On-farm applications of advanced bioengineering

Preliminary opportunity identification and assessment

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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.

We would also like to acknowledge the contributions of the stakeholders who contributed to this work, both from CSIRO and the wider advanced bioengineering community.

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Foreword

In August 2021, CSIRO released the *A National Synthetic Biology Roadmap*, which found that under a high growth, high market share scenario, synthetic biology could unlock up to $27 billion in annual revenue and 44,000 new jobs for Australia by 2040. It also identified food and agriculture as one of the largest emerging markets for synthetic biology applications.

Advanced bioengineering (also referred to as synthetic biology) is the design and production of novel, functional biological products through the application of engineering principles and genetic technologies. While high level information outlining potential use cases for bioengineering solutions in agriculture exists, there is little guidance on who, how and what is practically needed to achieve on-farm impact and deliver on those opportunities identified.

This research explores the most impactful bioengineering opportunities that exist to overcome challenges with pests and disease, waste and crop loss, as well as take advantage of opportunities with new crops, reduced/alternative inputs, new production systems and markets for Australian agriculture, in addition to potential areas for development and adoption.

Consideration was given to who is currently doing work in this space, both domestically and internationally, as well as commercial bioengineering and other technology applications currently available to the agriculture sector, or that could be repurposed for agricultural use.

The report provides guidance on the current "state of play" of bioengineering in Australian agriculture and informs government, industry and AgriFutures Australia on research and commercialisation opportunities to engage in advanced bioengineering, including the breadth and depth of opportunities, the likely impact and the necessary steps to delivery.

This report has been produced under AgriFutures Australia's National Challenges and Opportunities Arena which focuses on thought provoking and horizon-scanning research to inform debate and policy on issues of importance across rural industries.

It is an addition to AgriFutures Australia's diverse range of over 2000 research publications, most of which are available for viewing, free downloading or purchasing online at: www.agrifutures.com.au

Michael Beer
General Manager, Business Development
AgriFutures Australia

Executive summary

This report provides a preliminary assessment of eight on-farm applications of advanced bioengineering techniques that could benefit Australia's agriculture, aquaculture and forestry industries over the next 10 years. Advanced bioengineering (also referred to as synthetic biology) is the design and production of novel, functional biological products through the application of engineering principles and genetic technologies. The intent of the report is to help AgriFutures Australia and their producer stakeholders better understand the potential benefits that advanced bioengineering can offer and facilitate discussions around the most valuable applications of this technology area for Australia's agriculture industries.

Advanced bioengineering can help address key agricultural and environmental challenges

Advanced bioengineering solutions can harness the power of biological processes to improve agricultural productivity, detect and control pest and disease threats, reduce traditional agrochemical use, remediate land and water, and improve animal welfare. These solutions can support the agricultural sector's ambition to boost farm-gate output to $100 billion by 2030.[1]

For technology developers, the successful commercialisation of advanced bioengineering solutions for Australia's food and agriculture sector could unlock up to $19.2 billion in annual revenue and 31,200 new jobs for Australia by 2040.[2]

Australia has bioengineering research strengths, but deeper industry collaboration will be necessary to bridge the commercialisation gap

Australia has a strong and growing advanced bioengineering research community;[3] however, awareness of and engagement with these emerging solutions is low amongst agricultural producers. Ensuring end-users are engaged in co-design and demonstration of bioengineering opportunities will be critical to the successful commercialisation and adoption of these emerging solutions.

1 DAWE (2021) Delivering Ag2030, May 2021. Department of Agriculture, Water and the Environment, Canberra. https://www.awe.gov.au/sites/default/files/documents/ag-2030.pdf

2 CSIRO Futures (2021) A National Synthetic Biology Roadmap: Identifying commercial and economic opportunities for Australia. CSIRO, Canberra.

3 Australia ranks 9th globally for research impact for synthetic biology (led by the University of Queensland), and 13th internationally for patent numbers. Critical Technologies Policy Coordination Office (2021) Synthetic biology. <https://www.pmc.gov.au/sites/default/files/publications/ctpco-tech-cards-synthetic-biology-aust_0.pdf>.

Findings of the preliminary analysis

Eight opportunities were assessed (see Table 1) after a scoping exercise (see Appendix A). Assessment included a consideration of current technical and commercial maturity, key challenges to reaching commercial maturity, and the primary benefits over existing products.

While the majority of opportunities have an existing commercially available product, there is often only one or two globally, and they have a relatively small market share compared to more traditional, competing approaches. Coupled with the breadth of each of these opportunity areas, this highlights that there are product development opportunities for Australian businesses across all eight fields. There is also variation between different applications in each opportunity. As such, assessments for individual technologies or businesses may not match with the overall opportunity assessment below.

Producers, technology developers and other potential investors will weight the framework criteria differently, and so prioritise different opportunities for further investment (see Next steps). Making informed investment decisions will require conducting deeper analysis on prioritised opportunities and specific applications within them. This could include economic analysis into the size of the opportunity, defining R&D activities to further mature these applications, and identifying implementation considerations.

Table 1: Summary of preliminary opportunity analysis

		MATURITY		CHALLENGE						PRIMARY BENEFIT			
	OPPORTUNITY	Commercial availability	Maximum TRL	Technical	Plug and play	Effectiveness	Cost	Public attitude	Regulation	Yield	Product quality	Cost saving	Environment, human health and animal welfare
1	Engineered biosensors for product quality	Green	9			Red	Red				Green	Green	
2	Engineered biosensors for animal and crop health	Green	9			Red	Red			Green	Green		Green
3	Biomanufactured animal feed	Green	9	Red			Red	Red	Red	Green	Green	Green	Green
4	Biomanufactured agricultural chemicals	Green	9	Red		Red	Red		Red			Green	Green
5	Engineered bioremediation solutions	Green	9	Red			Red	Red	Red	Green			Green
6	Engineered biological agricultural treatments	Green	9	Red		Red	Red	Red	Red	Green	Green		Green
7	Engineered biosensors for environmental conditions	Yellow	6			Red	Red			Green	Green		Green
8	On-farm bioenergy solutions	Yellow	5	Red	Red		Red		Red				Green

Commercial availability rating

- Green: Commercial scale-up (CRI 3) feasible in 5 years or less
- Yellow: Commercial scale-up (CRI 3) feasible in 5-10 years

Challenge rating

- Red: Potentially significant challenge that could delay commercialisation of some applications in this opportunity
- White (blank): Not expected to be a significant challenge that delays commercialisation of applications in this opportunity

Benefit rating

- Green: Expected to be a primary benefit compared to conventional solutions
- White (blank): Not expected to be a primary benefit compared to conventional solutions

Contents

1 Introduction

What is advanced bioengineering?

Advanced bioengineering (also referred to as synthetic biology) is the design and production of novel, functional biological products through the application of engineering principles and genetic technologies. It offers greater speed and precision in biological design and engineering compared to previous generations of genetic engineering approaches with potential applications across a range of sectors.[4]

The successful commercialisation of advanced bioengineering solutions for Australia's food and agriculture sector could unlock up to $19.2 billion in annual revenue and 31,200 new jobs for Australia by 2040.[5] However, most agricultural producers – in fact, most Australians[6] – have limited awareness of this emerging field of technology and how it might support the agriculture sector's economic and environmental goals.

Advanced bioengineering can help address key agricultural and environmental challenges

Advanced bioengineering solutions can harness the power of biological processes to improve agricultural productivity, detect and control pest and disease threats, reduce traditional agrochemical use, remediate land and water, and improve animal welfare. These solutions can support the agricultural sector's ambition to boost farm-gate output to $100 billion by 2030.[7]

Table 1 describes three biotechnologies that can be applied in the agriculture sector (biomanufacturing, biosensors and biologicals) and highlights how advanced bioengineering solutions can improve upon existing approaches.

Table 1: Advanced bioengineering can optimise the functionality, performance and cost-effectiveness of biomanufacturing, biosensors, and biologicals to enable their application in diverse challenges

TECHNOLOGY	BENEFITS OF ADVANCED BIOENGINEERING	ON-FARM OPPORTUNITIES
Biomanufacturing A production process that employs biological systems (e.g., yeasts, cyanobacteria, algae) to convert carbon-based feedstocks into target compounds through fermentation.	• Production of a broader range of products with higher specificity • Use of more diverse feedstocks • Optimised production pathways with greater productivity and efficiency.[8]	• Agricultural chemicals • Animal feed and feed additives • Bioenergy solutions
Biosensors A class of sensor that uses biological systems (e.g., molecules, proteins, cells, or cell groups) to detect and respond to target molecules.	• Improved operating parameters such as optimised detection ranges and detection rates • Greater robustness, selectivity and sensitivity • Improved safety (e.g., enhanced immobilisation).[9]	• Environmental (soil and water) conditions • Animal and crop health • Product quality
Biologicals Products that contain functional biological systems (e.g., enzymes, RNA, microbes) as active ingredients may offer alternatives to chemical solutions for diverse agricultural challenges.	• Increased efficacy and cost effectiveness through improved functionality and stability • Improved safety (e.g., blocking disease-causing agents, preventing the formation of harmful molecules).[10]	• Agricultural treatments (fertilisers and pesticide alternatives) • Bioremediation solutions

4 CSIRO Futures (2021) A National Synthetic Biology Roadmap: Identifying commercial and economic opportunities for Australia. CSIRO, Canberra.

5 CSIRO Futures (2021) A National Synthetic Biology Roadmap: Identifying commercial and economic opportunities for Australia. CSIRO, Canberra.

6 CSIRO (2021) Public attitudes towards synthetic biology. Viewed 1 April 2022, <https://research.csiro.au/synthetic-biology-fsp/public-attitudes/>

7 DAWE (2021) Delivering Ag2030, May 2021. Department of Agriculture, Water and the Environment, Canberra. https://www.awe.gov.au/sites/default/files/documents/ag-2030.pdf

8 Kelwick R, Webb A, Freemont P (2020) Biological Materials: The Next Frontier for Cell-Free Synthetic Biology. Frontiers in Bioengineering and Biotechnology, 8. DOI: 10.3389/fbioe.2020.00399; DePalma A (2014) Transforming Biomanufacturing Operations: Utilizing synthetic biology Techniques in the Production of Novel Biotherapeutics. Genetic Engineering and Biotechnology News, 34(17). DOI: 10.1089/gen.34.17.13.

9 Moratti C, Scott C, Coleman N (2022) Synthetic Biology Approaches to Hydrocarbon Biosensors: A Review. Frontiers in Bioengineering and Biotechnology, 9. DOI: 10.3389/fbioe.2021.804234.

10 Perpetuo E, Souza C, Nascimento C (2011) Engineering Bacteria for Bioremediation. In Carpi A (ed.) Progress in Molecular and Environmental Bioengineering - From Analysis and Modeling to Technology Applications, IntechOpen. DOI: 10.5772/19546; Kumar J, Ramlal A, Mallick D, Mishra V (2021) An Overview of Some Biopesticides and Their Importance in Plant Protection for Commercial Acceptance. Plants, 10(6):1185. DOI: 10.3390/plants10061185; Mitter E., Tosi M, Obregón D, Dunfield K, Germida J (2021) Rethinking Crop Nutrition in Times of Modern Microbiology: Innovative Biofertilizer Technologies. Frontiers in Sustainable Food Systems. DOI: 10.3389/fsufs.2021.606815.

Australia has bioengineering research strengths, but deeper industry collaboration will be necessary to bridge the commercialisation gap

Developing and deploying bioengineered solutions to agricultural challenges may help to strengthen Australia's competitive edge in agriculture. Australia has identified synthetic biology as a critical technology expected to have a high impact on Australia's economic prosperity in key sectors including agriculture.[11] However, several other countries - including some of Australia's closest export competitors (e.g., the United States, Denmark and France) have also identified advanced bioengineering as an important emerging technology.[12]

Australia has a strong and growing advanced bioengineering research community[13] however awareness of and engagement with these emerging solutions is low amongst agricultural producers. Ensuring end-users are engaged in co-design and demonstration of bioengineering opportunities will be critical to the successful commercialisation and adoption of these emerging solutions. Greater coordination among Australian governments, industry and research stakeholders will be critical if the nation is to overcome the barriers to commercialisation and take full advantage of the benefits that bioengineering can offer to Australia's agriculture, aquaculture and forestry industries.

11 Critical Technologies Policy Coordination Office (2021) Synthetic biology. <https://www.pmc.gov.au/sites/default/files/publications/ctpco-tech-cards-synthetic-biology-aust_0.pdf> (accessed 3 March 2022).

12 CSIRO Futures (2021) A National Synthetic Biology Roadmap: Identifying commercial and economic opportunities for Australia. CSIRO, Canberra.

13 Australia ranks 9th globally for research impact for synthetic biology (led by the University of Queensland), and 13th internationally for patent numbers. Critical Technologies Policy Coordination Office (2021) Synthetic biology. <https://www.pmc.gov.au/sites/default/files/publications/ctpco-tech-cards-synthetic-biology-aust_0.pdf>.

2 Methodology and framework definitions

This project consisted of two main steps; a scoping phase and a preliminary assessment phase (see Figure 1). After consideration of the framework ratings and a more comprehensive stakeholder engagement around the preliminary findings of this report, it would be valuable to prioritise a smaller number of opportunities for more detailed assessment.

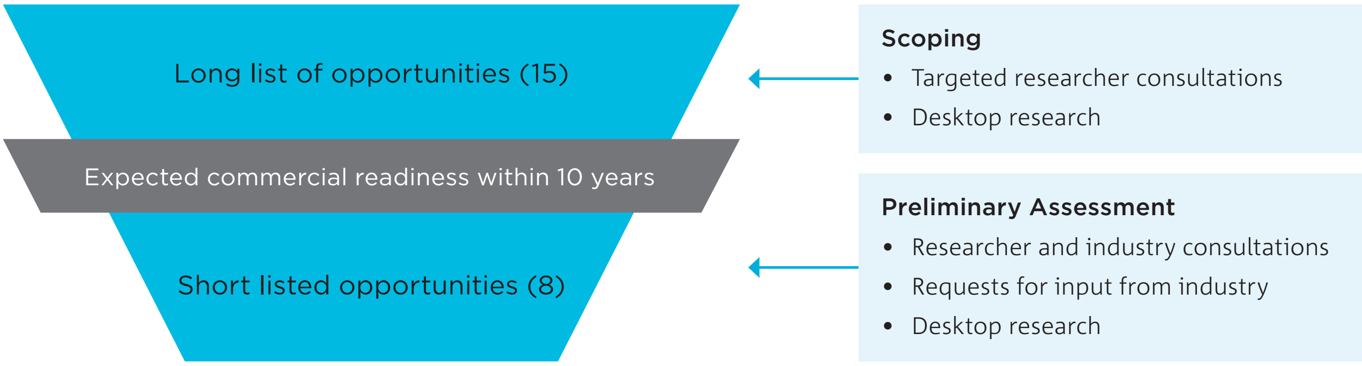


Figure 1: Summary of project methodology

Scoping

The scoping phase identified and considered 15 advanced bioengineering opportunities that were specific to agriculture via desktop research and interviews with targeted researchers. Estimates of the minimum time to commercial feasibility were assessed for each technology by considering technical maturity and key commercialisation barriers such as cost, regulation, competitive alternatives, technical challenges and social license.

