pacific market.

So, based on this contextual information above, it has been assumed for the ambitious scenario that Australia could capture **1.5%** of the market share (representing how the country currently represents over 1.5% of current precision fermentation companies globally). This means Australia could be ambitiously supplying around **225,000 tonnes** of microorganism-based protein products through fermentation that year to both domestic and overseas markets, valued at around **A$2.2 billion** at retail.

379 BCG (2021) Food for Thought.

380 CSIRO Futures (2021) A National Synthetic Biology Roadmap: Identifying commercial and economic opportunities for Australia.

381 Good Food Institute (2021) 2020 State of the Industry.

Revenue

As with the plant-based products manufacturing price benchmark, it is assumed that Australian precision fermentation-derived protein manufacturers will earn on average **A$5,000 per tonne** of protein product sold.

Therefore, taking around the conservative BAU scenario for how much Australia supplies in 2030, it can be said that Australian precision fermentation facilities could be producing over **A$374 million** worth of protein products in 2030. For the ambitious scenario, this becomes **A$1.1 billion**.

Jobs

As with the CSIRO Synthetic Biology report,[382] biotechnology was used as a proxy industry to calculate the future jobs of the precision fermentation protein industry for Australia. Figures from the 2021 IBISWorld report on biotechnology in Australia were used.[383] Following the same method as the Synthetic Biology report, the 2030 average wage per worker was calculated at approximately A$145,000. Additionally, the ten-year average wage/revenue ratio was calculated to be approximately 26% for the 2018-2027 period.

Taking these figures, along with the total revenue figure above, the total employment is estimated to be around **670 jobs** in the conservative scenario and **2,020 jobs** in the ambitious scenario.

A.7 Cultivated meats

Global opportunity: A$26 billion in global sales by 2030.

Global opportunity

McKinsey predicts that cultivated meat could reach US$20 billion by 2030 in a medium growth scenario where cultivated meat can replicate processed meat and whole cuts; with sales limited to North America, Europe, and select Asia-Pacific countries.[384]

They also provide a low growth 2030 scenario of US$5 billion where cultivated meat is only able to replace processed meats and sales limited to North America, Europe, and parts of the Asia-Pacific. Likewise, they provide a 2030 high growth scenario of US$25 billion where it can replicate a variety of cuts and reaches parts of meat-consuming countries and regions around the world.

The medium growth scenario of US$20 billion by 2030 was adopted and converted to Australian dollars.[385] This gives a figure of approximately A$26 billion. Only the global opportunity is presented here because, while it is likely that Australian R&D into cultivated meat will progress, it is unlikely there will be many cultivated meat products commercially available in Australia by 2030.

It should be noted that estimates for cultivated meat are currently highly variable given the emerging nature of the product, with few revenue forecasts available and conflicting production volume forecasts. McKinsey projects 1.5 million tonnes being produced by 2030 under their medium growth scenario. In contrast, Frost & Sullivan forecasts an even smaller figure of 26,000 tonnes in demand for cell-cultured protein by 2030.[386]

382 CSIRO Futures (2021) A National Synthetic Biology Roadmap: Identifying commercial and economic opportunities for Australia.

383 IBISWorld (2021) Australia Industry (Anzsic) Report X0001, Biotechnology in Australia.

384 McKinsey & Company (2021) Cultivated meat: Out of the lab, into the frying pan. Viewed 29 November 2021, <https://www.mckinsey.com/industries/agriculture/our-insights/cultivated-meat-out-of-the-lab-into-the-frying-pan>.

385 1 USD = 1.29 AUD based on the 2000 to 2020 exchange rate average.

386 Frost & Sullivan (2021) Global Meat Analogs Protein Ingredients Growth Opportunities.

Appendix E – Emerging protein opportunities

R&D is enabling many new protein production systems that have the potential to contribute to the global protein mix. The table below identifies other possible protein opportunities that could be value-adding in Australia.

