Curbing antimicrobial resistance

A technology-powered, human-driven approach to combating the 'silent pandemic'.

CSIRO Australia's National Science Agency

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Steering Committee

Ms Sue MacLeman FTSE, Associate Professor Branwen Morgan, Professor Ronald Quinn AM FTSE, Mr Phillip Butler FTSE, Professor Emily Hilder FTSE, Dr Anne Astin AM PSM.

Project Team

Dr Audrey Rollin, Ms Candice Raeburn, Dr Cath Latham, Mr Peter Derbyshire, Mr Suryodeep Mondal.

Expert Review Group

Professor Anton Peleg FAHMS, Dr Dimity Dornan AO FTSE, Dr John Bell FTSE, Adjunct Professor Trevor Danos AM FTSE, Dr Tara Sutherland.

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Executive summary

Antimicrobial resistance (AMR) is a looming global health crisis, recently designated one of the top 10 public health threats facing humanity by the World Health Organisation (WHO). AMR has the ability to render some of the most critical antimicrobial drugs ineffective. It can spread among microorganisms in health and agricultural settings, before making its way out into the environment and causing significant harm to human and animal hosts. Losing effective antimicrobial treatments against infections would be catastrophic for health. Without preventative action, it is estimated that by 2050 AMR would lead to 10 million people dying every year and cost the global economy US$100 trillion.

There are currently extensive global investments into the research and development (R&D) of new antibiotics. This is critical to ensure new drugs will be available when AMR leaves many of the current medicines used to tackle infections ineffective. However, developing new antibiotics is only one of the paths open to manage AMR. A multi-faceted, transdisciplinary approach is required if the world is to avoid being thrust back into a pre-antimicrobial age where simple infections are deadly, and some surgeries are too risky to perform.

New technology-based interventions to help prevent, understand, and control AMR – such as anti-fouling surface technology and new surveillance and detection methods – need to be viewed as key tools in our arsenal. With this perspective in mind, this report does not focus on the discovery of new antibiotics. Rather, it hones in on new and emerging technology-based solutions to prevent the evolution and spread of resistance, and seeks to maintain and extend the effectiveness of antibiotics for longer. Emphasis is placed on preventative technologies that can make an impact on human, animal, and environmental health, now and into the future.

Through research and consultation with multi-disciplinary experts, this report has identified the key challenges and opportunities for Australia to improve prevention, detection, diagnosis, and response to drug-resistant infections and reduce the impacts of AMR.

Consultations involved over 100 stakeholders spanning government, academia, and industry, and key technologies that could be used to reduce the prevalence and spread of AMR were identified.

Consultations also explored the barriers to implementation of the technology-based solutions, and key enablers to ensure they are able to make significant gains against AMR.

The message from stakeholders was clear – there is a lack of coordination in the efforts against the rise of AMR, significant data siloes across states and sectors, and a need to increase community understanding about the issues and impacts of AMR. A need to streamline and simplify pathways to market was also called out as a key requirement to enable technology-based AMR solutions to get to the places they are needed the most – both within healthcare settings, and beyond. The criticality for rapid technology solution development and deployment is exacerbated by the acceleration of AMR from the impacts of climate change, and need to better monitor and manage the current and emerging issues associated with increased AMR prevalence. These challenges need to be overcome if Australia, and the world, is to get on top of the rising rates of AMR in the environment and the looming threat to global human and animal health.

Challenges

Lack of trusted and complete multi-sectoral data to inform decision-making and drive behavioural change to mitigate the impact of AMR

Climate change accelerating the emergence and spread of AMR across sectors

Lack of new technologies and treatments for prevention, detection, diagnosis, and treatment of AMR coming to market

Lack of awareness, understanding, accountability, and responsibility to improve AMR outcomes

Enablers

Data

- Interoperability
- Common data model
- Artificial Intelligence and Machine Learning

Standardisation

- Technology
- Data
- Regulation

Commercialisation

- Infrastructure
- Translation
- Funding

Implementation

- End-to-end planning
- Change management
- Continual improvement

Education

- Behaviour change
- Citizen science
- Equity

Potential solutions

Integrated surveillance and sensing systems

Integrated surveillance and sensing technologies including environmental sensors to monitor AMR across sectors

Point-of-care diagnostics

Simple, affordable and action-oriented point-of-care diagnostics to enable timely diagnosis and treatment of infections

Vaccination technologies

A data-driven, risk-based approach to vaccine production, leveraging new and emerging vaccination technologies

Prevention through design

Designing our farms, hospitals, and other high-risk settings to prevent the spread and growth of AMR organisms by deployment of antimicrobial surfaces, air sterilisation technologies, and engineering solutions

Outcomes

Comprehensive data and action-oriented insights to respond to risks and improve health outcomes

Reduced incidence of AMR in humans, animals, and the environment

More solutions to manage communicable diseases – particularly AMR – in the market

Educated, empowered, enabled and aligned citizens and sectors

In addition to identifying key challenges and the pathways forward, stakeholders were also asked to assess Australia's readiness to adopt, adapt, or further develop the potential solutions identified. Analysis of these findings provide a snapshot of areas where Australia is ready to realise the benefits of these solutions, and areas where more work should be undertaken. Along with the challenges presented by the COVID-19 pandemic, a silver lining has emerged in the shape of an increased awareness of the impact of communicable diseases, improved vaccination infrastructure and point-of-care (POC) diagnostic capability, and a greater understanding of the importance of public health surveillance. This leaves Australia well positioned to leverage these lessons and to apply them in the domain of AMR.

AMR doesn't respect national, state, or sectoral boundaries. So, it is critical that solutions are designed from a One Health perspective, acknowledging the undeniable interplay between humans, animals, and the environment. This will be key to making sure that in creating a solution for one sector, a problem is not being generated for another. Sectors impacted by and contributing to the spread of AMR will need to work together – across Australia and beyond – in taking action to manage, mitigate and control AMR.