This list was then filtered using two criteria:

- Opportunities that involved genetic engineering of animals and crops were deemed out of scope.
- Opportunities that are not expected to have commercially feasible applications within 10 years were deemed out of scope.

Seven opportunities were excluded from the scope using these criteria. The full results of the scoping phase are reported in Appendix A: Scoping results.

Preliminary assessment

An assessment framework was developed to identify and compare the eight selected opportunities. Desktop research, targeted consultations and expert reviews were used to populate and refine information across the following categories:

- Maturity, benefits, and challenges (criteria and rating approaches are described below).
- Industry and research examples – to convey the scope and maturity of different applications being developed within each opportunity.

The full results of the preliminary assessment are presented in Chapter 3 *Preliminary analysis of opportunities.*

Maturity

The Technology Readiness Level (TRL) and Commercial Readiness Index (CRI) frameworks were used to describe the maturity of identified applications within each opportunity. Figure 1 describes each TRL level (1-9) and their relationship to the Commercial Readiness Index (CRI), which provides a similar classification system for commercial progression of an opportunity.

Each opportunity assessment includes a rating for 'expected time to commercial availability'. This has been defined as the amount of time it is estimated to take for the application to begin scale-up into a commercial offering (CRI 3). At this stage, the application would have completed small-scale commercial trials and will start becoming more widely available for the benefit of producers. Estimates were developed through desktop research and consultations and are low confidence, as actual commercialisation timelines will depend on many factors, including market demand and the application proponent's success in overcoming identified challenges.

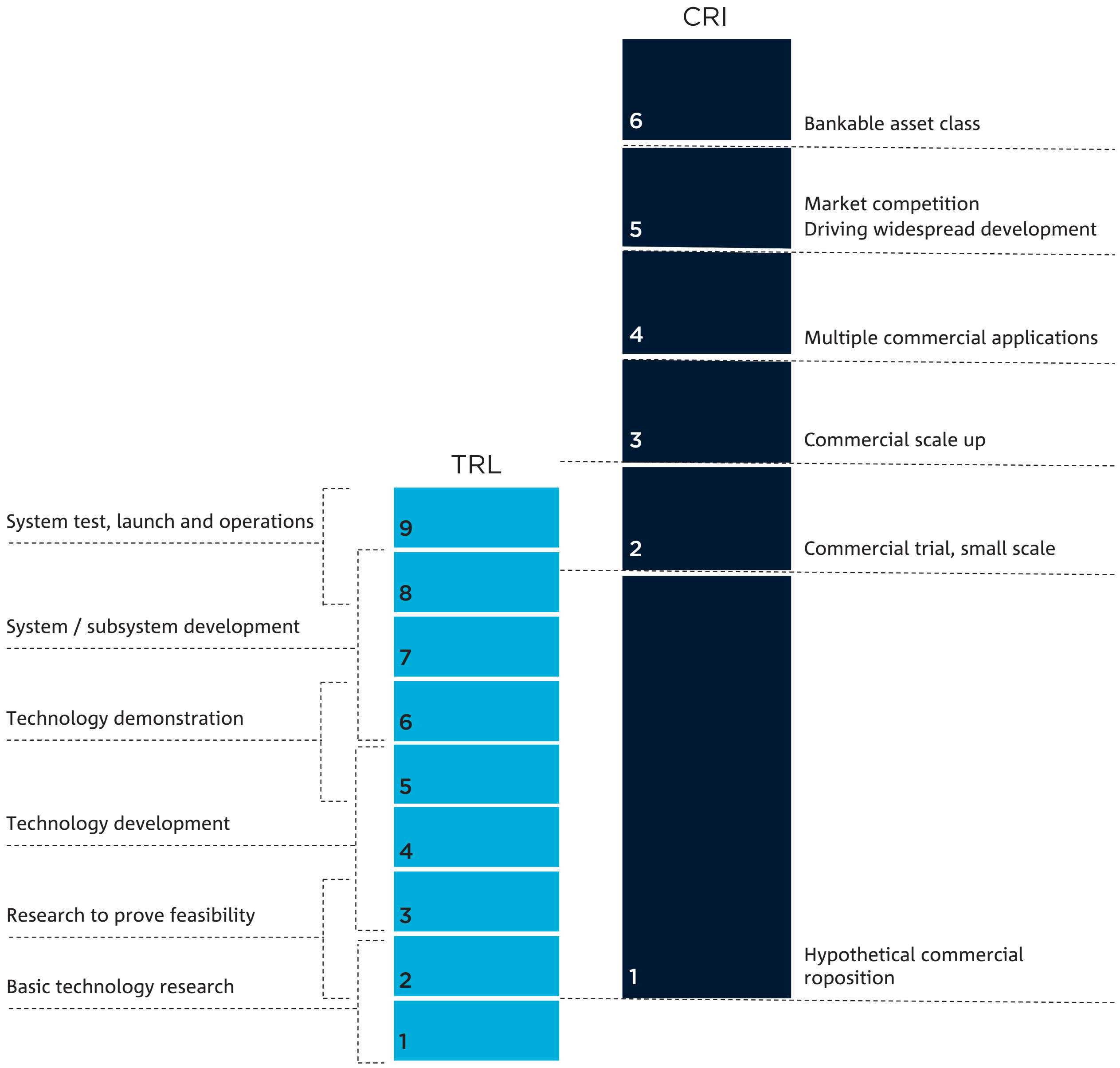


Figure 2: Technology Readiness Levels and Commercial Readiness Index[14]

14 Adapted from ARENA (2014) Commercial Readiness Index. <https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf>

Benefits

Table 2 below outlines the benefit categories considered during preliminary assessment, alongside core questions that were used to frame the literature reviews and guide consultations. Each category was assessed to determine whether or not this was intended to be a primary benefit provided by the use of advanced bioengineering approaches compared to current products/solutions.

Table 2: Benefit categories

BENEFIT	DESCRIPTION
Yield	Is increasing agricultural output expected to be a primary benefit of the opportunity?
Product quality	Is supporting the production of a higher quality agricultural product (e.g., increased nutrition, reduced risk of contaminants) expected to be a primary benefit of the opportunity? Potential consumer health benefits that relate to product quality would also be noted here.
Reduced costs	Is reducing costs for producers (e.g., materials, equipment, labour) expected to be a primary benefit of the opportunity?
Environment, human health and animal welfare	Is providing environmental sustainability, biosecurity, human health (including occupational health and safety), or animal health and wellbeing benefits expected to be a primary benefit of the opportunity?
Other	Other benefits may be identified, however they are not given ratings or included in the summary visuals.

Challenges

Table 3 below outlines the challenge categories considered during preliminary assessment, alongside core questions that were used to frame the literature reviews and guide consultations. Each challenge category was assessed to determine the extent to which they might delay commercialisation of the opportunity beyond the estimated time to commercial availability.

Table 3: Challenge categories

CHALLENGE	DESCRIPTION
Technical	Are technical challenges expected to delay the development and commercialisation of the opportunity?
Plug and play	Will the opportunity require significant process changes, new infrastructure (including information technology), or new skill sets to enable their on-farm deployment?
Effectiveness	Are other products/solutions expected to offer similar or better efficacy? If so, what are they?
Cost	Are other products/solutions expected to be more cost-competitive? If so, what are they? Are the development costs of the opportunity expected to outweigh the expected benefits?
Public perception	Will the opportunity face significant social acceptance challenges that will be difficult to overcome in the next 10 years?
Regulation	Is the opportunity expected to face lengthy regulatory approval processes or related challenges that could delay commercialisation in Australia? If so, why? NB: This challenge considers typical regulations associated with the Gene Technology Regulator (which regulates GMOs in Australia) and Australian Pesticides and Veterinary Medicine Authority (which regulates animal feed products, and agricultural chemicals and biological treatments). The ratings provided are preliminary and have not yet been reviewed by these two parties. Regulations related to the jurisdiction of the Environmental Protection Authority have not been considered in this project.
Intellectual property	Is the opportunity likely to face freedom to operate challenges associated with the intellectual property landscape? NB: This challenge is not rated or included in the summary visual. The comments are based on desktop literature reviews and expert commentary. A patent scan would be necessary to accurately assess freedom to operate for each opportunity and this is outside the scope of this project.

3 Preliminary analysis of opportunities

This chapter provides preliminary analysis for the eight selected opportunities. Table 4 summaries this analysis and may assist in the selection of prioritised opportunities for further analysis (see Chapter 4 *Next steps*).

While the majority of opportunities have an existing commercially available product, there is often only one or two globally, and they have a relatively small market share compared to more traditional, competing approaches. Coupled with the breadth of each of these opportunity areas, this highlights that there are product development opportunities for Australian businesses across all eight fields.

There is also variation between different applications in each opportunity. As such, assessments for individual technologies or businesses may not match with the overall opportunity assessment below.

Table 4: Summary of preliminary opportunity analysis

	MATURITY		CHALLENGE						PRIMARY BENEFIT			
OPPORTUNITY	Commercial availability	Maximum TRL	Technical	Plug and play	Effectiveness	Cost	Public attitude	Regulation	Yield	Product quality	Cost saving	Environment, human health and animal welfare
1 Engineered biosensors for product quality	[green]	9			[red]	[red]				[green]	[green]	
2 Engineered biosensors for animal and crop health	[green]	9			[red]	[red]			[green]	[green]		[green]
3 Biomanufactured animal feed	[green]	9	[red]			[red]	[red]	[red]	[green]	[green]	[green]	[green]
4 Biomanufactured agricultural chemicals	[green]	9	[red]		[red]	[red]		[red]			[green]	[green]
5 Engineered bioremediation solutions	[green]	9	[red]			[red]	[red]	[red]	[green]			[green]
6 Engineered biological agricultural treatments	[green]	9	[red]		[red]	[red]	[red]	[red]	[green]	[green]		[green]
7 Engineered biosensors for environmental conditions	[yellow]	6			[red]	[red]			[green]	[green]		[green]
8 On-farm bioenergy solutions	[yellow]	5	[red]	[red]		[red]		[red]				[green]

Commercial availability rating

- [green] Commercial scale-up (CRI 3) feasible in 5 years or less
- [yellow] Commercial scale-up (CRI 3) feasible in 5-10 years

Challenge rating

- [red] Potentially significant challenge that could delay commercialisation of some applications in this opportunity
- [white] Not expected to be a significant challenge that delays commercialisation of applications in this opportunity

Benefit rating

- [green] Expected to be a primary benefit compared to conventional solutions
- [white] Not expected to be a primary benefit compared to conventional solutions

3.1 Engineered biosensors for product quality

Engineered biosensors can be developed for rapid and non-destructive determination of product quality factors such as nutrient levels, contaminant and toxin concentrations, and compounds that may indicate ripeness or product degradation. This opportunity can be applied across agricultural, aquaculture and livestock industries to determine the pre-farm gate quality of crop and animal products.

Advanced bioengineering can improve operating parameters compared to traditional biosensors, including optimised detection ranges, robustness, selectivity, and sensitivity, as well as increasing the functionality and immobilisation of biological cells so that they can be contained and deployed safely.[15]

Preliminary consultations suggest that opportunities for early commercial success may include cost-effective food safety testing, and biosensors for ripeness to help reduce food waste. Food waste is estimated to cost the Australian economy $20 billion annually and an estimated 31% of Australian food waste occurs during primary production.[16]

The improved selectivity of advanced biosensors offers the opportunity to discriminate between molecules that may be misinterpreted as a singular signal. For example, carvone and octenol are structurally similar, however, the former is known to have significant properties that benefit human health, while the latter may be associated with mould contamination in produce.[17]

TRL	Expected time to commercial availability
Up to 9	1-5 years

Industry examples

- PPB Technology (AUS) uses biosensing techniques to measure lactose and protease levels in milk samples (CRI 2). PPB is also developing assays to measure the concentration of mycotoxins in fruit products (TRL 4).

Research examples

- Meat and Livestock Australia (MLA) are funding research into meat quality biomarkers (TRL 2-3).[18]
- Researchers at SRM University (India) are developing biosensors that measure the concentration of volatile amines which are an indicator of bacterial degradation in fish products (TRL 2-3).
- Australian Wine Research Institute, Queensland University of Technology (QUT) and CSIRO have collaborated to explore the use of biosensors to rapidly detect levels of smoke contamination in wine grapes (TRL 2).[19]
- University of Sydney researchers are currently investigating biosensors for detection of ethylene as a measure of crop ripeness (TRL 2).[20]

15 Moratti C, Scott C, Coleman N (2022) Synthetic Biology Approaches to Hydrocarbon Biosensors: A Review. Frontiers in Bioengineering and Biotechnology, 9. DOI: 10.3389/fbioe.2021.804234.

16 DAWE (2020) A Roadmap for reducing Australia's food waste by half by 2030. Viewed 13 April 2022, <https://www.awe.gov.au/sites/default/files/documents/roadmap-reducing-food-waste.pdf>

17 Di Pietrantonio F, Benetti M, Cannatà D, Verona E, Palla-Papavlu A, Fernández-Pradas JM, Serra P, Staiano M, Varriale A, D'Auria S (2015) A surface acoustic wave bio-electronic nose for detection of volatile odorant molecules. Biosensors and Bioelectronics, 15(67), 516-23. DOI: 10.1016/j.bios.2014.09.027.

18 MLA (2021) RD&A stocktake: A summary of MLA's research, development and adoption (RD&A) projects from June 2018 – November 2020. P.PSH 0816 <https://www.mla.com.au/globalassets/mla-corporate/research-and-development/documents/mlas-rda-stocktake_feb21.pdf>

19 ARC Centre of Excellence in Synthetic Biology (2021) Biosensors to be a winemaker's aide. <https://www.coesb.com.au/biosensors-to-be-a-winemakers-aide/>

20 Moratti C (n.d.) Synthetic biology approaches to hydrocarbon biosensors <https://www.sydney.edu.au/science/about/our-people/research-students/claudia-moratti-950.html>

BENEFIT	SIGNIFICANCE	EXPLANATION
Yield	☐	• On-farm product quality biosensors will not have a direct effect on yield.
Product quality	■	• Biosensors can be used to evaluate and predict high product quality by determining the presence of relevant markers (i.e., nutrient or contaminant indicators) or reporting a threshold concentration limit. The presence of harmful bacteria or enzymes that may degrade product quality and present consumer health risks can also be detected. • Biosensors can also detect non-compliant products that do not adhere to appropriate regulations and standards.
Cost savings	■	• Engineered real-time biosensors may be cheaper than alternative solutions, especially when existing methods of analysis require sending samples to off-site analytical laboratories.[21] For example, nanomaterial-based biosensors are far less expensive than conventional instruments for analysis such as ultra-violet (UV)-vis spectroscopy and high-performance liquid chromatography (HPLC) that incur higher labour, logistics, and operational costs (e.g., solvents and separation columns).[22] • Early detection of defects or contaminants before products leave the farm or enter the processing element of the supply chain may save money by providing opportunities to address the issue or abandon the product batch early on. • Current testing methods for agricultural products typically provide results after the product is packaged, and potentially marketed. On-site detection methods may reduce costs associated with product recall.
Environment, human health and animal welfare	☐	• Low-cost and early detection methods can increase the coverage of product testing and lower the chance of contaminated products entering the market. This will help protect human health and maintain Australia's reputation as a trusted supplier for high-quality products. • No direct environmental and animal welfare benefits are expected.