Table 14: Emerging protein opportunities

OPPORTUNITY	DESCRIPTION	EXAMPLES
Protein from air (CO_2)	Protein made from captured atmospheric carbon (in some cases, from industrial emissions) and microbial fermentation using single-cell bacteria. Mid-stage TRL* with limited commercial products.	• **Air Protein (USA) –** Focus on scaling up the production of air-based meat and demonstrating the versatility of platform to make products across a variety of categories, including poultry, beef, pork, and seafood.[387] • **Solar Foods (FI) –** Protein product (Solein) submitted to the EU Commission for novel food approval. Solar Foods estimates that commercial production will begin in the first half of 2023.[388] • **Deep Branch (UK) –** Scalable, sustainable generation of high value protein using microbes to convert carbon dioxide from industrial emissions into protein that is used in fish and poultry feed.[389]
Protein from plastic	Harnessing bacteria that naturally break down plastics into protein. Very early TRL.	• **Food Generator (US/DE) –** Early-stage research collaboration from University of Illinois Urbana-Champaign, and Michigan Technological University.[390]
Mycoprotein / fungal	Harnessing naturally existing proteins produced by fungi and mycelium for alternative meat and feed products. Mid- to late-stage TRL with numerous commercial scale examples.	• **Quorn (UK) –** Commercially producing mycoprotein products for 19 countries, through fermentation of a fungus found in soil.[391] • **Nature's Fynd (US) –** Scaling production of Fy fungi protein ingredient in a new commercial facility in Chicago.[392] • **Fable Foods (AU) –** Expanding Australian and overseas production of alternative meat products using protein ingredients found in shiitake mushrooms.[393] • **Novozymes (DE) –** Launched a global platform for research institutions, NGOs, and companies to receive scale-up support for fungal and mycelium protein products under development.[394]
Animal free whole cuts	Similar to mycoprotein (above), fermented protein products that aim to mimic whole cuts of meat with fibrous, aligned, intact tissues. Mid-stage TRL as prototypes and production facilities are still under development.	• **Meati (USA) –** Developing mycelium based single ingredient, whole-cut steak and chicken products. Planning construction of a production plant and commercial launch in 2022.[395] • **Atlast Food Co (USA) –** Creating whole cut plant-based meats like bacon and steak using mycelium.[396]

387 Air Protein (2021) FAQ and Resources. Viewed 16 November 2021, <https://www.airprotein.com/faq-and-resources>.

388 Solar Foods (2021) Solein submitted to the European Commission for novel food approval. Viewed 16 November 2021, <https://solarfoods.fi/our-news/solein-submitted-to-the-european-commission-for-novel-food-approval/>.

389 Deep Branch (2020) Ground-breaking carbon recycling project launches with £3million Innovate UK funding. Viewed 16 November 2021, <https://deepbranch.com/2020/07/17/react-first_launch/>.

390 Merck (2021) A Food Generator that turns waste into meals. Viewed 16 November 2021, <https://www.merckgroup.com/en/research/science-space/envisioning-tomorrow/scarcity-of-resources/food-generator.html>.

391 Souza Filho PF, Andersson D, Ferreira JA and Taherzadeh MJ (2019) Mycoprotein: environmental impact and health aspects. World Journal of Microbiology & Biotechnology 35(10), 147. DOI: 10.1007/S11274-019-2723-9./60

392 Food Navigator USA (2021) Nature's Fynd raises $350m in Series C to build nutritional fungi protein platform, gears up for late 2021 launch. Viewed 17 November 2021, <https://www.foodnavigator-usa.com/Article/2021/07/19/Nature-s-Fynd-raises-350m-in-Series-C-to-build-nutritional-fungi-protein-platform-gears-up-for-late-2021-launch>.

393 Shu C (2021) Mushroom-based meat alternative startup Fable Food raises $6.5M AUD, will launch in the US. Viewed 17 November 2021, <https://techcrunch.com/2021/08/11/mushroom-based-meat-alternative-startup-fable-food-raises-6-5m-aud-will-launch-in-the-u-s/>.

394 Novozymes (2021) Novozymes is combining cutting-edge science and business expertise to help feed the world sustainably. Viewed 17 November 2021, <https://www.novozymes.com/en/news/news-archive/2021/9/novozymes-is-combining-cutting-edge-science-and-business-expertise>.

395 Sovino C (2021) Expect Fungi-Based Steak On Your Plate By 2022: Meati Raises $50 Million. Viewed 16 November 2021, <https://www.forbes.com/sites/chloesorvino/2021/07/06/expect-fungi-based-steak-on-your-plate-by-2022-meati-raises-50-million/?sh=13906a213264>.