Australia has the potential to be a strong global contributor in the development of technologies to combat AMR and should aspire to be a world-leader in its management. Australia has a wealth of creative and practical solutions for detection and prevention of AMR emerging in our own backyard. The challenge is ensuring these solutions make it through the commercialisation process to the places they are needed, in a streamlined and coordinated way, and in a manner that ensures equity is at the heart of the national management strategies. Australia also needs to ensure sectors are supported in taking the coordinated approach required to tackle this multi-faceted challenge, and to prevent disparate and siloed approaches from continuing to form.

Through the analysis presented in this report, actions that Australia can take at the local and global level to control, mitigate and manage AMR and that will complement global efforts to develop new antimicrobials have been identified. Overall, two high-level recommendations emerged from the project that will propel Australia forward to achieve its technology-powered, human-driven potential, and to prevent the rise and spread of AMR.

	Infrastructure readiness	**Skills availability**	**Social and ethical readiness**	**Economic and commercial readiness**	**Policy and regulatory readiness**
Integrated sensing and surveillance systems	◔	◑	◑	◔	◔
Point-of-care diagnostics	◑	◕	◕	◑	◑
Vaccination technologies	◑	◑	◕	◑	◕
Preventative design: High-risk settings	◔	◕	◑	◔	◔

KEY

Not ready		**More work required**		**Ready**
○	◔	◑	◕	●

Recommendation 1: Establish centralised coordination and leadership for AMR management to align and coordinate domestic and international activities across human health, animal health and environmental health sectors.

To support a unified approach, we recommend the establishment of centralised coordination and leadership for AMR management to align domestic and international activities across sectors. Without this coordination it will be difficult to address the lack of awareness, understanding, accountability, and responsibility to improve AMR outcomes, and to tackle the impacts of climate change that can accelerate the emergence and spread of AMR across sectors. This leadership should:

- Provide national, multi-sectoral representation and coordination.
- Drive the development of an enabling policy, regulatory, financial, and commercial landscape.
- Ensure long term AMR strategy is accompanied by robust implementation plans, and reporting and review.
- Integrate AMR management into urban and environmental planning practices.
- Lead on AMR messaging, awareness, and education.

Recommendation 2: Streamline and optimise the commercialisation process to support Australian AMR solutions entering the market.

This coordinated leadership should be accompanied by streamlining and optimising the commercialisation process to support Australian AMR solutions entering the market. This could be achieved by the Australian and State Governments, in collaboration with the private sector and industry associations, providing pathways to market and support for new AMR prevention and mitigation technologies. Currently, there are policy, regulatory and financial barriers that severely hinder this process, limiting our options to manage and combat AMR.

By streamlining processes both domestically and internationally for new AMR technologies to enter the global market, we could manufacture and distribute the best new AMR technologies to where they are needed, as rapidly as possible.

It is crucial that this process:

- Establish central AMR oversight to track and manage AMR funding and solutions.
- Create a streamlined process for expediting AMR solutions.
- Advocate for international alignment, collaboration, and harmonisation.
- Support regulator capacity and capability to bring AMR solutions to market.
- Leverage strategic partnering approaches across sectors as a practicable delivery solution.

These recommendations are key to efficient and effective management of AMR, and to supporting a viable marketplace for Australian innovations, economic prosperity, and societal wellbeing. These high-level recommendations are supported by the following policy priorities:

1. Develop robust One Health data policies and standards.
2. Establish fit-for-purpose, sustainable regulation, funding models, and financial incentives.
3. Treat priority AMR solutions as a public good.

There was strong consensus on the need for additional fundamental AMR research, as well as research into point-of care-diagnostics and vaccines, and innovative and alternative technology-based solutions.

Australia is at a critical juncture in the approach to mitigation and management of the devastating impacts of AMR, and how the country works with international counterparts to tackle this global crisis. Strong and decisive action is required if Australia are to slow the rate of AMR evolution and continue to build the healthy, sustainable, equitable, technology-powered future that is well within the nation’s reach.

Part I

Introduction

Introducing One Health

One Health is a collaborative and multisectoral approach to achieving optimal health outcomes by recognising the interconnection between people, animals, plants, and their shared environment (see Figure 1). The approach considers impacts at local, regional, national, and global levels, and accommodates the critical element of environmental and climate change that will drive AMR impacts across human health, animal health and environmental health sectors. As such, One Health approaches are called out as a required strategy for managing and reducing the effects of AMR in Australia and abroad (Australian Government, 2019; WHO, 2019).

Figure 1: An overview of a One Health approach

Bacteria, viruses, fungi, and parasites are ubiquitous in the environment and can be beneficial or destructive to the health of humans, plants, and animals. As a result, finding treatments to infections and diseases caused by harmful microbes has been a focus of traditional and modern medicine alike (Figure 2). Since the mass production of penicillin in the mid-20th century, antibiotics have saved countless lives by treating illnesses like pneumonia, tuberculosis, and *staphylococcus* infections that may otherwise be fatal.

Microbes can develop resistance to antimicrobial agents, which means that they are no longer effective in eliminating harmful microorganisms. Resulting infections caused by these resistant microbes are hard – or impossible – to treat with available therapies. As soon as the first family of antibiotics was developed its effectiveness began to decline. Within six years of its widespread use, penicillin was no longer effective against roughly a quarter of staphylococcal infections in hospitals where it was routinely used (Kirby, 1944) (Chambers, 2001). This is catastrophic for human health outcomes, which can rapidly and severely decline without availability of effective treatments for infections. Without action to stop the prevalence of antimicrobial resistance (AMR), there is a risk losing these life-saving interventions and returning to a pre-antimicrobial era.

Resistance to antimicrobial agents, which is carried on specific genes, can spread between microorganisms. A key contributor to the emergence of antimicrobial resistance in the broader community and environment is antibiotic-resistant bacteria in healthcare settings.