21 Chen Y-T, Lee Y-C, Lai Y-H, Lim J-C, Huang N-T, Lin C-T, Huang J-J (2020) Review of Integrated Optical Biosensors for Point-of-Care Applications. Biosensors, 10(12). DOI: 10.3390/bios10120209; Martins T, Ribeiro A, de Camargo H, Filho P, Cavalcante H, Dias D (2013) New Insights on Optical Biosensors: Techniques, Construction and Application. In (Ed.), State of the Art in Biosensors - General Aspects. IntechOpen. DOI: 10.5772/52330

22 Su X, Sutarlie L, Jun Loh X (2020) Sensors, Biosensors, and Analytical Technologies for Aquaculture Water Quality. Research: a science partner journal. DOI: 10.34133/2020/8272705

CHALLENGE	SIGNIFICANCE	EXPLANATION
Technical		• Due to their use in healthcare, the technology of engineered biosensors is largely understood. While technology challenges are not expected to be a significant challenge to implementation, engineered biosensors will need to ensure they have appropriate reliability, sensitivity, selectivity, stability, and usability for their target application.[23] • Any potential toxicity or contamination risks associated with biosensing materials will also need to be considered due to the nature of testing products for human consumption.[24]
Plug and play		• This is not expected to be a significant challenge. However, usability and easy interpretation of results can be expected to support the uptake of biosensors by producers. Efficient, automated systems could be expected to improve the commercial viability of biosensors.
Effectiveness		• There are a wide variety of sensors and analytic tools that do not utilise advanced bioengineering techniques. However, advanced bioengineering may be used to develop more effective biosensors where existing options do not offer satisfactory performance. For example, engineered biosensors with increased selectivity can discriminate between molecules that may typically be misinterpreted as a singular signal (i.e., common odorants in crop products, such as carvone and octenol).[25]
Cost		• Researchers noted that identifying the right product quality targets to engineer biosensors for is challenging as the economics requires that the targeted challenge be of sufficient scale to justify the R&D and manufacturing setup costs for a new solution. Similarly, for challenges where affordable and effective sensing and analytic solutions for on-farm use already exist, engineering new solutions may not be cost effective due to the potentially significant development costs and the time and resources required to engineer systems suitable for field applications.[26]
Public attitude		• Not expected to pose a significant challenge to on-farm implementation.
Regulation		• Regulatory challenges are not expected to pose a significant challenge to on-farm implementation in most cases, as most biosensors are expected to be cell-free systems that will not involve the use of live GMOs.[27]
Intellectual property	(Not rated)	• High-level analysis suggests that there is an increasing trend in patent applications for biosensors in the agri-food industry. In terms of applications, there is a moderate degree of interest in patents for product quality biosensors, however, few of these employ advanced bioengineering principles. Moreover, the backgrounds of those applying for these patent rights appear to be rather decentralised and diverse, suggesting there is little IP competition for engineered environmental biosensors.

23 Neethirajan S, Ragavan V, Weng X, and Chand R (2018). Biosensors for Sustainable Food Engineering: Challenges and Perspectives. Biosensors, 8(1), 23. DOI: 10.3390/bios8010023

24 Neethirajan S, Ragavan V, Weng X, and Chand R (2018). Biosensors for Sustainable Food Engineering: Challenges and Perspectives. Biosensors, 8(1), 23. DOI: 10.3390/bios8010023

25 Di Pietrantonio F, Benetti M, Cannatà D, Verona E, Palla-Papavlu A, Fernández-Pradas JM, Serra P, Staiano M, Varriale A, D'Auria S (2015) A surface acoustic wave bio-electronic nose for detection of volatile odorant molecules. Biosensors and Bioelectronics, 67, 516-23. DOI: 10.1016/j.bios.2014.09.027.

26 Moratti C, Scott C, Coleman N (2022) Synthetic Biology Approaches to Hydrocarbon Biosensors: A Review. Frontiers in Bioengineering and Biotechnology, 9. DOI: 10.3389/fbioe.2021.804234.

27 Moratti C, Scott C, Coleman N (2022) Synthetic Biology Approaches to Hydrocarbon Biosensors: A Review. Frontiers in Bioengineering and Biotechnology, 9. DOI: 10.3389/fbioe.2021.804234; Del Valle I, Fulk E, Kalvapalle P, Silberg J, Masiello C, Stadler L (2021) Translating New Synthetic Biology Advances for Biosensing into the Earth and Environmental Sciences. Frontiers in Microbiology, 11. DOI: 10.3389/fmicb.2020.618373.

3.2 Engineered biosensors for animal and crop health

Biosensors can be engineered for rapid on-farm detection of animal and crop health-related targets, including pathogens, physiological health biomarkers, and medicinal concentrations (such as antibiotics). For example:

- Within agricultural and forestry sectors, engineered biosensors can support in-field early detection of health markers that can mitigate risks of plant disease and loss, and indicate the physiological state of vegetation to advise growth strategies.[28] Detection of root pathogens is particularly relevant to the forestry industry.[29]
- Within animal husbandry and aquaculture sectors, biosensors have the potential to target biomarkers associated with physiological and immunological wellbeing of livestock and marine life. Biosensors may prove a cost-effective method for animal health monitoring (e.g., disease detection, monitoring antibiotic resistance), supporting animal welfare (e.g., monitoring physiological wellbeing by measuring stress biomarkers), improving productivity (e.g., detection of reproductive cycles), and ensuring product quality (e.g., monitoring animal nutrition).[30]

Advanced bioengineering can expand the capabilities of biosensors and increase the variety of targets that biosensors can be applied to.[31] Advanced bioengineering may allow for improved operating parameters compared to traditional biosensors – including optimised detection ranges, robustness, selectivity and sensitivity – and increased immobilisation of biological cells so that they can be contained and deployed safely.[32]

The most significant challenge noted by researchers during scoping discussions was identifying the right challenges for engineered biosensors to target. Potential high value applications that were suggested during initial consultations include early detection of diseases (e.g., amoebic gill disease in Atlantic salmon, estimated to cost the Tasmanian industry $40 million a year in treatment and lost productivity[33]), biosecurity threats, and monitoring antibiotic resistance.

TRL	Expected time to commercial availability
Up to 9	1-5 years

28 Kulabhusan P, Tripathi A, Kant K (2022) Gold Nanoparticles and Plant Pathogens: An Overview and Prospective for Biosensing in Forestry. Sensors, 22(3). DOI: 10.3390/s22031259.

29 Roberts M, Gilligan C, Kleczkowski A, Hanley N, Whalley A and Healey J (2020) The Effect of Forest Management Options on Forest Resilience to Pathogens. Frontiers Forests and Global Change, 3(7). DOI: 10.3389/ffgc.2020.00007.

30 Neethirajan S, Tuteja S, Huang S, Kelton D (2017) Recent advancement in biosensors technology for animal and livestock health management. Biosensors and Bioelectronics, 98, 398-407. DOI: 10.1016/j.bios.2017.07.015; Nelis J, Bose U, Broadbent J, Hughes J, Sikes A, Anderson A, Caron K, Schmoelzl S, Colgrave M (2022) Biomarkers and biosensors for diagnosis of pH noncompliant, dark cutting beef predisposition, and welfare in cattle. Comprehensive Reviews in Food Science and Food Safety, 1(42). DOI: 10.1111/1541-4337.12935; Endo H, Wu H (2019) Biosensors for the assessment of fish health: a review. Fisheries Science, 85, 641–654. DOI: 10.1007/s12562-019-01318-y.

31 Slomovic S, Pardee K, Collins J (2015) Synthetic biology devices for in vitro and in vivo diagnostics. Proceedings of the National Academy of Sciences, 112(47), 14429-14435. DOI: 10.1073/pnas.1508521112.

32 Moratti C, Scott C, Coleman N (2022) Synthetic Biology Approaches to Hydrocarbon Biosensors: A Review. Frontiers in Bioengineering and Biotechnology, 9. DOI: 10.3389/fbioe.2021.804234.

33 CSIRO (2021) Reducing impact of Atlantic salmon gill disease. <https://www.csiro.au/en/research/animals/breeding/salmon-gill-disease-agd>.

Industry examples

- Biotangents (UK) have developed a platform biosensor technology for portable rapid diagnosis of disease. The technology is currently capable of testing cattle for bovine viral diarrhoea (estimated CRI2-3), and the company is developing testing capabilities for brucellosis and mastitis (CR 1).[34]
- PPB Technology (AUS) are investigating biosensors for the management of bovine fertility and health (TRL 2).

Research examples

- Researchers at Griffith University (AUS) have investigated microfluidic electrochemical immunosensors that can detect plant pathogens in walnut plant samples with high specificity and sensitivity.[35]
- ERA-LEARN (EU) has launched a Cofund Call (2021-2024) for biosensors that can detect for bovine mastitis in cattle herds.[36]
- A UK-China research project led by Cranfield Univeristy is developing wearable biosensors for dairy cattle that could identify the disease brucellosis at an earlier stage. In tandem, a portable test is being developed to allow rapid confirmatory diagnosis of suspected cases.[37]

34 Biotangents (n.d.) On farm benefits <https://www.biotangents.co.uk/farms>

35 Dyussembayev K, Sambasivam P, Bar I, Borwnlie A, Shiddiky M, Ford R (2021) Biosensor Technologies for Early Detection and Quantification of Plant Pathogens. Frontiers in chemistry, 9. DOI: 10.3389/fchem.2021.636245.

36 ERA-LEARN (2021) 1st ICRAD Joint Cofund Call. Project: Channel-based biosensors to support a precision agriculture approach for improved bovine mastitis management. <https://www.era-learn.eu/network-information/networks/icrad/1st-icrad-call-2019/channel-based-biosensors-to-support-a-precision-agriculture-approach-for-improved-bovine-mastitis-management>.

37 Cranfield University (2020) Wearable health sensors will help detect disease in livestock <https://www.cranfield.ac.uk/press/news-2020/wearable-health-sensors-for-livestock>

BENEFIT	SIGNIFICANCE	EXPLANATION
Yield		• A primary benefit of engineered biosensors is their ability to provide advanced disease detection that can minimise damages to both crops and animals. Frequently occurring diseases are considered one of the major factors limiting crop productivity, and similarly, infectious diseases in the livestock industry result in a marked decline in productivity and product consumption.[38] • Monitoring and alleviating stress levels in livestock and fish can improve mortality and productivity rates. Likewise, monitoring the physiological markers for plant stress could improve productivity for generating higher quality crops.[39] • Labour productivity may also be enhanced if biosensors are integrated into remote detection systems.
Product quality		• Early detection of pathogens and diseases provides low-impact treatment opportunities which improve the product quality of products across agricultural, aquaculture and livestock industries while limiting antibiotic use.
Cost saving		• Cost saving is not considered a primary benefit of animal health sensors, but early detection of harmful, and potentially lethal pathogens may prevent crop losses due to disease or stress. Likewise, animal diseases can be treated early to minimise detrimental health impacts in livestock and aquaculture animals.[40] • Engineered biosensors for animal and crop health may minimise economic losses associated with missing fertility windows and delays in identifying sub-clinical health issues. • Engineered biosensors can be developed for in-field pathogen detection and so may enable earlier interventions and offer a greater value proposition when compared to lab-based solutions.[41] For example, traditional methods for fungi and bacteria identification in crops rely on symptom observation and culture-based methods in which a sample is grown under controlled conditions before it is identified by trained personnel using microscopy.
Environment, human health and animal welfare		• Early detection of crop diseases can discourage the overuse of environmentally persistent and harmful agrochemicals used to treat disease appearance and avoid crop loss.[42] • Engineered biosensors can support biosecurity efforts by allowing for swift infection diagnosis and intervention, minimising the ability of pathogens to spread both within farm, and beyond. Early detection and treatment of diseases in animals has potential benefits to human health by reducing the evolution rates of pathogens that could cross the species barrier, minimising the risk of zoonotic diseases to humans. • Supports animal welfare via the early detection of harmful pathogens and diseases, which may help to minimise risks of antimicrobial resistance by reducing the use of antibiotics and similar preventative treatments. • May minimise OH&S risks through the use of remote detecting systems that reduce human contact with potentially harmful diseases and pathogens, compared to current DNA-based testing methodologies that require genetic samples to be collected.[43]

38 Kundu M, Krishnan P, Kotnala R, Sumana G (2019) Recent developments in biosensors to combat agricultural challenges and their future prospects, Trends in Food Science & Technology, 88, 157-178. DOI: 10.1016/j.tifs.2019.03.024.

39 Sehgal A, Sita K, Siddique K, Kumar R, Bhogireddy S, Varshney R, HanumanthaRao B, Nair R, Prasad P, Nayyar H (2018) Drought or/and Heat-Stress Effects on Seed Filling in Food Crops: Impacts on Functional Biochemistry, Seed Yields, and Nutritional Quality, Frontiers in Plant Science, 9. DOI: 10.3389/fpls.2018.01705.

40 Kundu M, Krishnan P, Kotnala R, Sumana G (2019) Recent developments in biosensors to combat agricultural challenges and their future prospects, Trends in Food Science & Technology, 88, 157-178. DOI: 10.1016/j.tifs.2019.03.024.

41 Dyussembayev K, Sambasivam P, Bar I, Borwnlie A, Shiddiky M, Ford R (2021) Biosensor Technologies for Early Detection and Quantification of Plant Pathogens. Frontiers in chemistry, 9. DOI: 10.3389/fchem.2021.636245.

42 Kulabhusan P, Tripathi A, Kant K (2022) Gold Nanoparticles and Plant Pathogens: An Overview and Prospective for Biosensing in Forestry. Sensors, 22(3), 1259. DOI: 10.3390/s22031259.

43 Vidic J, Manzano M, Chang C, Jaffrezic-Renault N (2017) Advanced biosensors for detection of pathogens related to livestock and poultry. Veterinary Research, 48(11). DOI: 10.1186/s13567-017-0418-5.