396 Atlast (2021) Bio. Viewed 16 November 2021, <https://www.atlastfood.co/media-kit>.

OPPORTUNITY	DESCRIPTION	EXAMPLES
Microalgae	Growing a variety of algae species, able to produce protein ingredients using carbon dioxide, light, and sea or bore water. Mid-stage TRL as prototypes and pilot facilities are still under development.	• **Venus Shell Systems (AU)** – Developing a pilot seaweed farm that uses light, carbon dioxide, water, and residue to produce molecules used in a range of products including foods (muesli, pasta), digestive health and skin care products.[397] • **Provectus Algae (AU)** — Expecting to use an industrial scale algae platform for commercially viable bulk protein production within the next decade (by 2031).[398] • **Algae Pharm (AU)** – Growing commercial quantities of algae in ponds of bore water and salt; planning use in alternative protein products for livestock, pet, and human consumption.[399]
Protein production in plants using disarmed viral vectors	Viral vectors can be used to temporarily direct the production of food, chemicals, and pharmaceutical proteins in plants. These vectors offer improvements to the yield and speed of protein production in plant-based manufacturing.[400] Very early TRL.	• Researchers in the US have used a disarmed viral vector to produce antibodies against the Ebola virus in a plant related to tobacco.[401] • Researchers in Spain have used a viral vector to produce antifungal proteins in a plant related to tobacco. These antifungal proteins have potential uses in both medicine and agriculture.[402]
Artificial Intelligence (AI)/machine learning informed alternate protein	Using computer models to accelerate development of microbial strains able to produce novel food properties and ingredients. Mid-stage TRL.	• **NotCo (CL) –** using AI to develop plant-based foods such as meat and milk alternative products. AI is used to create recipes that match the taste, colour or texture of existing foods or result in new flavours.[403] • **Amai Proteins (IL)** – creating proteins with novel properties for the mass food market using computational protein design and fermentation.[404] • **Protera (FR/CL) –** applying deep learning to large protein databases to predict the structure and function of proteins that can enable new and improved food products. In 2020, Protera raised $5.6 million scale production of a natural protein preservative for baked goods.[405]
Cell cultured beverages	Cultivating mammalian cells to produce beverages that are nutritionally and functionally comparable to animal-based products. Early to mid-stage TRL.	• **BioMilk (IL) –** culturing mammary cells from cows, sheep, or camels to produce alternative milk products without livestock farms. BioMilk is working to improve production efficiency and eventually licence their technology to the dairy industry.[406] • **BIOMILQ (US) –** culturing human mammary cells to produce an infant milk product that is nutritionally similar to breastmilk.[407] Raised $21 million in 2021 for process development and optimisation.[408]

*TRL: Technology Readiness Level

397 ABC (2020) New seaweed processing plant opens in southern NSW - The Science Show. Viewed 17 November 2021, <https://www.abc.net.au/radionational/programs/scienceshow/new-seaweed-processing-plant-opens-in-southern-nsw/12512334>.

398 Watson E (2021) 'If we can control the light, we can control the DNA...' Provectus Algae unlocks algae's potential as an industrial platform for high-value ingredients. Viewed 17 November 2021, <https://www.foodnavigator-usa.com/Article/2021/07/06/If-we-can-control-the-light-we-can-control-the-DNA-Provectus-Algae-unlocks-algae-s-potential-as-an-industrial-platform-for-high-value-ingredients>.

399 ABC News (2020) Rural algae farm produces alternative plant-based protein, rich in Omega-3, in Goondiwindi. Viewed 17 November 2021, <https://www.abc.net.au/news/rural/2020-06-16/goondiwindi-outback-algae-farm-producing-plant-based-protein/12317032>.

400 Kopertekh L and Schiemann J (2017) Transient Production of Recombinant Pharmaceutical Proteins in Plants: Evolution and Perspectives. Current Medicinal Chemistry 26(3), 365–380. DOI: 10.2174/0929867324666170718114724.