This leads to impacts beyond the healthcare sector with resistance genes weaving their way through the environment, as well as human and animal hosts. For example, antibiotics used in a hospital or healthcare setting can end up in the wastewater system and induce resistance in microbes in the broader environment. Water containing pathogenic microbes can also infiltrate into soils and be passed along to livestock and crops, extending the problem to the veterinary and agriculture sectors.

AMR is undoubtedly one of the world's most pressing global public health issues and was recently declared as one of the top 10 public health threats facing humanity by the World Health Organisation (WHO, 2019). At a global level, it was estimated that 4.95 million deaths were associated with AMR in 2019, which is expected to continue rising (Murray et al., 2022a). One review estimated that by 2050, AMR will kill 10 million people each year costing the world economy US$100 trillion (O'Neill, 2016).

As well as a looming health crisis, AMR threatens to disrupt global progress made on the United Nations' seventeen sustainable development goals (SDGs; (UN, 2022), exacerbating poverty, hunger, inequality, and jeopardising health and wellbeing (Figure 3).

While Australia has been taking decisive action to reduce its use of antibiotics in recent years, and implementing national strategies such as 'Australia's National Antimicrobial Resistance Strategy – 2020 and Beyond', it still has a high prescription rate relative to other equivalently developed countries (ACSQHC, 2020;

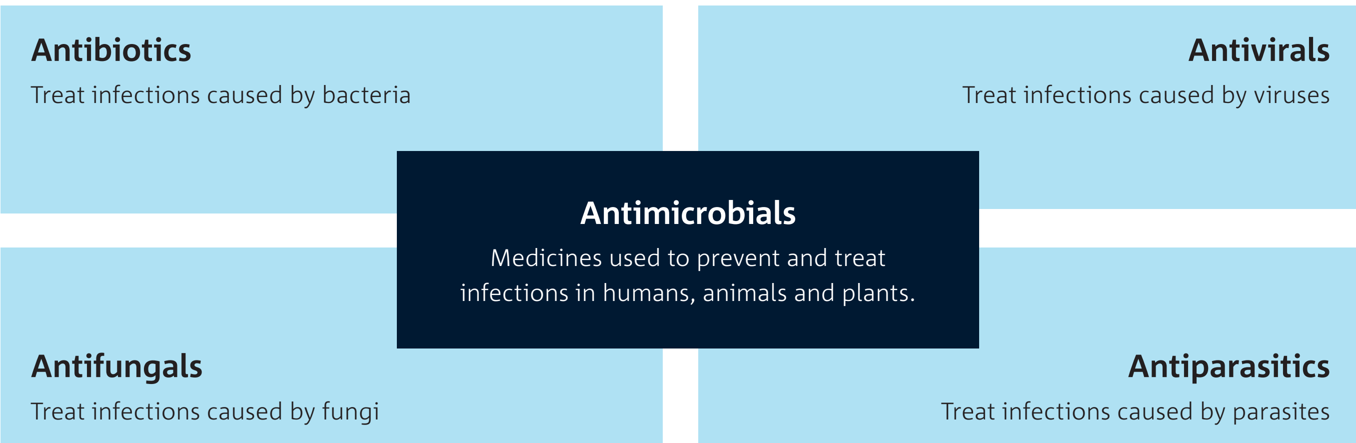


Figure 2: A simple overview of antimicrobials

Australian Government, 2019). Actions such as restricting the use of certain antibiotics in primary production animal settings to maintain their use for human health, benchmarking practitioners antimicrobial practices, and the introduction of antimicrobial stewardship (AMS) programs in human health settings have all led to a marked reduction in rates of prescription (Langham & Cheng, 2019). Yet there is a long way to go on the journey to combat the rise of AMR. As action is taken to manage AMR, there is a need to acknowledge the network of interconnected issues that span human, animal, and environmental domains. The relationship between these domains is dynamic, with activities in one area often impacting another. Efforts by a single sector cannot prevent or eliminate the problem.

Effective and long-lasting solutions for AMR will require a holistic One Health approach, with coordinated action across all impacted sectors, both in Australia, and abroad.

SDG 1: No poverty

Increases in AMR could push an additional 24 million people into poverty by 2030

SDG 2: Zero hunger

In a high AMR-impact scenario, there is possible 7% loss in livestock production by 2030, reducing the availability of animal protein

SDG 3: Good health and well-being

As the efficacy of antibiotics wanes, it becomes harder to treat infections and common surgeries become risky

SDG 6: Clean water and sanitation

Pharmaceutical and microbial waste can reach and contaminate water sources, soils and crops

SDG 8: Decent work and economic growth

The impact of AMR on global GDP could amount to losses of US$3.4 trillion by 2030

SDG 9: Industry, innovation and infrastructure

Investment in R&D is vital for the development of AMR solutions

SDG 10: Reduced inequality

Global economic growth would slow, widening economic inequality between countries

SDG 13: Climate action

Climate change is resulting in changing patterns of disease and increased reliance on antimicrobials

SDG14: Life below water

It is vital that worldwide aquaculture has appropriate regulation to ensure the appropriate use of antimicrobials

SDG15: Life on land

Antimicrobial contamination in the environment can disrupt biodiversity and ecosystems

Figure 3: AMR threatens to disrupt past and future SDG progress

1.1 Objectives

The purpose of this report is to highlight the critical issues that AMR poses to Australia, and steps the nation needs to take to solve it collaboratively and creatively. This report is focused on identifying key technologies and their enablers to solve some of Australia's key challenges relating to AMR, looking beyond research into new antimicrobials. It explores new and emerging technologies such as environmental sensors, rapid tests, biomimicry-inspired antimicrobial surfaces and emerging vaccination techniques that can be used to prevent, detect, diagnose, and respond to drug-resistant infections. These will be critical to ensure that Australia can mitigate and manage the impacts of AMR. As there are extensive global efforts into developing new antimicrobial agents, this report has instead specifically focused on the contributions that technology-based interventions can make towards fighting AMR prevalence.