CHALLENGE	SIGNIFICANCE	EXPLANATION
Technical		• Due to their use in healthcare, the technology of engineered biosensors is well understood. While technology challenges are not expected to be a significant challenge to implementation, engineered biosensors will need to ensure they have appropriate reliability, sensitivity, selectivity, stability, usability, and fast response rates for their target application.[44]
Plug and play		• This is not expected to be a significant challenge, especially compared to traditional laboratory testing which can be labour intensive and often require skilled technicians to operate.[45] Laboratory testing can also have typical turnaround times in the order of 2-10 days.[46] • However, some engineered biosensors may still involve complex and time-consuming labour steps. Designing solutions with simple operating procedures that can produce rapid results can be expected to improve adoption by producers.
Effectiveness		• Advanced bioengineering may be used to develop more effective biosensors where existing options do not offer satisfactory solutions.[47] For example, current real-time diagnostic tools (e.g., some antibody-based methods that detect substances produced by the invading pathogen) can lack sensitivity.[48] • Engineered biosensors targeting physiological crop health will need to compete with emerging real-time phenomics technologies which may offer a highly effective solution if they become cost competitive.[49]
Cost		• Researchers noted that identifying the right animal and crop health targets to engineer biosensors for is challenging as the economics requires that the targeted challenge be of sufficient scale to justify the R&D and manufacturing setup costs for a new solution. Similarly, for challenges where affordable and effective sensing and analytic solutions for on-farm use already exist, engineering new solutions may not be cost effective due to the potentially significant development costs and the time and resources required to engineer systems suitable for field applications.[50]
Public attitude		• Not expected to pose a significant challenge to on-farm implementation because biosensors will not involve the release of GMOs. CSIRO research has found that public attitudes towards the use of advanced bioengineering are more supportive when there is a health or environmental benefit.[51]
Regulation		• Not expected to pose a significant challenge to on-farm implementation as most biosensors are expected to be cell-free systems.
Intellectual property	(Not rated)	• High-level analysis suggests there is an increasing trend in patent applications for biosensors in the agri-food industry. While the biosensors that detect for markers of animal and crop health appear to be one of the more common applications, the majority of these do not employ advanced bioengineering principles. Moreover, the backgrounds of those applying for these patent rights appear to be rather decentralised and diverse, suggesting there is room for growth with little IP competition for advanced engineered health biosensors.[52]

44 Neethirajan S, Ragavan V, Weng X, and Chand R (2018). Biosensors for Sustainable Food Engineering: Challenges and Perspectives. Biosensors, 8(1), 23. DOI: 10.3390/bios8010023.

45 Fang Y, Ramasamy R (2015) Current and Prospective Methods for Plant Disease Detection. Biosensors, 5(3), 537-561. DOI: 10.3390/bios5030537.

46 Vidic J, Manzano M, Chang C, Jaffrezic-Renault N (2017) Advanced biosensors for detection of pathogens related to livestock and poultry. Veterinary Research, 48(11). DOI: 10.1186/s13567-017-0418-5.

47 Del Valle I, Fulk E, Kalvapalle P, Silberg J, Masiello C, Stadler L (2021) Translating New Synthetic Biology Advances for Biosensing into the Earth and Environmental Sciences. Frontiers in Microbiology, 11. DOI: 10.3389/fmicb.2020.618373.

48 Verosloff M, Chappell J, Perry K, Thompson J, Lucks J (2019) PLANT-Dx: A Molecular Diagnostic for Point-of-Use Detection of Plant Pathogens. ACS synthetic biology, 8(4), 902–905. DOI: 10.1021/acssynbio.8b00526.

49 Roitsch T, Cabrera-Bosquet L, Fournier A, Ghamkhar K, Jiménez-Berni J, Pinto F, Ober E (2019) Review: New sensors and data-driven approaches-A path to next generation phenomics. Plant Science, 282, 2-10. DOI: 10.1016/j.plantsci.2019.01.011.

50 Moratti C, Scott C, Coleman N (2022) Synthetic Biology Approaches to Hydrocarbon Biosensors: A Review. Frontiers in Bioengineering and Biotechnology, 9. DOI: 10.3389/fbioe.2021.804234.

51 CSIRO (2021) Public attitudes towards synthetic biology. Viewed 1 April 2022, <https://research.csiro.au/synthetic-biology-fsp/public-attitudes/>.

52 Thakur M, Wang B, Verma M (2022) Development and applications of nanobiosensors for sustainable agricultural and food industries: Recent developments, challenges and perspectives. Environmental Technology & Innovation, 26. DOI: 10.1016/j.eti.2022.102371.

3.3 Biomanufactured animal feed

Biomanufacturing can be applied to produce sustainable proteins (e.g., single cell proteins) and additives (e.g., probiotics, enzymes, and metabolic modifiers) for use in animal feed. These products can optimise nutrient utilisation which can increase animal health, production efficiency and product quality. For example:

- Biomanufacturing feed products that can address nutritional challenges such as the supply of certain amino acids and the unsustainable use of wild caught fish in aquaculture feed
- Biomanufacturing livestock feed additives for methane inhibition in ruminants.

Advanced bioengineering can improve the efficiency of biomanufacturing processes, enable the production of new compounds, and improve the activity and stability of existing feed supplements (such as enzymes and prebiotics).[53]

Preliminary consultations and commercial precedents suggest that opportunities for early commercial success may include high value and lower volume feed supplements (such as prebiotics and enzymes that can increase animal health and productivity), compared to bulk-feed production. For example, phytase enzymes may present an opportunity due to their potential to enhance digestibility of nutrients, reduce antinutritional effects of phytate (which hinders protein and nutrient uptake), and reduce inorganic phosphorus excretion.[54]

TRL	Expected time to commercial availability
Up to 9	1-5 years

53 Speight R, Navone L, Gebbie L, Blinco J, Bryden W (2022) Platforms to accelerate biomanufacturing of enzyme and probiotic animal feed supplements: discovery considerations and manufacturing implications. Animal Production Science. DOI: 10.1071/AN21342.

54 Pakbaten B, Heravi R, Kermanshahi H, Sekhavati M, Javadmanesh A, Ziarat M (2019) Production of Phytase Enzyme by a Bioengineered Probiotic for Degrading of Phytate Phosphorus in the Digestive Tract of Poultry. Probiotics Antimicrobial Proteins, 11(2), 580-587. DOI: 10.1007/s12602-018-9423-x; Jatuwong K, Suwannarach N, Kumla J, Penkhrue W, Kakumyan P, Lumyong S (2020) Bioprocess for Production, Characteristics, and Biotechnological Applications of Fungal Phytases. Frontiers in microbiology, 11, 188. DOI: 10.3389/fmicb.2020.00188.

Industry examples

- Adisseo (France) used bioengineering techniques to optimise the gene expression of a fungus so that it would overproduce a combination of targeted enzymes that boost animal nutrition and feed digestibility (estimated CRI 4+).[55]
- Novozymes (Denmark) use biomanufacturing to produce a range of enzyme and probiotic supplements to support animal health and nutrition (estimated CRI3+).[56]
- Bioproton (AUS) is working with Queensland University of Technology (QUT) to engineer production strains and pathways for common feed additives. This includes engineering yeast strains to improve phytase production rates for use in swine and poultry feeds (CRI 2)[57], and fermentation-based production pathways for astaxanthin, a nutritional antioxidant and colourant used in animal feed and aquaculture industries (CRI 1).
- Provectus Algae (AUS) is developing algal-based biomanufacturing platforms targeting compounds with applications in the aquaculture feed market (CRI 1).
- StringBio (India) is engineering fermentation pathways to convert methane into protein-rich products aimed at addressing the macronutrient requirement of animals (estimated CRI 1).[58]
- Deep Branch Biotechnology (UK) is engineering microbes that transform the CO_2 and hydrogen in flue gases into protein to replace soy and fishmeal in aquaculture and agriculture feeds (estimated CRI 1).
- NovoNutrients (US) is developing pathways to use CO_2 and hydrogen gases to grow microbes that can produce nutritionally balanced, single-cell protein meals suitable for aquaculture, livestock and poultry markets (estimated CRI 1). [59]
- KnipBio (US) is developing microbial proteins produced via fermentation with high amino acid content designed to improve fish health. This has potential to enable a significant improvement in the survival of salmonids (estimated CRI 1).
- Danisco Animal Nutrition (US) has engineered a microbial catalyst that enables the production of phytase enzymes which can improve the digestibility of phosphorus and other nutrients in animal feeds.

Research examples

- QUT is developing an integrated facility capable of discovering, developing, manufacturing and testing novel animal feed supplements and bulk feeds concentrating on microbial fermentation production and delivery systems.[60]
- The University of Queensland is developing feed cultures enriched with purple phototrophic bacteria, that can be used as a substitute for commercial protein sources in aquaculture feeds.[61]
- CSIRO is investigating the use of engineered yeast and algae strains that are capable of producing and accumulating bromoform as viable livestock feed additives. Bromoform inhibits the formation of methane in ruminant livestock.[62]

55 eFeedLink (2016) Adisseo launches a new enzyme solution: Rovabio Advance, the only feedase [Press release]. Viewed 25 March 2022, https://www.efeedlink.com/contents/07-01-2016/16edf362-80ed-4dff-9289-a0d895c3bafc-d181.html; Adisseo (n.d.) ROVABIO ADVANCE, THE ONLY FEEDASE. <https://www.adisseo.com/en/rovabio-advance-the-only-feedase/>

56 Novozymes (n.d.) Beautiful biology. Viewed 12 April 2022, <https://www.novozymes.com/en/biology>

57 Navone L, Vogl T, Luangthongkam P, Blinco J, Luna-Flores C, Chen X, von Hellens J, Speight R (2021) Synergistic optimisation of expression, folding, and secretion improves E. coli AppA phytase production in Pichia pastoris. Microbial Cell Factories, 20(1), 8. DOI: 10.1186/s12934-020-01499-7.

58 Alternative Protein Products or Solutions for Animal Nutrition – Sustainable and Better Performance (2022). <https://www.stringbio.com/animal-nutrition.html> (accessed 24 March 2022).

59 Turning Polluted Air into Fish Feed Ingredient (2017). <https://www.aquafeed.com/af-article/7718/Turning-polluted-air-into-fish-feed-ingredient/> (accessed 24 March 2022)

60 Queensland University of Technology (n.d.) Biomanufacturing advanced animal feed supplements. <https://research.qut.edu.au/cab/projects/biomanufacturing-advanced-animal-feed-supplements/>

61 Capson-Tojo G, Batstone D, Grassino M, Vlaeminck S, Puyol D, Verstraete W, Kleerebezem R, Oehmen A, Ghimire A, Pikaar I, Lema J, Hülsen T (2020) Purple phototrophic bacteria for resource recovery: Challenges and opportunities. Biotechnology Advances, 43. DOI: 10.1016/j.biotechadv.2020.107567.

62 CSIRO (2021) FutureFeed. Viewed 1 April 2022, <https://www.csiro.au/en/research/animals/livestock/futurefeed>

BENEFIT	SIGNIFICANCE	EXPLANATION
Yield		• Biomanufactured feed additives are primarily designed to improve the nutrient value and digestibility of animal feed. For example, biomanufactured enzymes can be used to remove antinutritional components in animal feed to increase the utilisation and digestibility of nutrients.[63] This can be expected to improve animal health and growth rates.
Product quality		• Biomanufactured feed ingredients and supplements can improve animal nutrition, helping to optimise the nutritional profile of animal products. They can also improve their taste and appearance.
Cost saving		• Biomanufactured animal feed additives may reduce feed costs by improving nutritional efficiency and animal production efficiency. For example, DSM's RONOZYME® HiPhos feed enzyme to improve digestibility claims to achieve substantial savings on feed.[64] • Specific bioengineered nutrients can result in more cost-effective feed formulations and provide significant cost reductions given that feed accounts for nearly 60% of production cost in commercial aquaculture.[65] This can be achieved by increasing production levels in the microbial production strains, increasing survivability (by improving thermal stability etc.) and in the case of enzyme additives, improving activity rates.[66]
Environment, human health and animal welfare		• Biomanufactured feed additives are designed to increase animal health by improving nutritional content, digestibility, and the protection of protein, amino acids and fats.[67] This ensures nutrients are not prematurely degraded, increasing nutrient efficiency and energy utilisation.[68] • Feed additives may reduce Greenhouse Gas (GHG) emissions by inhibiting methane production in livestock and reducing nitrogen and phosphorus discharge in aquaculture. • This opportunity also promotes reduced usage of non-sustainable animal feed ingredients by providing more environmentally friendly alternatives.
Other	(Not rated)	• There is potential for local biomanufacturing of animal feed and additives to help secure domestic feed availability in the case of international supply chain issues.

63 Mahima, Verma A, Kumar V, Roy D (2012) Scope of Biotechnology in Animal Nutrition. Asian Journal of Animal Sciences, 6, 316-318. DOI: 10.3923/ajas.2012.316.318.

64 DSM (n.d.) RONOZYME® HiPhos: DSM Performance Solutions. <https://www.dsm.com/anh/products-and-services/products/feed-enzymes/ronozyme-hiphos.html> (accessed 5 April 2022).

65 Sathishkumar G, Bhavatharaniya U, Felix N, Ranjan A, Prabhu E (2021) Strategies to Reduce Feed Cost by Improving Gut Health and Nutrient Utilisation of Fish in Aquaculture. Institute of Fisheries Post Graduate Studies. <https://enaca.org/enclosure/?id=1139>

66 Speight R, Navone L, Gebbie L, Blinco J, Bryden W (2022) Platforms to accelerate biomanufacturing of enzyme and probiotic animal feed supplements: discovery considerations and manufacturing implications. Animal Production Science. DOI: 10.1071/AN21342.

67 Getabalew M, Alemneh T (2019) The Application of Biotechnology on Livestock Feed Improvement. Archives in Biomedical Engineering & Biotechnology, 1(5). DOI: 10.33552/ABEB.2019.01.000522.

68 Kamalak A, Canbolat Ö, Gurbuz Y, Özay O (2005) Protected Protein and Amino Acids in Ruminant Nutrition. KSU. Journal of science and engineering, 8(2).

CHALLENGE	SIGNIFICANCE	EXPLANATION
Technical		• There are precedents for the use of engineered biomanufacturing for both animal (see industry examples, above) and human food ingredients (e.g., Impossible Foods use an engineered yeast to manufacture ingredients for their plant-based protein products). However, technical challenges related to scalability, infrastructure, reliability and delivery for non-feedlot animals can be expected for new opportunities. • Collaborating across the value chain to demonstrate product effectiveness and value (e.g., though animal trials), while also developing the biomanufacturing pathways necessary to produce them economically at scale, will be a key challenge that slows commercialisation of some applications. • The lack of suitable infrastructure to support the scale-up of biomanufacturing in Australia may also slow development, including the ability to conduct full-scale animal trials for feed products that contribute a significant volume of the animal's diet.[69]
Plug and play		• Biomanufactured feed and feed additives will be designed as substitutes or additions to animal diets.
Effectiveness		• Biomanufactured feed and feed additives have potential to outcompete alternative solutions on environmental or productivity metrics, but they will be competing in a large established market. For commercial success products must demonstrate proof of efficacy across various stages of the research process, particularly through microbiome analysis and field trials.
Cost		• It is yet to be seen whether biomanufacturing bulk ingredients (e.g. proteins) for animal feed will be economically competitive. Higher-value ingredients required in smaller volumes will likely offer a greater value proposition compared to bulk-feed production in the short-medium term.
Public attitude		• This may present a significant challenge to commercialisation for some applications. • Biomanufactured feed additives will not typically contain any GM material. However, because of their association with GM products, consumable products produced by biomanufacturing may be perceived as unnatural and may elicit social concern. • Whole cell products such as single cell proteins will be classified as GMOs. Producers are often reluctant to use GM-feed products because of societal attitudes towards GM. However, this reluctance may be overcome where these products address significant nutritional challenges such as the supply of certain amino acids, or sustainability issues such as the use of wild caught fish for aquaculture feed.
Regulation		• Regulatory approval processes could delay commercialisation of some applications, especially when the animal feed product is not one that is already approved for use by the APVMA. • Engineered whole cell products (e.g., single cell proteins, probiotics) can also be expected to face longer regulatory pathways than biomanufacturing of feed additives produced do not contain live GMOs.
Intellectual property	(Not rated)	• Preliminary consultations suggest that the IP landscape is complex in this field with lots of claims for application of specific microbial products in aquaculture.