401 Phoolcharoen W, Bhoo SH, Lai H, Ma J, Arntzen CJ, Chen Q and Mason HS (2011) Expression of an immunogenic Ebola immune complex in Nicotiana benthamiana. Plant biotechnology journal 9(7), 807–816. DOI: 10.1111/J.1467-7652.2011.00593.X.

402 Shi X, Cordero T, Garrigues S, Marcos JF, Daròs JA and Coca M (2019) Efficient production of antifungal proteins in plants using a new transient expression vector derived from tobacco mosaic virus. Plant Biotechnology Journal 17(6), 1069–1080. DOI: 10.1111/PBI.13038.

403 London L (2020) NotCo: Creating Plant-Based Food Alternatives with AI. Viewed 22 November 2021, <https://digital.hbs.edu/platform-digit/submission/notco-creating-plant-based-food-alternatives-with-ai/>.

404 Amai Proteins (2018) Home. Viewed 22 November 2021, <https://www.amaiproteins.com/>.

405 Cumbers J (2020) Say Goodbye To Moldy Bread: AI-Driven Biotech Startup Is Fermenting Natural Ingredients To Double Bakery Shelf Life. Viewed 22 November 2021, <https://www.forbes.com/sites/johncumbers/2020/07/07/startup-protera-rises-in-the-51-billion-clean-label-market-with-cultured-ingredients-that-double-bakery-shelf-life/>.

406 Watson E (2021) Cell-cultured milk: Tech fantasy or a liquid goldmine? BioMilk goes public. Viewed 29 November 2021, <https://www.foodnavigator-usa.com/Article/2021/04/23/Cell-cultured-milk-Tech-fantasy-or-a-liquid-goldmine-BioMilk-goes-public>.

407 Watson E (2021) Cell-cultured human milk will be nutritional gamechanger for infant formula, says BIOMILQ, 'but it's not bio-identical to mother's milk'. Viewed 29 November 2021, <https://www.foodnavigator-usa.com/Article/2021/06/01/Cell-cultured-human-milk-will-be-nutritional-gamechanger-for-infant-formula-says-BIOMILQ-but-it-s-not-bio-identical-to-mother-s-milk>.

408 Watson E (2021) BIOMILQ raises $21m in series A round to accelerate production of cell-cultured human milk. Viewed 29 November 2021, <https://www.foodnavigator-usa.com/Article/2021/10/20/BIOMILQ-raises-21m-in-series-A-round-to-accelerate-production-of-cell-cultured-human-milk>.

Appendix F – Country-based protein initiatives

Table 15: Select countries and associated protein initiatives

COUNTRY	PROTEIN FOCUSED INITIATIVES
Australia	Relevant national initiatives include: • Ag2030 – Government plans to exceed $100 billion farm gate output by 2030.[409] • CSIRO's Future Protein Mission – Aiming to create new protein ingredients and products that earn an additional $10 billion in revenue by 2030.[410] • National Agriculture Innovation Policy Statement – sets out four new innovation priorities for Australian agriculture (exports, climate resilience, biosecurity and digital agriculture).[411] • The Modern Manufacturing Strategy – includes food manufacturing as a key focus area.[412] Strong focus on agriculture and food systems: • In 2021-22, agricultural production is expected to reach a record value of over $78 billion.[413] • Exports make up approximately 70% of the value of agriculture, forestry, and fisheries production.[414] • Agriculture accounts for over half (55%) of land use and a quarter (25%) of water extractions in Australia.[415]
The Netherlands	Reputation for food and agricultural accelerators: • Startlife – accelerator that has helped to grow 3,000+ companies and is well positioned to support plant-based protein opportunities.[416] • OnePlanet Research Centre – focussed on digital and AI approaches to food sustainability.[417] Home to Foodvalley: • A region of the Netherlands has been labelled the 'Silicon Valley of food' given the number of food companies and agriculture innovation research centres in the area.[418] • Protein cluster – a Foodvalley business network supporting collaboration across all levels of the supply chain.[419]

409 Department of Agriculture Water and the Environment (2021) Delivering Ag2030. Viewed 20 January 2022, <https://www.awe.gov.au/agriculture-land/farm-food-drought/ag2030>.

410 CSIRO (n.d.) Future Protein. Viewed 8 November 2021, <https://www.csiro.au/en/about/challenges-missions/future-protein-mission>.