The analysis presented in this report takes a One Health approach bringing together perspectives from a range of sectors and disciplines to provide solutions, advice, and recommendations to combat the increasing prevalence of AMR (Figure 4). This involves acknowledging the undeniable interplay between humans, animals, and the environment when considering solution development and implementation.

1.2 Methodology

This report was informed by research and consultations with multisectoral stakeholders from across Australia, overseen by a steering committee and an expert review group of Fellows from the Australian Academy of Technological Sciences and Engineering (ATSE) and the Australian Academy of Health and Medical Sciences (AAHMS). Stakeholders consulted included representatives from the primary production sector, healthcare industry, policymakers, regulators, research, and industry organisations and associations.

In total, ATSE engaged 100 stakeholders through surveys, roundtable discussions, and expert interviews. Evidence was gathered through an initial exploratory survey in March 2022 and supplemented with roundtable conversations, expert interviews, and desktop research. The data collection concluded with a technology readiness assessment survey (May 2022) completed by multi-sectoral experts who were directly or indirectly involved with AMR. An overview of the project methodology can be seen in Figure 5.

Objective 1

Identify existing and emerging technologies that can reduce the prevalence and spread of AMR, particularly technologies with a prevention focus.

Objective 2

Examine Australia's ability to implement new technologies and highlight opportunities to support market entry of new products.

Objective 3

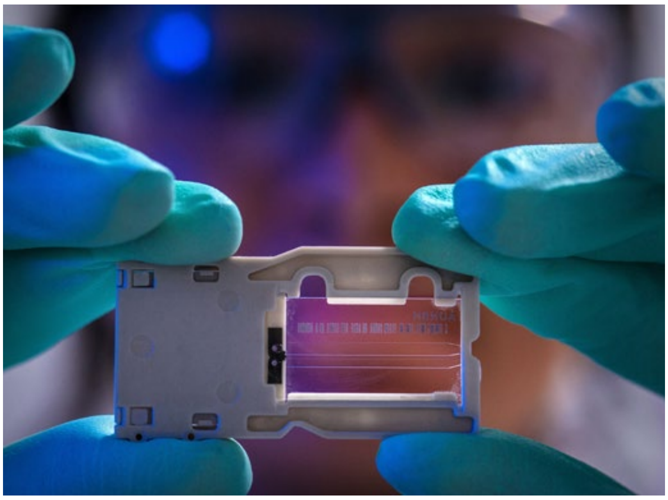
Bring together sectors and disciplines to generate new, transdisciplinary solutions and provide glimpses into Australia's potential futures based on chosen solution pathways.

Objective 4

Provide advice and recommendations to policy-makers, sectors that comprise a One health approach and developers of new technologies.

Figure 4: Key report objectives

Research, analysis, and consultation identified four key challenges that Australia needs to tackle if the nation is to make substantial gains against AMR across the next decade. Within the framework of these challenges, the project identified technologies and enablers that will help prevent and manage the impacts of AMR, leading Australia towards a more positive future. The contents of this framework were identified and validated through expert stakeholder consultation. A representation of the complete analytical framework is shown in Figure 6.