69 Speight R, Navone L, Gebbie L, Blinco J, Bryden W (2022) Platforms to accelerate biomanufacturing of enzyme and probiotic animal feed supplements: discovery considerations and manufacturing implications. Animal Production Science. DOI: 10.1071/AN21342.

3.4 Biomanufactured agricultural chemicals

Biomanufacturing can produce a wide variety of chemical compounds that can be used in agricultural and livestock industries. This may include chemicals that are currently produced via traditional industrial processes, or the production of nature-identical compounds that are not economic to extract in their natural form (e.g., nootkatone – a chemical found in minute quantities in grapefruit skin that has insecticidal properties). Biomanufacturing of chemical compounds has broad potential applications including in cropping (e.g., pesticides, herbicides, fertiliser), livestock and aquaculture (e.g., veterinary medicines).

Advanced bioengineering can be employed to optimise biomanufacturing pathways to generate targeted chemical compounds, to allow for increased flexibility of feedstocks, and to improve the productivity and efficiency of biomanufacturing processes.[70]

Preliminary consultations suggest that opportunities for early commercial success may include biomanufacturing high-value natural compounds that aren't found in economic concentrations in nature, rather than manufacturing identical replacements of traditional agrochemicals. For example, biomanufacturing alternative pesticides.[71] Biomanufacturing high-value materials in small to medium volumes has been demonstrated in food manufacturing and medical industries, which may set a precedent for success.

TRL	Expected time to commercial availability
Up to 9	1-5 years

Industry examples

- BioPhero (DNK) has developed and scaled fermentation processes to produce identical pheromones to those produced by insects, allowing for the biomanufacturing of pheromone-based insecticidal solutions (estimated CRI 3+).
- Evolva (US) has developed a fermentation-based manufacturing process for nootkatone (estimated CRI 2-3) and is seeking to commercialise this product for use in personal insect repellent, however research has also shown that this compound has potential applications in plant protection.
- Provectus Algae (AUS) is developing an algal-based biomanufacturing platform with potential to produce natural pesticides. (estimated CRI 1).
- Bondi Bio (AUS) is developing a cyanobacteria-based biomanufacturing platform that may be applied to manufacture natural agrochemicals such as nootkatone (estimated CRI 1).
- DSM (NL) has developed a biomanufacturing pathway that improves upon existing processes for the commercial production of a synthetic antibiotic (Cephalexin), which may be used to treat mastitis in cattle.[72]
- Vestaron (US) uses engineered yeast strains to produce the active ingredients for their peptide-based bioinsecticides.[73]

70 Kelwick R, Webb A, Freemont P (2020) Biological Materials: The Next Frontier for Cell-Free Synthetic Biology. Frontiers in Bioengineering and Biotechnology, 8. DOI: 10.3389/fbioe.2020.00399.

71 István U (2010) Chapter 3 - Pest Control Agents from Natural Products. In (Eds.), Robert K, Hayes' Handbook of Pesticide Toxicology, Academic Press. DOI: 10.1016/B978-0-12-374367-1.00003-3.

72 Biotechnology Innovation Organisation (n.d.) Current Uses of Synthetic Biology. <https://archive.bio.org/articles/current-uses-synthetic-biology>

73 VESTARON (n.d.) Science. <https://www.vestaron.com/science/> (accessed 8 April 2022).

Research examples

- A joint CSIRO-Corteva (US) research effort is currently engineering a fungal system that can produce natural crop protection products at industrially relevant quantities through fermentation (TRL 2).[74]

BENEFIT	SIGNIFICANCE	EXPLANATION
Yield		• Agrochemicals produced using advanced bioengineering approaches to biomanufacturing can be expected to have the same or similar effects on yield to existing products.
Product quality		• Biomanufacturing of naturally occurring compounds (e.g., natural pesticides, herbicides) may have a consumer health benefit if they reduce chemical residues in agricultural products, however this is not a primary benefit.
Cost savings		• Bioengineering is applied to optimise biomanufacturing pathways to increase the efficiency of producing the target compound. This can reduce energy requirements compared to traditional production. Savings will vary between processes and techno-economic analysis of different product pathways will increase understanding of the magnitude of this likely benefit. • This benefit is dependent on scaling up biomanufacturing processes and minimising time- and labour-intensive steps to ensure that biomanufacturing costs can be competitive.[75]
Environment, human health and animal welfare		• Biomanufacturing is intended to be an environmentally sustainable manufacturing process that may reduce carbon emissions, conserve water and energy, and reduce waste compared to traditional methods.[76] • Life cycle analysis of individual opportunities is critical to understanding the environmental impacts associated with different production pathways. For example, an LCA conducted by Fraunhofer IBP found that ecotoxicity could be reduced by 30-50% by replacing conventional pesticides with mating disruption techniques using biomanufactured pheromones produced via fermentation. • There may also be potential OH&S benefits if the biomanufactured compound/s replace a harmful agricultural chemical.
Other	(Not rated)	• Domestic (and potentially distributed) production of agricultural chemicals could secure supply chains and reduce the carbon footprint and costs associated with importation.

74 Corteva Agriscience (2021) Heterologous expression of natural products in fungal hosts. <https://www.openinnovation.corteva.com/collaborate-with-us/past-challenges/heterologous-expression-fungi.html> (accessed 5 April 2022).

75 Clomburg J, Crumbley A, Gonzalez R (2017) Industrial biomanufacturing: The future of chemical production. Science, 6320(355). DOI: 10.1126/science.aag0804; Xu J, Xu X, Huang C, Angelo J, Oliveira C, Xu M, Xu X, Temel D, Ding J, Ghose S, Borys M, Li Z (2020) Biomanufacturing evolution from conventional to intensified processes for productivity improvement: a case study. MAbs, 12(1). DOI: 10.1080/19420862.2020.1770669.

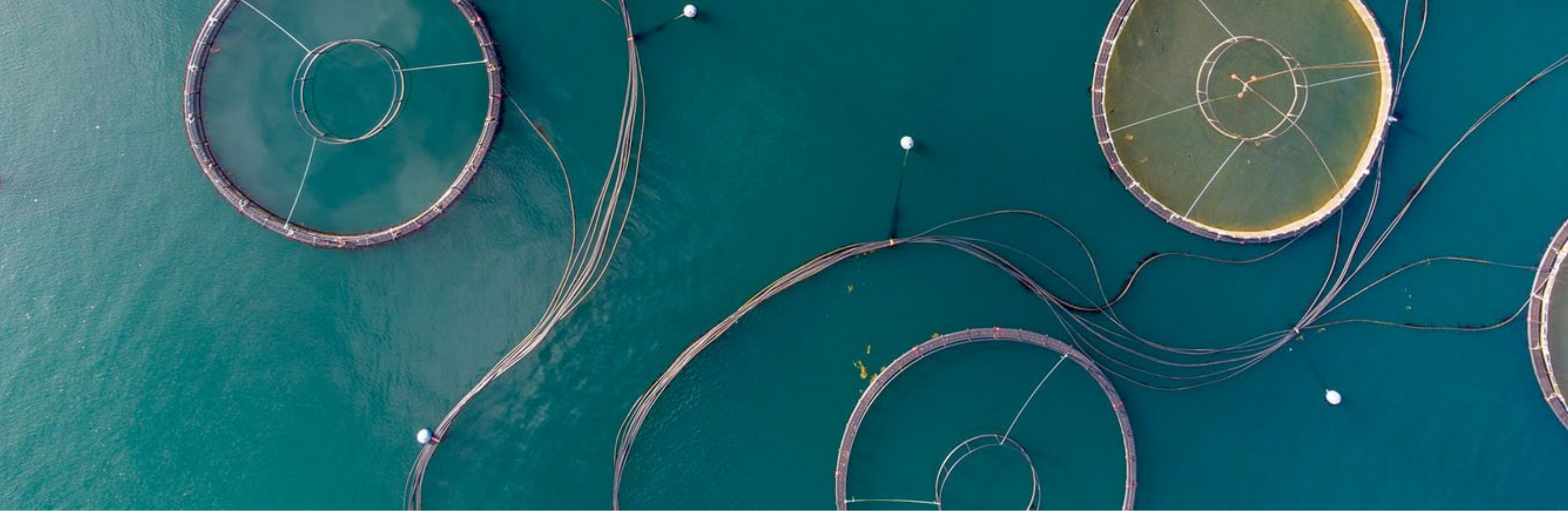
76 AMGEN (n.d.) Environment: biomanufacturing evolves with environmental benefits. <https://www.amgen.com/responsibility/environmental-sustainability/case-studies/biomanufacturing-evolves-with-environmental-benefits> (accessed 16 March 2022)

CHALLENGE	SIGNIFICANCE	EXPLANATION
Technical		• Technical challenges and maturity vary between biological pathways and target compounds. Chiral chemicals, notably chiral pesticides, may be particularly challenging to produce. This is because they typically require complex synthesis methods, expensive or challenging template molecules, and additional steps to separate the target molecule from their other chiral counterparts.[77] • General challenges may include scale-up for commercial production and the lack of suitable infrastructure, and the use of microbes and bacteria in industrial chemical settings.[78] The average process development for large-scale microbial production of chemicals is 5-10 years, and this is significantly more expensive than scaling up an equivalent chemical process with initial attempts often leading to reduced yields, undesirable by-products and diminished consistency between production batches.[79]
Plug and play		• These chemicals will be direct replacements for their traditionally manufactured counterparts and so will not require additional skills or infrastructure.
Effectiveness		• Biomanufactured conventional chemicals can be expected to have the same effectiveness as their traditional counterparts. • Satisfactory proof of effectiveness will be required to receive approval from the Australian Pesticides and Veterinary Medicines Authority (APVMA), and to compete with established products.
Cost		• The research, development and scale-up costs associated with engineering and infrastructure may be significant and could affect the commercial viability of some solutions. Early successes can be expected in high-value compounds required in small to medium volumes. This is where biomanufacturing has demonstrated an ability to provide cost effective solutions in other industries including food manufacturing and health.
Public attitude		• This opportunity is not expected to raise significant perception challenges because biomanufactured chemicals do not contain genetically modified material and are expected to offer environmental and health benefits.
Regulation		• Regulatory challenges could delay commercialisation of some applications, especially when the biomanufactured chemical is not one that is already approved by APVMA. • Biomanufacturing using GMOs will be regulated by the Gene Technology Regulator and the chemicals produced will be regulated by the APVMA. • Level 2 physical containment (PC2) certification is typically required for facilities that work with GMOs and the use of new GMOs for biomanufacturing will require approval. However, chemicals produced should not contain live GMOs so their on-farm application will not face regulatory barriers once the product is approved by the regulators.
Intellectual property	(Not rated)	• Preliminary analysis and consultation did not reveal any freedom • to operate insights.

77 Xu F, Kosjek B, Cabirol F, Chen H, Desmond R, Park J, Gohel A, Collier S, Smith D, Liu Z, Janey J, Chung J, Alvizo O (2018) Synthesis of Vibegron Enabled by a Ketoreductase Rationally Designed for High pH Dynamic Kinetic Reduction. Angewandte Chemie International Edition, 57(23), 6863-6867. DOI: 10.1002/anie.201802791.

78 Burk M, Van Dien S (2016) Biotechnology for Chemical Production: Challenges and Opportunities. Trends Biotechnology, 34(3), 187-190. DOI: 10.1016/j.tibtech.2015.10.007; Bellani C, Ajeian J, Duffy L, Miotto M, Groenewegen L, Connon C (2020). Scale-Up Technologies for the Manufacture of Adherent Cells. Frontiers in nutrition, 7. DOI: 10.3389/fnut.2020.575146.

79 Chubukov V, Mukhopadhyay A, Petzold C, Keasling J, Martín H (2016) Synthetic and systems biology for microbial production of commodity chemicals. npj Systems Biology and Applications, 2. DOI: 10.1038/npjsba.2016.9.



3.5 Engineered bioremediation solutions

Bioremediation is the process of using biological tools such as microorganisms and enzymes to degrade or remove environmental contaminants from water and soils. For example:

- Detoxifying contaminants left from agrochemical residues or organic pollutants is particularly relevant in agriculture.
- Bioremediation may also be employed to re-use livestock wastewater, and for the removal of heavy metals and marine toxins in aquacultural waterways.[80]

Advanced bioengineering principles can be employed to optimise the enzymes and metabolic pathways of microorganisms and enhance bioremediation activity for targeted contaminants.[81] This may include constructing or adapting catabolic pathways, preventing the formation of harmful intermediate molecules, and improving microbe affinity and specificity for target pollutants.

Preliminary consultations suggest that the degradation of legacy agrochemicals that cannot be readily degraded by existing remediation solutions (e.g., organochlorine insecticides that were banned in most countries in the 1990s due to their link to significant environmental and health issues) may be a valuable target for bioremediation solutions. However, consultations also suggested that Australia's current environmental regulations and policies do not always create a strong driver for bioremediation of pesticide contaminated land when other economic drivers are not present. The commercial failure of Orica's Landguard™ product in Australia, despite its technical success, illustrates this challenge.

TRL	Expected time to commercial availability
Up to 9	1-5 years

Industry examples

- Orica previously commercialised Landguard (TRL 9), an enzyme-based product developed with CSIRO for the rapid degradation of pesticide residues in soil and water. While the product was technically successful, it was not commercially successful in Australia due to limited demand. The patents for this technology are now being assigned to a biotechnology business in China who intends to commercialise the product.

Research examples

- The University of Sydney is undertaking research on the discovery and characterisation of bacteria for bioremediation of herbicides (TRL 2).
- CSIRO is conducting research (TRL 1-2) on bioremediation technologies targeting persistent organic pollutants known as per- and poly-fluoroalkyl substances (PFAS) that were used extensively in fire-fighting foams until the 1970s resulting in global environmental contamination in soils and waterways.
- The University of Minnesota (US) is developing a synthetic lichen (fungus and algae) biofilm that converts phosphorus and nitrogen compounds into proteins and other cellular products.[82]

80 Sun L, Zhao H, Liu J, Li B, Chang Y, Yao D (2021) A New Green Model for the Bioremediation and Resource Utilization of Livestock Wastewater. International Journal of Environmental Research and Public Health, 18(16). DOI: 10.3390/ijerph18168634; Usama M, Hussain N, Sumrin A, Shahbaz, A, Bilal M, Aleya L, Iqbal H (2021). Microbial bioremediation strategies with wastewater treatment potentialities – A review. Science of The Total Environment, 818. DOI: 10.1016/j.scitotenv.2021.151754.