411 Department of Agriculture Water and the Environment (2021) National Agricultural Innovation Policy Statement.

412 Australian Government (2020) Make It Happen: The Australian Government's Modern Manufacturing Strategy. Canberra.

413 Australian Bureau of Agricultural and Resource Economics (2021) Agricultural overview: December quarter 2021. Viewed 20 December 2021, <https://www.awe.gov.au/abares/research-topics/agricultural-outlook/agriculture-overview>.

414 Australian Bureau of Agricultural and Resource Economics and Sciences (2021) Snapshot of Australian Agriculture 2021. ABARES Insights (2). DOI: 10.1071/9780643094659.

415 Australian Bureau of Agricultural and Resource Economics and Sciences (2021) Snapshot of Australian Agriculture 2021. ABARES Insights (2). DOI: 10.1071/9780643094659.

416 Netherlands Foreign Investment Agency (2020) No Beef Here: How the Dutch are Innovating Plant-Based Proteins. Viewed 20 January 2022, <https://investinholland.com/news/no-beef-here-how-the-dutch-are-innovating-plant-based-proteins/>.

417 OnePlanet Research Center (2021) Home. Viewed 20 January 2022, <https://oneplanetresearch.nl/>.

418 Fast Company & Inc (2020) How the Netherlands became a plant-based protein powerhouse. Viewed 20 January 2022, <https://www.fastcompany.com/90573547/how-the-netherlands-became-a-plant-based-protein-powerhouse>.

419 The Protein Cluster (2018) The Protein Cluster. Viewed 20 January 2022, <https://www.theproteincluster.com/tpc/>.

COUNTRY	PROTEIN FOCUSED INITIATIVES
Canada	Strong ecosystem for plant-based proteins: • Canada offers a combination of features including access to raw commodities, international trade agreements, an attractive innovation ecosystem and a highly integrated supply chain.[420] • Up to CA$173 million of funding has been committed to the Protein Industries Supercluster.[421] Canada has set ambitious plans in their 2035 roadmap for the protein sector including:[422] • Aiming to become a hub for plant-based protein innovation. • Adding an additional CA$25 billion to plant-based sales per year. • Implementing regulatory system changes to enable the development and commercialisation of plant-based foods • Building, expanding, attracting and retaining companies (including internationals).
Singapore	Strong focus on alternative proteins: • Singapore's Agfood strategy includes sustainable proteins as a core theme. • First regulatory approval of cultured meat and the only country where alternative protein sales include cell-based products.[423] • Food Tech Innovation Centre to receive more than SG$30 million of investment funding from Temasek and A*STAR over 3 years.[424] • Good Protein Fund (capital from 32 companies) established to guide companies on IP, org design, scale-up, recruitment and fundraising activities.[425] • Home to South East Asia's most advanced infrastructure for scaling plant-based proteins. [426]
China	Focus on alternative protein production: • Cultivated meat was included in China's official Five-Year Agricultural Plan. According to GFI APAC, this indicates a national interest in cultivated meat and a high chance of future government funding in the area.[427] • Government R&D program called 'Green Biological Manufacturing' supported by US$93 million in funding for plant-based and cultivated meat manufacturing.[428] • Nestle invested AU$155 million for a new plant-based product production facility in China.[429]

420 Protein Industries Canada (2021) Sector Roadmap 2035. Viewed 21 January 2022, <https://www.proteinindustriescanada.ca/sector-roadmap>.

421 Government of Canada (2021) Canada's Protein Industries Supercluster. Viewed 21 January 2022, <https://www.ic.gc.ca/eic/site/093.nsf/eng/00012.html>.

422 Protein Industries Canada (2021) Sector Roadmap 2035. Viewed 21 January 2022, <https://www.proteinindustriescanada.ca/sector-roadmap>.

423 Green Queen (2020) Breaking: Eat Just Wins World's First Regulatory Approval For Cell-Based Meat In Singapore. Viewed 20 January 2022, <https://www.greenqueen.com.hk/amp/breaking-eat-just-wins-worlds-first-regulatory-approval-for-cell-based-meat-in-singapore/>.