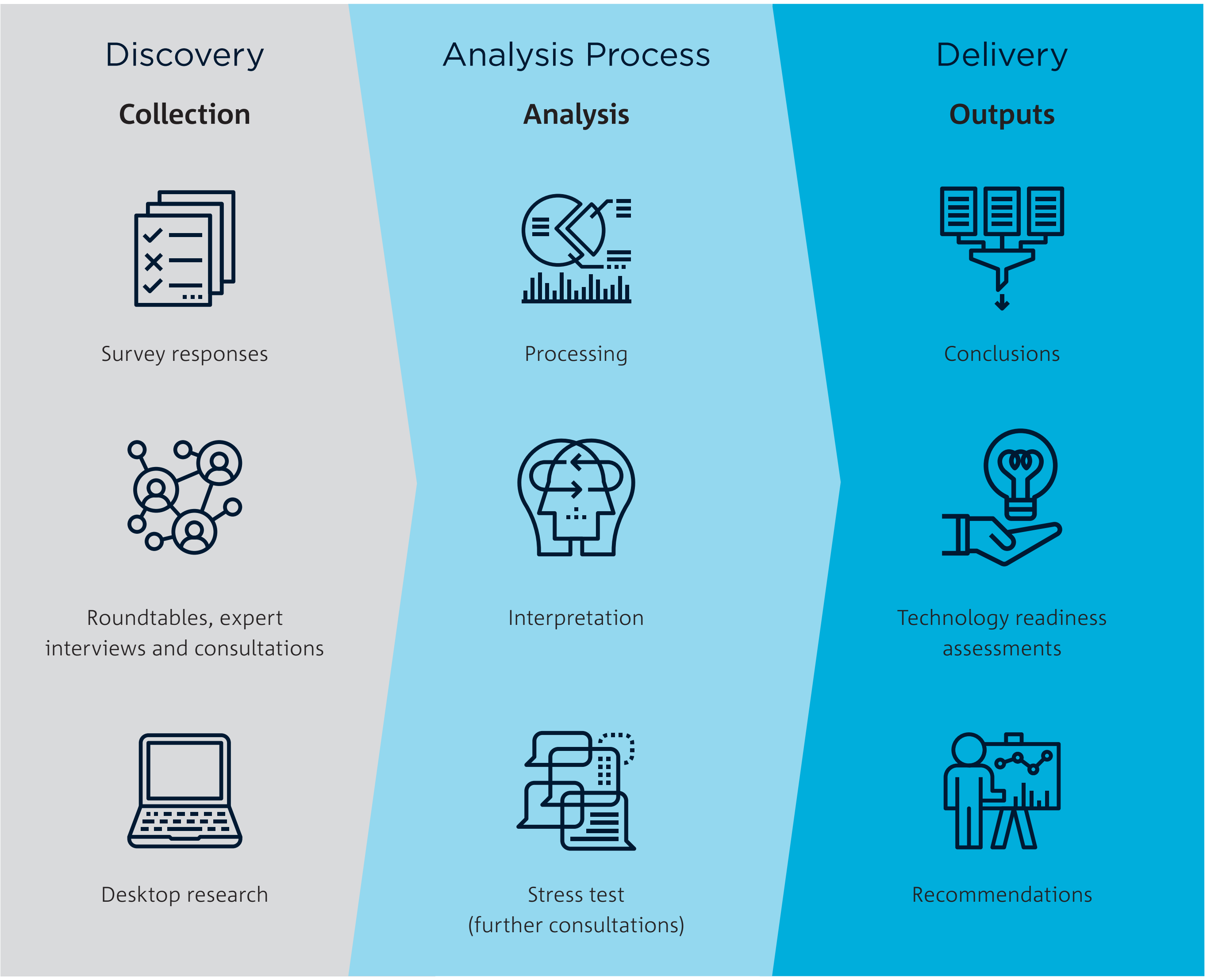


Figure 5: Project methodology used to generate ATSE's readiness indicators and recommendations

Challenges

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Climate change accelerating the emergence and spread of AMR across sectors

Lack of new technologies and treatments for prevention, detection, diagnosis, and treatment of AMR coming to market

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Educated, empowered, enabled and aligned citizens and sectors

Figure 6: Project framework highlighting potential solutions and enabling technologies to mitigate and manage AMR

Stakeholders were asked to consider Australia's readiness to develop, adopt and adapt the potential technology solutions over the next decade across five readiness parameters in Figure 7 from a range of 0 (not ready) to 4 (ready).

Quantitative and qualitative analysis was performed to generate the final readiness assessment ratings, policy and research priorities, and key report recommendations. Several themes also emerged throughout our research and consultation which have been summarised in Figure 8. These have been highlighted throughout the report and have been front-of-mind in forming the overall recommendations.

Figure 7: Readiness parameters

Build on what is working

There is a range of solutions that are working in certain sectors domestically and abroad that can be expanded to enable better AMR management, or that can act as launch pads for solutions. We should seek to celebrate our successes to date, and to focus on progress over perfection as we continue to take prioritised and sustainable steps towards our ideal future state.

Embrace collaborative, transdisciplinary problem solving

Large, interconnected problems can necessitate different ways of thinking and problem solving. Collaborative, transdisciplinary approaches to problem solving such as One Health are essential. Convergence science and systems-thinking methodologies will be key to fast-tracking innovation by sharing solutions across sectors, sparking ideas across groups, and understanding the impacts our interventions will have on the broader system.

Place equity at the heart of our strategies

AMR is a global issue, and does not respect geographic, sector, or industry boundaries. It is critical that we take a holistic approach to mitigating and managing AMR, ensuring solutions are developed and delivered equitably across sectors, citizens, and with a view to international coordination and alignment.

Remember the human element

Bringing together multiple stakeholder groups with competing priorities, drivers and needs is a big task. Activities such as education, awareness raising, and shifting the emphasis from a treatment focus to a prevention focus can require a large degree of trust, change management and time. The sociotechnical elements of solution deployment can't be overlooked and must be factored into planning and implementation of solutions.

Figure 8: Key themes that emerged through the consultation process

1.3 Structure of the report

This report provides an overview of the challenges facing the sectors that comprise a One Health approach, explores key AMR-related technologies and their application. It concludes with recommendations to support Australia to become a leader in mitigating and managing challenges presented by AMR and examine what scenarios could develop based on actions Australia does – or does not – take.

Part 2: Provides an outline of key challenges Australia will need to overcome to reduce the incidence of AMR by taking a prevention-first approach.

Part 3: Reviews key enabling technologies to drive change: data, standards, commercialisation, implementation, and education.

Part 4: Discusses Australia's readiness to implement four potential technology solutions, analysing each of them against the five readiness parameters.

Part 5: Explores future scenarios based on various measures or actions.

Part 6: Provides ATSE's conclusions, recommendations, research priorities, and policy priorities to prevent the rise and spread of AMR.

Part II

Challenges

Research and consultation identified four key challenges that Australia will need to address across the next decade to better mitigate and manage AMR and the loss of effective microbial treatments.

Challenge 1: Lack of trusted and complete multi-sectoral data to inform decision-making and drive behavioural change to mitigate the impact of AMR

Challenge 2: Climate change accelerating the emergence and spread of AMR across sectors

Challenge 3: Lack of new technologies and treatments for prevention, detection, diagnosis, and response

Challenge 4: Lack of awareness, understanding, accountability, and responsibility to improve AMR

> "AMR might need to get worse before it can get better. People don't care yet."
> – Interview respondent

2.1 Lack of trusted and complete multi-sectoral data to inform decision-making and drive behavioural change to mitigate the impact of AMR

High quality data that is fit-for-purpose is required to inform decision-making and drive behavioural change. A lack of fit-for-purpose data makes it not only challenging to manage disease spread and resistance emergence, but also to reliably quantify the economic imperative behind AMR management. While AMR is predicted to cost the global economy US$100 trillion, the ability to perform predictions with a high level of confidence and trust requires a high level of data quality (O'Neill, 2016). This confidence is essential in ensuring evidence and insights provided to decision-makers and funding bodies are meaningful and actionable. Currently, available data sets on the prevalence of resistance in environmental surroundings are lacking, incomplete or disconnected. Without a clear understanding of where the biggest risks lie, fit-for-purpose management strategies cannot be developed and implemented.