81 Perpetuo E, Souza C, Nascimento C (2011) Engineering Bacteria for Bioremediation. In Carpi A (ed.) Progress in Molecular and Environmental Bioengineering - From Analysis and Modeling to Technology Applications, IntechOpen. DOI: 10.5772/19546.

82 Barnharst T, Rajendran A, Hu B (2018) Bioremediation of synthetic intensive aquaculture wastewater by a novel feed-grade composite biofilm. International Biodeterioration & Biodegradation, 126, 131-142. DOI: 10.1016/j.ibiod.2017.10.007.

BENEFIT	SIGNIFICANCE	EXPLANATION
Yield		• Bioremediation may assist in restoring agricultural productivity for degraded land and water.
Product quality		• Bioremediation of agricultural land and water reduces the chance of contaminants entering products however existing food safety regulations should mean that any improvements are minimal.
Cost saving		• Engineered bioremediation solutions may offer cheaper and longer-term solutions compared to some traditional contamination solutions (e.g., pump and treat, and excavation practices), with lower equipment and labour costs.[83] However, there will not be a cost saving when there are limited commercial or productivity drivers (i.e., remediation is being undertaken purely for environmental stewardship reasons).
Environment, human health and animal welfare		• Bioremediation solutions are designed to restore contaminated land and water by degrading hazardous contaminants which can have benefits for the environment, animal, and human health.

CHALLENGE	SIGNIFICANCE	EXPLANATION
Technical		• Engineered enzymes for bioremediation are well understood (hydrolases, amylases, and cellulases are typically applied for agricultural use) and technically mature examples exist. The development of engineered microbial bioremediants is more technically challenging and will require extensive safety testing.
Plug and play		• Engineered bioremediation solutions will be direct substitutes for their chemical (and non-engineered biological) alternatives, where they exist.
Effectiveness		• Engineered enzymes have demonstrated high effectiveness for remediation of some pesticide residues.
Cost		• Bioremediation solutions that utilise non-engineered microorganisms may present similar economic value without the additional development costs required for engineering the bioremediant.
Public attitude		• There may be social concerns related to an engineered biological product's persistence and potential environmental impacts. Engineered cell-free products may elicit less concern, however bioremediation solutions that utilise naturally occurring, non-engineered microorganisms may be preferred to engineered products for this reason.
Regulation		• Engineered microbial bioremediation solutions will be regulated as GMOs which are subject to rigorous regulations including rules restricting their use to contained environments. Cell-free bioremediation solutions will have less strict regulatory controls.
Intellectual property	(Not rated)	• Analysis of the European Patent Office's worldwide database considered 2325 bioremediation patents filed from 1997-2017. Most patents describe the use of bacteria, fungi or enzymes for bioremediation in soil, water or sludges. The analysis found that bioengineering is still a recent trend in bioremediation with less than 1% of the patents referred to genetic engineering. China and the United States of America were the origins of the most patent filings, regardless of genetic engineering status.[84]

83 Novorem (n.d.) Comparing Remediation & Bioremediation: Which is best, and when? <https://novorem.com.au/comparing-remediation-and-bioremediation/> (accessed 17 March 2022)

84 Quintella C, Mata A, Lima L (2019) Overview of bioremediation with technology assessment and emphasis on fungal bioremediation of oil contaminated soils. Journal of Environmental Management, 241, 156-166. DOI: 10.1016/j.jenvman.2019.04.019.

3.6 Engineered biological agricultural treatments

Engineered biologicals are agricultural treatments that use engineered biological systems (e.g. microbes) or components (e.g. RNAi) as their primary active ingredient. Biologicals can supplement or replace traditional agricultural chemicals to provide sustainable crop protection and productivity solutions.

Agricultural and forestry examples include topical pesticide sprays, microbial-based fertilisers to improve crop nitrogen fixation and crop productivity, and the peptide mediated delivery of agrochemicals to ensure delivery is efficient and targeted. Engineered biological treatments may also be employed in the aquaculture sector to control water-borne pests and diseases. Further, engineered biological treatments may offer vaccination solutions to immunise animals against disease, improving animal health and welfare.

Advanced bioengineering can provide an opportunity to further improve the efficacy (and therefore cost effectiveness) of biological treatments. Specifically, these techniques may be employed to improve the tolerance of insecticides, herbicides, and pesticides to environmental stress, improve target specificity, and block transmission of human disease-causing agents

Preliminary consultations suggest that opportunities for early commercial success may include treatments that are based on engineered biological components that cannot reproduce (e.g., RNAi-technologies) and the development of novel herbicides that can counter the growing number of herbicide resistant weeds. Given that chemical herbicide discovery can be heavily restricted by regulation, there may be scope for engineered organisms and biological molecules.

TRL	Expected time to commercial availability
Up to 9	1-5 years

Industry examples

- Pivot Bio (US) have developed nitrogen-fixing microbes that reduce the use of traditional ammonia fertiliser in corn farming (estimated CRI 2-3).[85]
- RNAissance Ag (US) are developing topical RNAi sprays for crop protection that induce gene silencing in pathogens. By taking up the externally applied RNA, the expression of genes that promote disease development are inhibited (estimated TRL 6, CRI 1).[86] They are also designing double-stranded RNA (dsRNA) to target White Spot Syndrome virus in shrimp, by incorporating it into shrimp feed (estimated TRL 1-2).[87]
- MicroSynbiotix (US) is developing engineered microalgae to produce recombinant protein vaccines for fish (estimated CRI 1).[88]
- Sundew (DNK) is developing engineered microalgal chloroplasts for use as delivery systems for bioencapsulated vaccines and silencing RNAi to prevent diseases (estimated CRI 1).[89]

85 Pivot Bio (n.d.) Solutions form the soil. Viewed 8 April 2022, <https://www.pivotbio.com/our-science>

86 RNAiSSANCE AG (n.d.) Solutions. <https://www.rnaissanceag.net/solutions/#insect>

87 RNAiSSANCE AG (n.d.) Solutions. <https://www.rnaissanceag.net/solutions/#insect>

88 MicroSynbiotix (n.d.) Oral Vaccines Built with Synthetic Biology. Viewed 8 April 2022, <https://www.microsynbiotix.com/how-we-do-it.html>

89 Sudew (n.d.) Technology. Viewed 8 April 2022, <https://www.sundew.bio/technology>

Research examples

- The ARC Sustainable Crop Protection Hub is developing RNAi-based bio-pesticide sprays (Estimated TRL 5+).[90]
- CSIRO and NuFarm are working collaboratively to develop and run a pre-commercial pilot trial of a novel biofungicide to prevent sclerotinia outbreaks, a common fungal disease, in canola crops (TRL 5).[91]
- CSIRO is developing advanced RNAi technology for crop protection (TRL 3).[92]
- CSIRO is investigating root associated microbes that can release phosphate from soil (TRL 5).[93]
- CSIRO is researching the design and engineering of novel peptides for enhanced delivery and/or uptake of agrochemicals (TRL 3).

BENEFIT	SIGNIFICANCE	EXPLANATION
Yield		• Most biological agricultural treatments will be designed to improve agricultural productivity. For example, biofertilisers may increase agricultural output through improving the utilisation of nutrient availability in soil.[94] Nitrogen-fixing biofertilisers are able to convert nitrogen to ammonia which can be used by the host plant for development.[95]
Product quality		• Biologicals including fertilisers, pesticides and treatments for disease all contribute to the production of high-quality products. • Crops and end-products grown in soils associated with the heavy use of traditional agrochemicals (e.g., pesticides) can be at risk of increased disease incidence and nutrient reduction. Biological agricultural alternatives (e.g. biopesticides) may deliver the same benefits as their traditional counterparts without compromising product quality.[96]
Cost saving		• The costs associated with biological treatments will vary between applications. Some will have potential cost savings, however this is not considered to be a primary benefit of all applications in this opportunity.
Environment, human health and animal welfare		• Biofertilisers may help to reduce GHG emissions through reducing the amount of ammonia needed for plants and the reduction of nitrous oxide.[97] Nitrogen run-offs can also be reduced, which is a major environmental problem leading to algal blooms in rivers/lakes and the sea.[98] • Some traditional agrochemicals have been linked to health impacts including increased cancer risk and foetal impairments. Many do not naturally degrade in the environment and may negatively impact natural ecosystems. Biological alternatives may be designed to provide safe and environmentally benign solutions for agricultural production. For example, biopesticides may offer lower toxicity and persistence, and can be designed to only affect specific or closely related targets. • Biologicals may offer solutions to immunise animals against disease and improve animal health and welfare.

90 Sustainable Crop Protection ARC HUB (n.d.) RESEARCH. <https://crophub.com.au/research>

91 NuFarm (n.d.) Actinobacteria: A Collaboration with CSIRO. <https://www.nufarmpartnerforgrowth.com/actinobacteria>; Australia Government (2022) CRC Projects selection round outcomes. Last updated 24 March 2022. <https://business.gov.au/grants-and-programs/cooperative-research-centres-projects-crcp-grants/crc-projects-selection-round-outcomes> (accessed 5 April 2022).

92 CSIRO (n.d.) RNAi MkII: Targeted method of regulating gene activity for crop protection and trait modulation. <https://www.csiro.au/en/work-with-us/ip-commercialisation/marketplace/rnai-mkii>

93 Richardson A, Simpson R (2011) Soil Microorganisms Mediating Phosphorus Availability. <https://publications.csiro.au/rpr/download?pid=csiro:EP111410&dsid=DS3>

94 Mitter E, Tosi M, Obregón D, Dunfield K, Germida J (2021) Rethinking Crop Nutrition in Times of Modern Microbiology: Innovative Biofertilizer Technologies. Frontiers in Sustainable Food Systems. DOI: 10.3389/fsufs.2021.606815.

95 Wagner S (2011) Biological Nitrogen Fixation. Nature Education Knowledge, 3(10). <https://www.nature.com/scitable/knowledge/library/biological-nitrogen-fixation-23570419/>

96 Kumar J, Ramlal A, Mallick D, Mishra V (2021) An Overview of Some Biopesticides and Their Importance in Plant Protection for Commercial Acceptance. Plants, 10(6). DOI: 10.3390/plants10061185.

97 Cardaso A, Junqueira J, Reis R, Ruggieri A (2020) How do greenhouse gas emissions vary with biofertilizer type and soil temperature and moisture in a tropical grassland? Pedosphere, 30(15), 607-617. DOI: 10.1016/S1002-0160(20)60025-X.

98 NECi (2018) Algae-based Biofertilizer from Runoff Water! <https://nitrate.com/algae-based-biofertilizer-runoff-water>

CHALLENGE	SIGNIFICANCE	EXPLANATION
Technical		• General technical challenges for biological treatments include formulation preferences, biological issues (storage and field stability, efficacy consistency), difficulty finding and employing natural carriers that exhibit desired properties, choice of adjuvant (substances that enhance biological responses to the treatment) and identifying targets in on-farm scenarios.
Plug and play		• Engineered biological treatments may require minor changes to processes such as differing storage and application (e.g., frequency, volume, target) requirements compared to traditional chemicals.[99] However, this is not expected to be a significant challenge.
Effectiveness		• Engineered biologicals may face competition from both traditional agrochemicals, and natural biological alternatives (e.g., non-engineered microbial biopesticides). • Bioengineering can be expected to be applied when current solutions are not sustainable and alternative sustainable options (such as biologicals sourced from nature or biomanufactured products) are not sufficiently effective or may have other adverse effects. For example, a heavy reliance on chemical pesticides and inconsistent field results by natural fungal biopesticides, has led researchers to investigate DNA technologies and synthetic gene insertion to generate more effective fungal biopesticides.[100]
Cost		• The ability to produce products cheaply and at scale may be a hurdle for some technologies, such as topical RNAi treatments, at least in the short term.
Public attitude		• CSIRO research has found that public attitudes towards the use of advanced bioengineering are more supportive when there is an environmental or health benefit.[101] However, biological treatments utilising genetically modified organisms may still elicit concerns related to the release of genetically modified material into the environment including their potential effect on non-target organisms.[102] Demonstrating safety will be critical to public support but cell-free biological treatments, such as RNAi-based technologies, may be more readily accepted as low-risk pesticide alternatives.[103]
Regulation		• Engineered biologicals that contain live GMOs can be expected to face significant longer approval processes while being assessed for safe use by the Gene Technology Regulator. Applications that are based on engineered biological components that cannot reproduce (e.g., RNAi-technologies) are expected to face less significant challenges but will still have to demonstrate that they are safe and effective to be approved for use by the APVMA.[104]
Intellectual property	(Not rated)	• Commercial interest in sprayable agricultural RNA-based compounds is increasing. This interest by large corporations may stimulate agricultural technology start-up companies to also engage with RNA applications. However, given the large economic requirements for biological agricultural treatments, the ability of start-ups to operate in this space might be limited. This may be compounded by large corporations dominating the potential market. Corporate IP policies may prefer acquisition or in-house development, which could inhibit collaboration with smaller companies.

99 AgriBusiness Global (2018) Biopesticides: Assessing the Opportunities and Challenges in R&D, Formulation. <https://www.agribusinessglobal.com/biopesticides/biopesticides-assessing-the-opportunities-and-challenges-in-rd-formulation/> (accessed 22 March 2022)

100 Lovett B, St Leger R (2018) Genetically engineering better fungal biopesticides. Pest Management Science, 74(4), 781-789. DOI: 10.1002/ps.4734.

101 CSIRO (2021) Public attitudes towards synthetic biology. Viewed 1 April 2022, <https://research.csiro.au/synthetic-biology-fsp/public-attitudes/>

102 Wozniak C, McClung G, Gagliardi J, Segal M, and Matthews K (2013) Chapter 4: Regulation of Genetically Engineered Microorganisms Under FIFRA, FFDCA and TSCA. In Wozniak C and McHughen A (Eds.), Regulation of Agricultural Biotechnology: The United States and Canada. DOI: 10.1007/978-94-007-2156-2_4.

103 Rank A, Koch A (2021) Lab-to-Field Transition of RNA Spray Applications - How Far Are We? Frontiers in Plant Science, 12. DOI: 10.3389/fpls.2021.755203.

104 CropLife Australia (n.d.) Safeguards and Regulation. <https://www.croplife.org.au/plant-science/safeguards-and-regulation/#:~:text=Agricultural%20chemicals%20are%20the%20most,they%20are%20available%20for%20use> (accessed 18 March 2022).