424 Temasek (2021) Temasek establishes the Asia Sustainable Foods Platform to accelerate the commercialisation of sustainable foods in Asia. Viewed 21 January 2022, <https://www.temasek.com.sg/en/news-and-resources/news-room/news/2021/Temasek-establishes-Asia-Sustainable-Foods-Platform-accelerate-commercialisation-sustainable-foods>.

425 Green Queen (2021) Good Protein Fund I: Singapore VC Raises US$25M To Build Sustainable Food System Through Alt Proteins. Viewed 21 January 2022, <https://www.greenqueen.com.hk/good-protein-fund-i-singapore-vc-raises-us25m-to-build-sustainable-food-system-through-alt-proteins/>.

426 Good Food Institute APAC (2021) MAPPED: Singapore's Plant-Based Meat B2B Ecosystem. Viewed 21 January 2022, <https://www.gfi-apac.org/blog/mapped-singapores-plant-based-meat-b2b-ecosystem/>.

427 Vegconomist (2022) China's Five-Year Agricultural Plan Includes Cultivated Meat for the First Time Ever. Viewed 31 January 2022, <https://vegconomist.com/cultivated/five-year-agricultural-plan/>.

428 The Good Food Institute (2021) Look closer: China is quietly making moves on cultivated meat. Viewed 21 January 2022, <https://gfi.org/blog/china-is-making-moves-on-cultivated-meat/>.

429 Food & Drink Business (2020) Nestlé expands China operations. Viewed 22 January 2022, <https://www.foodanddrinkbusiness.com.au/news/nestl-expands-china-operations>.

COUNTRY	PROTEIN FOCUSED INITIATIVES
Denmark	Strong focus on plants-based protein:[430] • The Danish government have dedicated EU€168 million to plant-based research and development. • An EU€78 million eco-scheme will pay Danish farmers bonuses for growing plant-based protein crops for human consumption. • Denmark's green proteins strategy for animals and humans has been backed by EU€35 million in funding over five years.
New Zealand	Working on emerging alternative protein opportunities: • Partnering with Singapore to research alternative protein opportunities, dedicating NZ$11.8 million into the New Zealand-Singapore Bilateral Research programme on future foods.[431] • Emerging Proteins NZ network set up to accelerate development of New Zealand's alternative proteins sector.[432]
USA	Reduced meat consumption and an increase in alternative protein opportunities: • American Heart Association's dietary guidelines have recommended reducing animal-based meat consumption.[433] • The USDA could guarantee up to US$200 million in loans for alternative protein companies.[434] • Two of the most well-known plant-based protein companies were founded in the US (Impossible and Beyond Meat).[435] • A market leader in synthetic biology R&D and scale-up, creating a favourable ecosystem for precision fermentation opportunities.[436]
Israel	Hub for alternative protein innovation: • Investments in alternative proteins are growing quickly with US$114 million raised in 2020, eight times greater than 2018 investment capital.[437] • According to GFI's database, Israel comprises 6% of alternative protein start-ups globally.[438] • Home to Super Meat a restaurant test kitchen allowing consumers to try cultivated chicken, 3D-printed cell-based meat and other alternative protein innovations.[439] • Released an Alternative Protein National Plan in 2020, a roadmap for Israel to become a global leader in alternative proteins.[440]

430 GFI Europe (2021) Denmark announces 1 billion kroner for plant-based foods in historic climate agreement. Viewed 22 January 2022, <https://gfieurope.org/blog/denmark-plant-based-investment-in-climate-agreement/>.

431 New Zealand Ministry of Foreign Affairs and Trade (2020) Singapore: Alternative Proteins. Viewed 31 January 2022, <https://www.mfat.govt.nz/en/trade/mfat-market-reports/market-reports-asia/singapore-alternative-proteins-9-december-2020/>.

432 Emerging Proteins NZ (2021) What will it take for the sector to thrive? Emerging Proteins in Aotearoa New Zealand: What will it take for the sector to thrive?

433 Geraghty M, Leonard J and Metrick C (2019) Sustainable Protein: Investing for Impact at the Nexus of Environment, Human Health and Animal Welfare.

434 The Breakthrough Institute (2020) Federal Support for Alternative Protein for Economic Recovery and Climate Mitigation.