Part of the challenge is establishing integrated surveillance of antimicrobial usage and AMR prevalence to get the reliable and connected data to take the next steps. This was a prominent theme that emerged from consultations and is one of the key objectives outlined in the Australian Government's 'National Antimicrobial Resistance Strategy – 2020 and Beyond' (Australian Government, 2019). While several initiatives currently exist in Australia to collect information on antimicrobial usage and AMR, they are disconnected from each other. In human health, the Antimicrobial Use and Resistance in Australia (AURA) surveillance system collects and reports on antimicrobial resistance and antibiotic use data from hospitals, aged care facilities, and the community (ACSQHC, 2021). Several health surveillance programs and state-based systems feed into the AURA system, but animal health surveillance is more disparate, comprising point-in-time surveys and pilot surveillance programs. There is limited consistent, comprehensive data available on plants and the environment, and there is no coordinated and ongoing surveillance across sectors in Australia.

Data collected through a One Health surveillance system should be interoperable between sectors – across health, agriculture, veterinary and the broader environment – to ensure 'apples are being compared with apples' and sensible insights are being drawn. To achieve this, standards will need to be established for sampling, laboratory testing and analysis, sensing technology system requirements, and the data they generate. Implementation of such a system will require agreement between sectors, sustainable funding models, and robust system governance.

2.2 Climate change accelerating the emergence and spread of AMR across sectors

The implications of climate change on human and animal health are numerous and becoming increasingly severe as the climate events and their impacts continue to escalate. Changes in environmental temperature are closely linked with changes in bacterial physiology, including rates of growth and infection, and the spread of antibiotic resistance genes (ARGs) (Philipsborn et al., 2016), (Sun et al., 2019). Higher temperatures are a crucial predictor of pathogenic bacterial growth rates and contribute to their increased carriage in people and animals (Burnham, 2021). Alarmingly, rising ambient temperatures have been identified as a leading contributor to the establishment of resistance (McGough et al., 2020).

A 2°C increase in global temperature is expected to lead to an increased frequency of droughts and flooding, generating a range of environmental effects that could encourage increased ARG transfer and mutations (IPCC, 2018). As the temperature warms, the atmosphere will retain more water, resulting in more severe storms and flooding. Flooding from extreme weather events negatively impacts sanitation infrastructure, increases congestion in already-crowded regions, and propagates antibiotic resistance through the flow and overflow of sewage – a proven reservoir for ARGs (Burnham, 2021). An increase in rainfall will also result in increased runoff from farms and industry and, consequently, result in higher levels of pollutants in the water. Pollutants have been shown to promote the production of ARGs and bacterial mutations that can exacerbate resistance (J. Chen et al., 2019). Increased nutrient-rich agricultural runoff will enhance the likelihood of algal blooms in water systems, and high bacterial concentrations will boost opportunities for the transfer of ARGs.

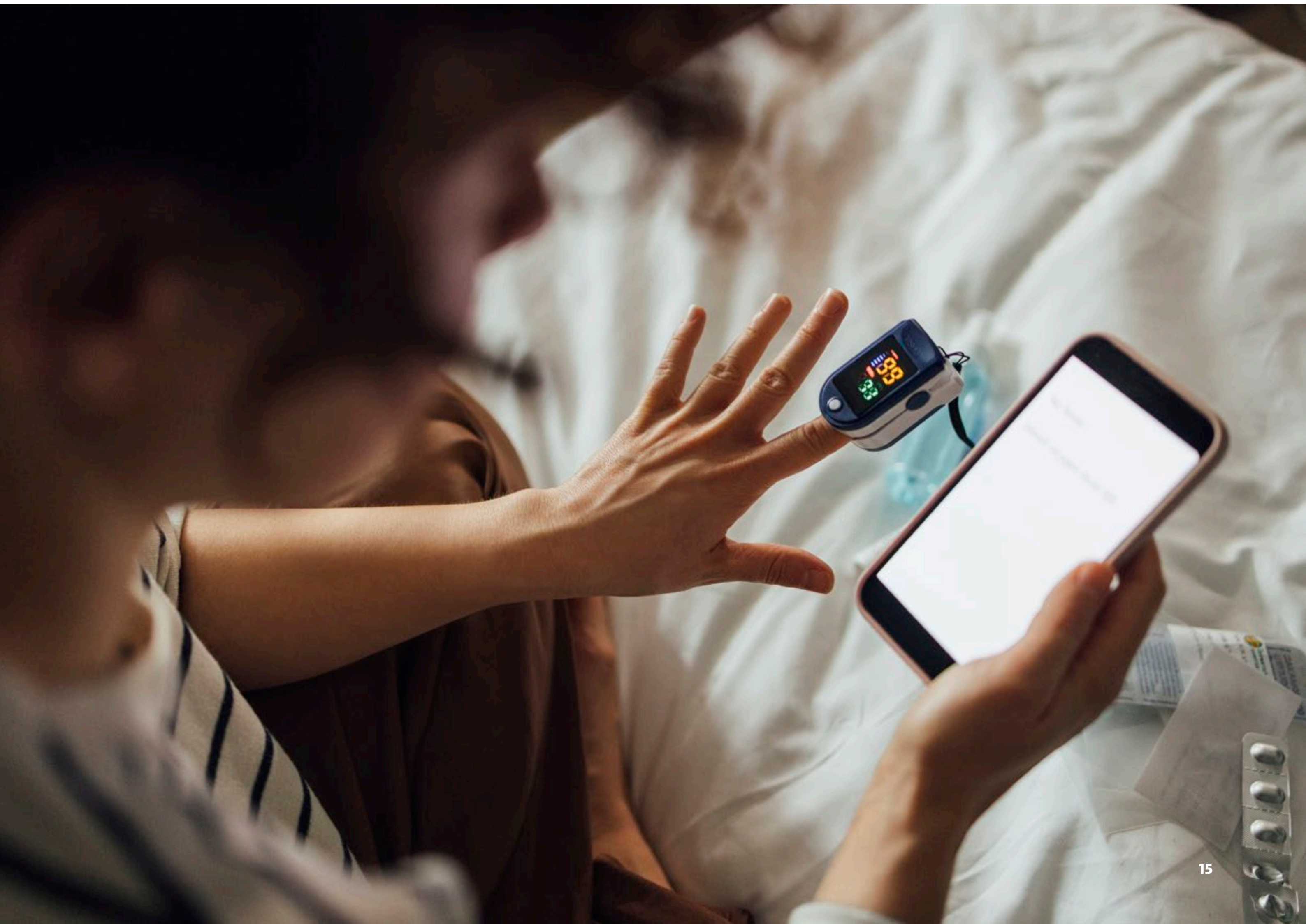
Aside from flooding, extreme weather events caused by climate change will also cause droughts in some regions. Droughts and the ensuing water scarcity lead to reduced sanitation and result in higher densities of people sharing the same water source or using contaminated water for agricultural purposes (van Huynh et al., 2019). A further concern is that crowding and sharing water can increase the likelihood of waterborne diseases becoming epidemics, as common symptoms like diarrhoea and vomiting cause further reductions in hygiene and increase contamination of water. Water scarcity caused by droughts and food shortages are closely linked and can contribute to poor nutrition along with an increase in diarrhoeal disorders. Malnutrition, overcrowding, and inadequate sanitation all increase the risk of children contracting antibiotic-resistant gut infections (Brander et al., 2017). This will inevitably result in more severe diarrhoea; a point of concern if antibiotic resistance increases as it would prevent current medications from being effective.