3.7 Engineered biosensors for environmental conditions

Biosensors can be developed for affordable, rapid, on-site determination of environmental conditions, including soil and water health. This includes:

- Monitoring agricultural and forestry soil and water sources for factors that can affect pre-harvest productivity (e.g., the presence of pesticide residues and contaminants, the presence of bacteria and pathogens, nutrient concentrations, pH and moisture levels).
- Monitoring water quality, gaseous concentrations, and the presence of toxic substances that may impact wellbeing, fertility and productivity of aquatic life.[105]
- Detecting potentially hazardous environmental conditions such as toxic contaminants in soil and foliage that may impact the health and wellbeing of livestock.

Advanced bioengineering may allow for improved operating parameters compared to traditional biosensors, including optimised detection ranges, robustness, selectivity and sensitivity. Advanced bioengineering may also increase the functionality and immobilisation of engineered biological components so they can be contained and deployed safely.[106]

Due to the challenges involved in the development and deployment of engineered whole cell biosensors (which are regulated as GMOs), the biosensor applications discussed here (and in 3.1 and 3.2) are cell-free systems. However, in the long-term, if public attitudes towards GMOs shift significantly, biosensing genes could be introduced into plants to enable them to act as environmental sensors.

Based on initial consultations and research, engineered environmental biosensors are more likely to be deployed where existing analytical approaches and biosensors are not fit for purpose, such as monitoring hard-to-observe reactions like iron and sulphur cycling in soils or marine sediment.[107] However, despite the growing market for on-farm sensing devices, no industry examples have been identified in this preliminary analysis. Some stakeholders noted difficulties in identifying environmental biosensor targets with large markets and strong value propositions. Integrating biosensors with emerging big data solutions for agriculture may help increase their value proposition. There may be opportunities to apply environmental biosensors in combination with bioremediation technologies (see 3.5) to identify and address issues such as agrochemical contamination.

TRL	Expected time to commercial availability
Up to 6 (for generic engineered biosensor technology)	1-5 years

105 Kundu M, Krishnan P, Kotnala R, Sumana G (2019) Recent developments in biosensors to combat agricultural challenges and their future prospects, Trends in Food Science & Technology, 88, 157-178. DOI: 10.1016/j.tifs.2019.03.024

106 Moratti C, Scott C, Coleman N (2022) Synthetic Biology Approaches to Hydrocarbon Biosensors: A Review. Frontiers in Bioengineering and Biotechnology, 9. DOI: 10.3389/fbioe.2021.804234.

107 Del Valle I, Fulk E, Kalvapalle P, Silberg J, Masiello C, Stadler L (2021) Translating New Synthetic Biology Advances for Biosensing into the Earth and Environmental Sciences. Frontiers in Microbiology, 11. DOI: 10.3389/fmicb.2020.618373.

Research examples

- CSIRO is using advanced bioengineering and bioinformatics techniques to identify and modify microbial genes that can bind to toxic metals and introducing them into aquatic organisms to detect the presence of metals in waterways.[108]
- University of Rome Tor Vergata researchers have been conducting research into paper-based biosensors for the detection of pesticides in soil content.[109]

BENEFIT	SIGNIFICANCE	EXPLANATION
Yield		• Engineered environmental biosensors are expected to improve productivity across agricultural, aquacultural and livestock industries by allowing for environmental conditions to be monitored and optimised. For example, the productivity of fish farming is highly reliant on environmental conditions with poor water quality and marine toxins affecting aquatic life growth rates, disease incidence and mortality.[110] • Environmental contaminants can threaten livestock infertility, reducing productivity.[111]
Product quality		• Poor ecological conditions can have a detrimental effect on the nutrient and metabolite concentrations of crops, as well as consumer properties such as colour, taste, and texture. For example, legumes grown in soil with higher levels of carbon dioxide may contain decreased zinc and iron concentrations.[112] Detecting and removing potentially harmful pollutants from the environment such as agrochemical residues and heavy metals can improve product quality.[113] • Poor water quality may also impact fish product quality, by increasing the likelihood of poor growth, disease symptoms or parasite infestations.[114]
Cost saving		• Cost saving is not considered a primary benefit of environmental biosensors. However, biosensors designed for in-field use are expected to compete with traditional lab-based analysis techniques that can be costly and time consuming.[115]
Environment, human health and animal welfare		• Engineered biosensors may provide greater environmental benefits than non-engineered systems by improving the ability to detect poor environmental conditions that can be rectified. • The ability to remediate polluted sites based on biosensor information can have positive flow on effects across the food chain, and on human health. • Developing remote sensing systems that reduce human interaction with harmful pollutants and contaminated environmental samples may minimise OH&S risks.

108 CSIRO (n.d.) Bio-prospecting for natural biosensors that detect pollution. <https://research.csiro.au/environomics/team-research-projects/metagenomic-mining-of-riboswitches-for-construction-of-rna-based-biosensors/> (accessed 21 March 2022)

109 Caratelli V, Fegatelli G, Moscone D, Arduini F (2022) A paper-based electrochemical device for the detection of pesticides in aerosol phase inspired by nature: A flower-like origami biosensor for precision agriculture. Biosensors and Bioelectronics, 205. DOI: 10.1016/j.bios.2022.114119.

110 Kundu M, Krishnan P, Kotnala R, Sumana G (2019) Recent developments in biosensors to combat agricultural challenges and their future prospects, Trends in Food Science & Technology, 88, 157-178. DOI: 10.1016/j.tifs.2019.03.024; Ajani P, Harwood T, Murray S (2017) Recent Trends in Marine Phycotoxins from Australian Coastal Waters. Marine drugs, 5(2). DOI: 10.3390/md15020033; Baechler B, Stienbarger C, Horn D, Joseph J, Taylor A, Granek E, Brander S (2020) Microplastic occurrence and effects in commercially harvested North American finfish and shellfish: Current knowledge and future directions. Limnology and Oceanography Letters, 5, 113-136. DOI: 10.1002/lol2.10122.

111 Guvvala P, Ravindra J, Selvaraju S (2020) Impact of environmental contaminants on reproductive health of male domestic ruminants: a review. Environmental Science Pollution Research International, 27(4), 3819-3836. DOI: 10.1007/s11356-019-06980-4.

112 Ahmed S, Stepp J (2016) Beyond yields: Climate change effects on specialty crop quality and agroecological management. Elementa: Science of the Anthropocene, 4. DOI: 10.12952/journal.elementa.000092.

113 Kundu M, Krishnan P, Kotnala R, Sumana G (2019) Recent developments in biosensors to combat agricultural challenges and their future prospects, Trends in Food Science & Technology, 88, 157-178. DOI: 10.1016/j.tifs.2019.03.024

114 Endo H, Wu H (2019) Biosensors for the assessment of fish health: a review. Fisheries Science, 85. DOI: 10.1007/s12562-019-01318-y.

115 Chen Y-T, Lee Y-C, Lai Y-H, Lim J-C, Huang N-T, Lin C-T, Huang J-J (2020) Review of Integrated Optical Biosensors for Point-of-Care Applications. Biosensors, 10(12). DOI: 10.3390/bios10120209; M Martins T, Ribeiro A, de Camargo H, Filho P, Cavalcante H, Dias D (2013) New Insights on Optical Biosensors: Techniques, Construction and Application. In (Ed.), State of the Art in Biosensors - General Aspects. IntechOpen. DOI: 10.5772/52330.

CHALLENGE	SIGNIFICANCE	EXPLANATION
Technical		• Due to their use in healthcare, the technology of engineered biosensors is well established. While technology challenges are not expected to be a significant barrier to implementation, engineered biosensors will need to ensure they have appropriate reliability, sensitivity, selectivity, stability, and usability for their target application.[116] The biological components may also face bioavailability, culture scale-up and immobilisation challenges.[117] • The development of open-source artificial intelligence programs that predict protein structures (e.g., AlphaFold release by Deepmind/Alphabet in 2021) has significantly improved the ability of biologists to design new functional proteins that could be used in biosensors and may rapidly accelerate technology development times.[118]
Plug and play		• Usability and easy interpretation of results can be expected to support the uptake of biosensors by producers. Efficient, automated systems could be expected to improve commercial viability in applications that require testing of many samples. • Biosensors can offer usability advantages over traditional laboratory equipment which can be time-consuming, laborious, expensive, and often require skilled technicians to operate.[119]
Effectiveness		• There are a wide variety of sensors and analytic tools that do not utilise advanced bioengineering techniques in the agricultural sector. However, advanced bioengineering can be used to develop more effective sensors where existing options do not offer satisfactory solutions.
Cost		• Researchers noted that identifying the right environmental targets to engineer biosensors for is challenging as the economics requires the targeted challenge be of sufficient scale to justify the R&D and manufacturing setup costs for a new solution. Similarly, for challenges where affordable and effective sensing and analytic solutions for on-farm use already exist, engineering new solutions may not be cost effective due to the potentially significant development costs and the time and resources required to engineer systems suitable for field applications.[120]
Public attitude		• Not expected to pose a significant challenge to on-farm implementation. CSIRO research has found that public attitudes towards the use of advanced bioengineering are more supportive when there is an environmental benefit.[121]
Regulation		• Regulatory challenges are not expected to pose a significant challenge to on-farm implementation in most cases, as most biosensors are expected to be cell-free systems that will not involve the release of live GMOs.[122]
Intellectual property	(Not rated)	• High-level analysis suggests there is an increasing trend in patent applications for biosensors in the agri-food industry. However, in terms of applications, patents for environmental biosensors appear to be limited, with even fewer using advanced bioengineering principles. The backgrounds of those applying for these patent rights are decentralised and diverse, suggesting there is little IP competition for engineered environmental biosensors.

116 Neethirajan S, Ragavan V, Weng X, and Chand R (2018). Biosensors for Sustainable Food Engineering: Challenges and Perspectives. Biosensors, 8(1), 23. DOI: 10.3390/bios8010023.

117 Moratti C, Scott C, Coleman N (2022) Synthetic Biology Approaches to Hydrocarbon Biosensors: A Review. Frontiers in Bioengineering and Biotechnology, 9. DOI: 10.3389/fbioe.2021.804234.

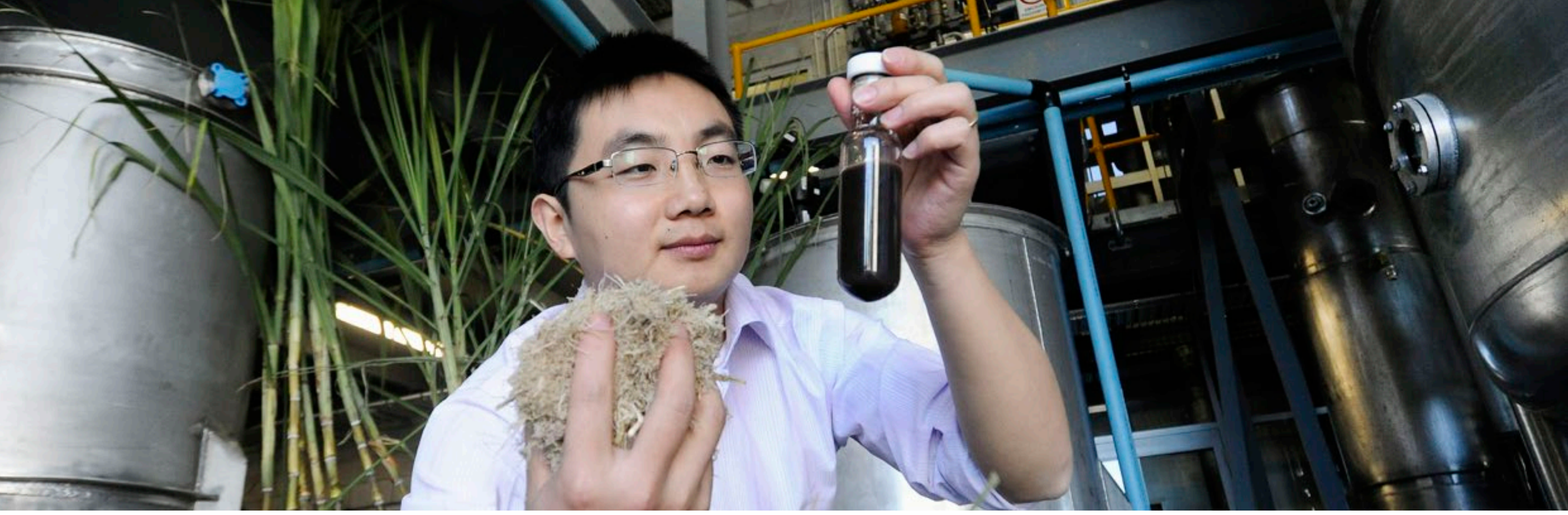
118 Callaway E (2022) What's next for AlphaFold and the AI protein-folding revolution, Nature. https://www.nature.com/articles/d41586-022-00997-5 (accessed 14 April 2022).

119 Fang Y, Ramasamy R (2015) Current and Prospective Methods for Plant Disease Detection. Biosensors, 5(3), 537-561. DOI: 10.3390/bios5030537.

120 Moratti C, Scott C, Coleman N (2022) Synthetic Biology Approaches to Hydrocarbon Biosensors: A Review. Frontiers in Bioengineering and Biotechnology, 9. DOI: 10.3389/fbioe.2021.804234.

121 CSIRO (2021) Public attitudes towards synthetic biology. Viewed 1 April 2022, <https://research.csiro.au/synthetic-biology-fsp/public-attitudes/>.

122 Moratti C, Scott C, Coleman N (2022) Synthetic Biology Approaches to Hydrocarbon Biosensors: A Review. Frontiers in Bioengineering and Biotechnology, 9. DOI: 10.3389/fbioe.2021.804234; Del Valle I, Fulk E, Kalvapalle P, Silberg J, Masiello C, Stadler L (2021) Translating New Synthetic Biology Advances for Biosensing into the Earth and Environmental Sciences. Frontiers in Microbiology, 11. DOI: 10.3389/fmicb.2020.618373.



3.8 On-farm bioenergy solutions

TRL	Expected time to commercial availability
Up to 5	5-10 years

On-farm bioenergy solutions encompass a range of bioengineering-enabled processes that can convert biomass produced on farms (including waste products such as bagasse from sugarcane and straw waste from grain crops) into sustainable fuels for on-farm use. These fuels may then be used for renewable heat and power generation, transport and farm vehicles, and as an input to fertiliser production. This opportunity has the potential to be applied across most agricultural industries as long there is a suitable feedstock available, such as agricultural and forestry residues, and non-food crops.[123]

Modelling undertaken by the Grains Research and Development Corporation (GRDC) found that conversion of straw waste produced on an average sized (4,000 hectare) grain farm could generate in the order of 200kg of hydrogen per day, which would be sufficient to replace all on-farm fertilizer, energy and fuel requirements.[124]

Advanced bioengineering allows for hydrogen producing microbes and biocatalysts to be modified to increase their effectiveness. This may involve increasing their enzymatic activity, eliminating competing metabolic pathways, or increasing their ability to process different feedstocks.[125]

For simplicity this evaluation has focused on the application of producing hydrogen using on-farm waste biomass when discussing benefits and challenges. However, biomanufacturing techniques could be used to produce a variety of fuels, including methane.