435 Food & Drink Business (2021) Report: Australian plant-based protein sector doubles in a year. Viewed 23 January 2022, <https://www.foodanddrinkbusiness.com.au/news/report-australian-plant-based-protein-sector-doubles-in-a-year>.

436 Bergin J (2020) Synthetic Biology: Global Markets.

437 GFI Israel (2021) Israel State of Alternative Protein Innovation Report 2021.

438 Green Queen (2021) Israel Alternative Protein Companies Tripled Investment In 2020, New Data Shows. Viewed 21 January 2022, <https://www.greenqueen.com.hk/israel-alternative-protein-companies-tripled-investment-in-2020-new-data-shows/>.

439 Green Queen (2020) Israel's Prime Minister Tries Aleph Farms Cultivated Steak & Pledges Government Support For Cell-Based Meat. Viewed 20 January 2022, <https://www.greenqueen.com.hk/amp/israels-prime-minister-tries-aleph-farms-cultivated-steak-pledges-government-support-for-cell-based-meat/>.

440 GFI Israel (2021) Israel State of Alternative Protein Innovation Report 2021.

Appendix G – Glossary

Absorptive capacity A firm's ability to identify, incorporate and apply new knowledge from external sources.[441]

Agriculture 4.0 The next generation of technologies set to revolutionise the agriculture and food sector, including robotics, remote sensing and machine learning, bioscience, novel farming techniques, and food innovation and processing.[442]

Bioreactor A culture vessel designed for growing organisms (yeast, bacteria or animal cells) under controlled conditions. They provide an effective environment for industrial scale conversion of raw materials into useful products.[443]

Cell culture media Any gel or liquid that supplies the nutrients necessary for cell cultures to survive and grow in an artificial environment.[444]

Circularity A term used to describe environmental, economic and technical systems that aim to eliminate waste and maximise the reuse of resources.

Co-products Secondary red meat products that are still valuable but less so than primary cuts of meat such as skin, bones, blood and organs.[445] Co-products are generally only intended for human consumption, whereas by-products can refer to edible or inedible materials.[446]

Crop pre-breeding Involves identifying and isolating desirable genetic traits (e.g. disease resistance) in crop wild relatives and introducing these into breeding lines that can be readily crossed with modern crop varieties.[447]

Cultivated meats The creation of animal cell-based proteins using tissue engineering concepts. Also known as cell-based meat, cell cultured meat, *in vitro* meat, lab grown meat and clean meat.

Fractionation Process that uses the difference in size, shape and density of starch, protein and fibre to separate these components of crops. Fractionation can occur via wet or dry processes.[448]

Hydrolysis A chemical reaction between a chemical substance (e.g. salts, proteins and fats) and water that leads to the decomposition of the substance and water.[449]

Industry 4.0 The fourth shift in manufacturing enabled by a set of technologies including big data, autonomous robots, smart and autonomous systems, additive manufacturing, the Internet of Things (IoT) and machine learning.[450]

In vitro Biological processes made to occur in an artificial environment outside a living organism.[451]

Life Cycle Analysis (LCA) A tool used to assess the environmental impact of a product's entire life span, from production until after the product is no longer used.[452]

Nutraceuticals Products consumed for specific medicinal, health, wellness and/or additional nutritional benefits (usually food-derived). This includes vitamins, supplements and minerals. Nutraceuticals often result from the convergence of food and pharmaceutical technologies.[453]

Offal Offal includes a variety of non-muscular parts of beef, sheep and lamb carcasses such as tongue, kidneys, liver and thyroid glands.[454]

Precision fermentation A process that uses microorganism strains such as bacteria and yeast to produce specific functional ingredients such as proteins for global food supply purposes.

Prions Transmissible pathogenic agents that can lead to abnormal folding of normal cellular proteins called prion proteins. The abnormal folding of these proteins leads to brain damage in humans and animals and is a characteristic sign of prion diseases.[455]

Synthetic biology The application of engineered biological solutions to industrial, health and environmental challenges.

Technology Readiness Level (TRL) A benchmarking tool used to track progress and development of a technology from early stage research (TRL 1) to system demonstration over its full range of expected conditions (TRL 9).[456]

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