The shared environment for humans and animals is increasingly overlapping as the global population grows. This increases the likelihood of pathogen transmission and resistance between the environment, humans, and animals. If climate change is not addressed, it will have a disproportionate impact on the health and well-being of people, especially in low- and middle-income countries around the world.

2.3 Lack of new technologies and treatments for prevention, detection, diagnosis, and response

There is a critical need for new technologies to detect and manage AMR more efficiently in Australia and around the world and there is no shortage of them under development. The most recent report from Global AMR R&D Hub's dynamic dashboard highlights that there are over 12,000 registered AMR projects totalling US$8.91 billion of investment, from the Hub's establishment in 2017 to 2021 (Global AMR R&D Hub, 2021). Australian investment places it as a leader in AMR R&D, featuring in the top 10 countries globally.

The challenge, however, is that there is a lack of established standards for testing methods, testing infrastructure, and a clear pathway to market. Without standards in place, the path of these technologies towards the settings where they are sorely needed is significantly hindered. This takes experts outside of their areas of expertise, and can act as a deterrent to pursuing an otherwise marketable idea.



For a new non-drug treatment technology to be introduced to the market, its safety and efficacy needs to be demonstrated. Evidence is needed to prove that the technology is accurate, is clinically useful, and provides a benefit to the patient (Kennedy, 2022). While some standards and guidelines exist to support the testing and evaluation of AMR technologies, there are gaps in what is available and whether they are fit-for-purpose. In the absence of robust guidance in this space, those involved in the commercialisation of products are often finding themselves without relevant protocols to use, or having to develop them from scratch. Furthermore, resources to perform the necessary clinical trials of new technologies to demonstrate safety and efficacy are poorly developed, and for technologies outside medicines (i.e. medical technologies such as invasive medical devices, surface technologies and air sterilisation technologies), the regulatory framework, approval process and methodological approaches are often less rigorous. This can unfortunately lead to products on the market but without the necessary clinical efficacy data to support its uptake by clinicians and healthcare institutions.

The ability of the policy and regulatory landscapes to align and keep pace with new technologies is also a challenge. Solving the problem of AMR using a One Health approach means a necessary alignment between various regulators. Relevant regulators for AMR technologies span several sectors and include Australian Pesticides and Veterinary Medicine Authority (APVMA), the Therapeutic Goods Administration (TGA), and the Environmental Protection Authorities (EPAs). There is also a need for greater clarity around which regulatory approval process an AMR solution needs to go through if it is to be applied in multiple settings. For example, antimicrobial surface coatings can be used for high-touch, high-contamination surfaces in many locations from hospitals to farm settings. Regulators need to be aligned and more importantly, regulations need to be fit for purpose so that approval processes can keep pace with technological potential. This alignment is required at the national level, but it is also required at the global level so Australian innovations can enter global markets. To do so, reducing barriers to entering this global market is essential.

To help overcome these barriers, there is a need for accredited testing facilities that allow these key tests to be performed. This starts at the laboratory level, where there is a dearth of services available to test new ideas, particularly with live microbes. Without evidence that these technologies work, clinicians are less likely to participate in testing when the goal is to further validate a product's efficacy and there is no guarantee of direct benefit to their patients. New technologies will often also need to navigate the pre-clinical and clinical trials process, which can be slow, complex, and expensive (Figure 9).

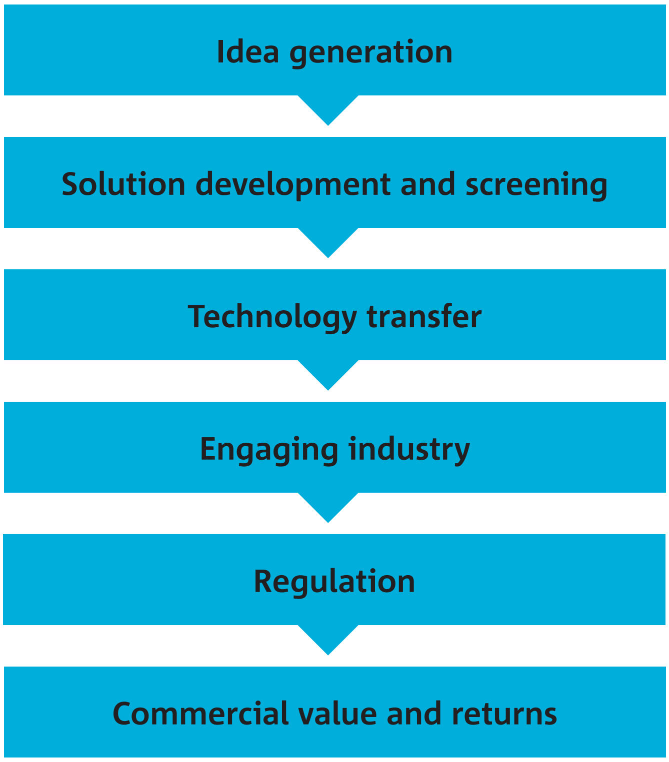


Figure 9: End-to-end pipeline for new AMR technology commercialisation. Framework adapted from (AAMRI, 2020)