Industry examples

- One Australian example was identified (CRI 1) however they requested not to be named as they felt the assessment of the broader opportunity did not accurately represent their individual business.

Research examples

- Hydrogen production from woody biomass via biological conversion (TRL 4-5) and bio-electrochemical conversion (TRL 2-4).[126]

123 ETIP Bioenergy (n.d.) Bioenergy for Everyone. Viewed 11 April 2022, <https://www.etipbioenergy.eu/everyone/biofuel-feedstocks>.

124 NB: These results were provided by a stakeholder. The GRDC has been contacted for validation and a proper reference.

125 Jianjun H (2021) Chapter 4 - Comparisons of biohydrogen production technologies and processes, Waste to Renewable Biohydrogen, Academic Press. In Zhang Q, He C, Ren J, Goodsite M (Eds.). DOI: 10.1016/B978-0-12-821659-0.00010-1.

126 Key players in Australia's research sector are identified in: Srinivasan, V., Temminghoff, M., Charnock, S., Hartley, P. (2019). 3.1.7 Biological hydrogen production. In Hydrogen Research, Development and Demonstration: Priorities and Opportunities for Australia, CSIRO;
Thibaut Lepage, Maroua Kammoun, Quentin Schmetz, Aurore Richel (2021) Biomass-to-hydrogen: A review of main routes production, processes evaluation and techno-economical assessment, 144. ISSN 0961-9534. DOI: 10.1016/j.biombioe.2020.105920.

BENEFIT	SIGNIFICANCE	EXPLANATION
Yield		• On-farm bioenergy production is not expected to have direct impacts on yield and agricultural productivity.
Product quality		• On-farm bioenergy production is not expected to have direct impacts on the quality of agricultural products.
Cost saving		• On-farm bioenergy facilities will require significant capital investment in the hydrogen production system, storage infrastructure, and systems (e.g., fuel cells, fuel cell vehicles). In the short term, the significant capital costs associated with deploying and operating on-farm bioenergy solutions are expected to outweigh any operational cost savings associated with producing hydrogen fuel from cheap feedstocks.[127]
Environment, human health and animal welfare		• Provides a sustainable energy source and may assist in waste management by using waste biomass as a feedstock. • Hydrogen may also be used as an input for on-farm ammonia fertiliser production. • By-products of biological hydrogen production (fatty acids, alcohols, etc.) may be utilised in other biological processes for energy recovery or as feedstocks for chemical production, further improving process sustainability.[128]
Other	(Not rated)	• On-demand hydrogen production systems could improve seasonal energy security for farms without requiring large hydrogen storage vessels, as the energy may be stored as biomass until it is required.[129] • May reduce reliance on traditional fuel markets, reducing producer exposure to price fluctuations, and logistical challenges associated with delivery of fuel to remote locations. This may have benefits for Australia's food security.

127 Lepage T, Kammoun M, Schmetz Q, Richel A (2021) Biomass-to-hydrogen: A review of main routes production, processes evaluation and techno-economical assessment, 144. DOI: 10.1016/j.biombioe.2020.105920.

128 Brown T (2017) Solar-Bio-GMO-Ammonia, powered by the 'Bionic Leaf'. Ammonia Energy Association. <https://dev.ammoniaenergy.org/articles/solar-bio-gmo-ammonia-powered-by-the-bionic-leaf/>; American Chemical Society (2017) A 'bionic leaf' could help feed the world [Press Release]. <https://www.acs.org/content/acs/en/pressroom/newsreleases/2017/april/bionic-leaf-could-help-feed-the-world.html>

129 Lepage T, Kammoun M, Schmetz Q, Richel A (2021) Biomass-to-hydrogen: A review of main routes production, processes evaluation and techno-economical assessment, 144. DOI: 10.1016/j.biombioe.2020.105920.

CHALLENGE	SIGNIFICANCE	EXPLANATION
Technical		• Significant engineering challenges can be expected during scale-up and infrastructure development to enable successful deployment of bio-energy solutions in on-farm environments. Hydrogen production on farms is expected to require significant investment in development and demonstration to reach technically maturity.[130]
Plug and play		• Biohydrogen production will require investment in new infrastructure (both for the production and use of produced hydrogen) to be implemented on-farm. Staff may require training to operate the hydrogen production system. At a minimum, new procedures for the collection, storage, processing, and disposal of feedstocks will be required.[131]
Effectiveness		• If successfully scaled, biological hydrogen production may offer a variety of potential advantages including reduced footprints, on-demand production with no reliance on variable renewable energy sources (i.e., sun/wind), reduced water consumption, and suitability for replacing seasonal energy requirements that are typically addressed by diesel generators.
Cost		• Biological options for hydrogen production are currently amongst the least economically competitive methods available for producing hydrogen.[132] • However, biological hydrogen production could become cost-competitive with other forms or hydrogen production as the technology matures. On-site and on-demand production can also negate many of the costs associated with transporting and storing hydrogen. There is also potential for farms to received carbon credits for turning waste biomass (e.g., straw waste that is typically burned) into sustainable fuels.
Public attitude		• Public attitudes towards on-farm implementation bioenergy solutions are not expected to pose a significant challenge. CSIRO research has found that public attitudes towards the use of advanced bioengineering are more supportive when there is an environmental benefit.[133]
Regulation		• Regulatory challenges could delay commercialisation of some biological hydrogen production technologies. Level 2 physical containment (PC2) certification is typically required for biomanufacturing facilities that work with GMOs and this may create challenges for on-farm deployment of biohydrogen production systems that utilise engineered living cells (e.g., yeasts or microbes). However, applications that use cell-free biocatalysts (e.g., engineered enzymes) may not face the same regulatory hurdles.
Intellectual property	(Not rated)	• Given the competition and complexity of the energy sector, it has been suggested that private investment may potentially lock up a large proportion of enabling technologies under various IP protection mechanisms.[134]

130 Srinivasan, V., Temminghoff, M., Charnock, S., Hartley, P. (2019). Hydrogen Research, Development and Demonstration: Priorities and Opportunities for Australia, CSIRO.

131 Lepage T, Kammoun M, Schmetz Q, Richel A (2021) Biomass-to-hydrogen: A review of main routes production, processes evaluation and techno-economical assessment, 144. DOI: 10.1016/j.biombioe.2020.105920.

132 Lepage T, Kammoun M, Schmetz Q, Richel A (2021) Biomass-to-hydrogen: A review of main routes production, processes evaluation and techno-economical assessment, 144. DOI: 10.1016/j.biombioe.2020.105920.

133 CSIRO (2021) Public attitudes towards synthetic biology. Viewed 1 April 2022, <https://research.csiro.au/synthetic-biology-fsp/public-attitudes/>

134 International Food Policy Research Institute (2020) BIOENERGY AND AGRICULTURE: PROMISES AND CHALLENGES, edited by Peter Hazell and R.K. Pachauri. <https://ebrary.ifpri.org/utils/getfile/collection/p15738coll2/id/128343/filename/128554.pdf>

4 Next steps

AgriFutures Australia intends to socialise the findings of this report with key stakeholders in order to help test the preliminary analysis and identify priority applications of advanced bioengineering for Australia's agriculture sector. Further analysis that would be valuable for prioritised applications could include exploring the following questions:

- Could Australia be a technology provider (or only a technology purchaser)?
- What value (quantitative economic assessment) could the application provide to farmers, fishers and foresters by 2040?
- What is the potential size of the global and Australian markets for each prioritised opportunity by 2040?
- What activities or investments could help to mature each application into real-world impact (e.g. R&D investments, regulation changes, skills development)?

Table 5 provides two example approaches for thinking through the prioritisation process, however many more exist. The first aims to identify opportunities that are most likely to be readily available to Australian producers in the nearer term, while the second aims to identify opportunities that might be the most attractive focus and investment areas for technology developers seeking to commercialise new products.

Regardless of the opportunities selected, it is recommended that AgriFutures Australia focus the scope of further analysis on individual applications within these opportunities, where possible. This will allow for more practical implementation considerations and R&D activities to be identified. Illustrative application examples have been provided for each of the opportunities.

Table 5: Focusing on criteria of interest in the assessment framework can suggest different sets of opportunities for further analysis

FOCUS AND OBJECTIVE	CRITERIA	RESULTING OPPORTUNITIES AND EXAMPLES	CONSIDERATIONS
Available applications Opportunities that may be available for use by producers in the nearer term.	• High TRL • Most industry examples identified	• **Biomanufactured** animal feed (e.g., enzymatic feed additives to support animal health and nutrition). • **Biomanufactured** agricultural chemicals (e.g., antibiotics to treat infections in livestock). • Engineered **biological** agricultural treatments (e.g., nitrogen-fixing microbes to reduce the use of ammonia fertilisers).	This focus will not necessarily identify areas where Australia could lead the way or generate new businesses/products.
Growth opportunities Opportunities in high growth markets that technology developers could consider targeting.	• High growth markets (CAGR) • Least challenges identified	• Engineered **biosensors** for improved product quality (e.g., detection of toxin concentrations in produce). • Engineered **biosensors** for animal and crop health (e.g., detection of bovine mastitis) • Engineered **biosensors** for environmental conditions (e.g., detection of soil health parameters - i.e., pH and nutrient levels).	This focus results in three biosensor opportunities which could limit the diversity of insights that can be generated (unless specific applications are selected). While sensors have the highest identified growth rates, they have the smallest target markets.

Appendix A: Scoping results

A high-level assessment of technical maturity and key barriers to commercialisation was undertaken for each of the 15 opportunities identified in the scoping phase. This analysis was used to estimate whether each opportunity is expected to be commercially available within 10 years. These ratings are indicative only and do not imply whether a commercialised product will be successful. The assessment was informed by expert opinion from relevant CSIRO experts and a limited literature review. Eight opportunities received a pass or pass with caveats rating and these were selected for the project.

CONSIDERATIONS	DESCRIPTION
Technical maturity	The Technology Readiness Level (TRL) of the most mature technology identified for this opportunity (TRL9).
Key challenges	Challenges that may delay the commercialisation of each opportunity (e.g., cost, effectiveness, safety and regulation, ethics and social license, technical challenges, compatibility with current practices).
Genetically modified crops and animals	Opportunities that involve the genetic modification of crops or animals are excluded from the project scope due to the ethical, social and technical challenges associated with their development.

→

RATING	DETAILS
Pass	Commercial applications are available OR it is expected that a commercial product could feasibly be developed within 10 years.
Pass with caveats	It is expected that a commercial product could feasibly be developed within 10 years if significant challenges can be overcome.
Fail	It is not expected that a commercial product could be developed within 10 years, or the opportunity is considered out of scope.

Figure 3: Technical maturity and key barriers were used to inform qualitative ratings of each opportunity's commercial feasibility within 10 years

Table 6: Results of the commercial feasibility assessment

OPPORTUNITY	DESCRIPTION	ESTIMATED TRL (UP TO)	KEY BARRIERS IDENTIFIED DURING SCOPING	JUSTIFICATION
Engineered biosensors for improved product quality	Using genetically coded biological elements for detection such as rapid on-farm biosensing of proteases in raw milk samples.	9	Technical and regulatory challenges, competition with alternative solutions.	High TRL and near-commercial products demonstrating market feasibility.
Engineered biosensors for animal and crop health	Using genetically encoded biological elements to detect pathogens and biomarkers associated with animal and crop health.	9	Competition with alternative solutions, potential regulatory challenges for engineered biological products.	High TRL and use of similar technologies in other sectors suggests technical feasibility within 10-years is possible. Significant challenges expected.
Biomanufacturing animal feed	Employing engineered biological systems to produce animal feed.	9	Cost, scale-up, competition with alternative solutions.	High TRL and commercial products demonstrating market feasibility.
Engineer biological agricultural treatments	Developing biological agricultural treatments such as topical RNA-based sprays and biological alternatives to fertiliser	9	Cost, technical challenges, regulatory challenges for engineered biological products, competition with alternative solutions.	High TRL suggests technical feasibility is possible within 10-years. Several engineered biological treatments are already under development. Significant challenges expected.

OPPORTUNITY	DESCRIPTION	ESTIMATED TRL (UP TO)	KEY BARRIERS IDENTIFIED DURING SCOPING	JUSTIFICATION
Biomanufacturing agricultural chemicals	Employing engineered biological systems to produce agrochemicals including pesticides, herbicides, fertilisers.	9	Cost, scale-up, competition with alternative solutions.	High TRL suggests technical feasibility within 10-years is possible, and several organisations are currently operating at low commercial readiness. Significant challenges expected.
Engineered bioremediation solutions	Using bioengineered microorganisms and enzymes to degrade and remove contaminants from the environment.	9	Limited demand/drivers/ incentives, regulatory challenges for engineered biological products	High TRL and precedent for a commercial product (though the product is no longer on the market).
Engineered biosensors for environmental conditions	Using genetically encoded biological elements to rapidly detect environmental conditions and contaminants.	6	Competition with alternative solutions, potential regulatory challenges for engineered biological products.	Medium TRL and use of similar technologies in other sectors suggests technical feasibility within 10-years is possible. Significant challenges expected.
On-farm bioenergy solutions	Employing engineered biological systems to produce fuels (e.g., hydrogen) from bio-mass for on-farm use.	5	Technical and economic challenges, adoption challenges (simplified and integrable systems), environmental considerations (by-product impacts), current demand for hydrogen/ammonia energy on farm is limited.	Medium-TRL suggests technical feasibility within 10 years is possible. Significant challenges expected.
Engineered novel crops	Employing genetic modification to create crops with enhanced nutritive profiles.	9	Cost, technical and regulatory challenges.	Genetically modified crops are out of scope.
Gene markers to identify male chicks prior to hatching	Developing engineered biological gene to identify the gender of chicks prior to hatching.	5	Social license (i.e., public concerns regarding the long-term effects of the technology).	Genetically modified animals are out of scope.
Engineered biological approaches to reducing methane emissions from ruminants	Employing engineered biological systems for the digestive system of ruminants to reduce methane emissions.	5	Competition with alternative solutions, technical challenges.	Genetically modified animals are out of scope.
Engineered biological waste solutions	Developing advanced bioengineered solutions to process wastes.	3	Competition from alternative solutions and weak value proposition for use of bioengineering, technical challenges, cost.	Low TRL, weak value proposition, and significant challenges. Some applications (e.g., on-farm bioenergy) are captured in other rows.
Engineered insects for waste management	Developing engineered biological insects to manage waste or convert waste to high value outputs.	3	Technical, economic, social license and regulatory challenges.	Genetically modified animals are out of scope.
Engineered crops with traits for productivity	Employing genetic modification to enhance the health and resilience of crops.	2	Cost, technical and regulatory challenges.	Genetically modified crops are out of scope.
Genetic control of invasive and pest species	Employing genetic modification to control the multiplying of invasive and pest species.	2	Technical, social license (irreversible threats to biodiversity), and regulatory challenges (technology not contained to geographical area).	Genetically modified animals are out of scope.

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