2.4 Lack of awareness, understanding, accountability, and responsibility to improve AMR

There is international and multi-sectoral agreement that a One Health approach is required to tackle the rising threat of AMR, but the approach is not without its challenges (Australian Government, 2019; WHO, 2019). To take this approach, shifts to more collaborative models of governance, funding, and information sharing will be required at both national and international levels. This heightened collaboration must balance the tension of working fast enough to implement solutions to both immediate problems, and those that lie ahead. The allocation of finite resources to address the complexities associated with increasing prevalence of AMR needs to achieve a multi-faceted balance between parties and competing drivers. It also needs to establish a consensus on who is responsible and accountable for the financial implications of reversing the current proliferation of AMR in the ecosystem, and actions needed to prevent future spread.

The organisations involved in the AMR response commonly function in silos, and a unified approach is essential within Australia, and to coordinate with other similar international bodies with aligned goals. The leadership and governance structure required to overcome this challenge needs to be complemented with an increase in awareness and understanding among the public, particularly regarding antibiotic misuse and how AMR spreads. This will be key to driving accountability, responsibility, and action. A comprehensive, clear, consistent, and compelling communication strategy which effectively conveys terminology and concepts related to AMR and the actions that can be taken to manage it is needed. Effective communication plays a substantial role in increasing community knowledge of critical healthcare concerns, leading to behavioural change. Raising awareness needs to be done in a manner that makes the issues relevant to the individual.

Despite advances in raising AMR awareness, important gaps that jeopardise multisectoral AMR coordination efforts and the successful execution of AMR national action plans exist. Behaviour modification is a strategic goal of the World Health Organisation's (WHO) global AMR action plan, although many countries lack the resources needed to achieve this and will require assistance in developing skills in this domain (Mathew et al., 2019). Figure 10 highlights the various factors that are required to bring about the desired collective behavioural change.

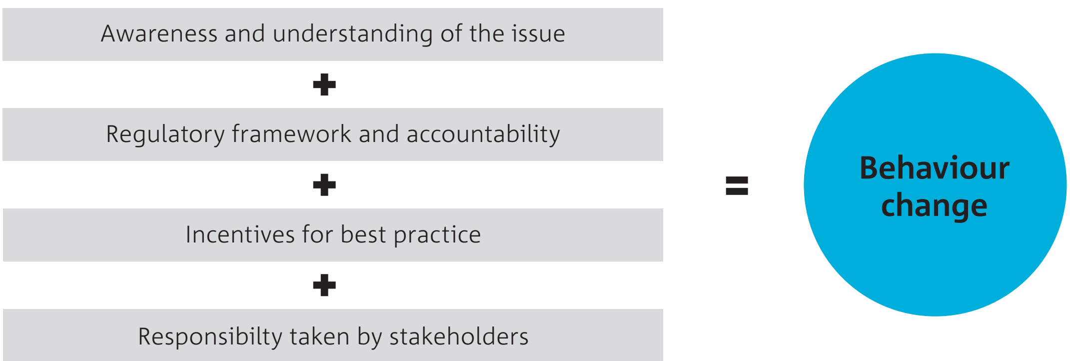


Figure 10: Translating awareness, understanding, accountability, and responsibility into behaviour change (Mathew et al., 2019; Pokhrel et al., 2015)

The complexity of AMR necessitates a coordinated multisectoral approach. Because of the high degree of political interest recently, the number of international coordinating initiatives focusing on AMR has grown. This includes the Transatlantic Taskforce on Antimicrobial Resistance (TATFAR) and the Joint Programming Initiative on AMR (JPIAMR). The United Nations (UN) has also recently expanded its strategic work on AMR with the formation of the ad hoc UN Interagency Coordination Group (IACG), which is tasked with providing practical guidance for approaches needed to address AMR and sustain global action in collaboration with the WHO, FAO (Food and Agriculture Organization), and OIE (Office International des Epizooties; (Hood et al., 2018).

However, the path to embedding a country's multisectoral cooperation into organisational processes and culture across sectors and departments is a complex one. At the operational level, it is critical to identify best practices, including how to effectively balance the priorities of specific ministries with cross-cutting challenges (Joshi et al., 2021). Using existing One Health platforms, supporting the incorporation or mainstreaming of AMR into existing programs and activities such as those addressing HIV/AIDS (Human Immunodeficiency Virus/Acquired Immunodeficiency Syndrome), tuberculosis and malaria, neonatal care, and food safety and quality should be prioritised. This will also help boost AMR awareness and contribute to the enabling environment required to implement AMR management and action plans more effectively.

Designing an effective and comprehensive communications plan also needs to be undertaken in an inclusive way that acknowledges Australia's cultural and linguistic diversity. For certain drug-resistant infections such as methicillin-resistant *S. aureus* (MRSA), Australia has some of the highest rates of AMR prevalence in the world. One study, from a predominantly Indigenous population in a remote region in Northern Australia, has highlighted that at least 40% of community-associated isolates of *S. aureus* were methicillin-resistant, whereas rates across the rest of the country are around 15–20% (Cuningham et al., 2020). Education and awareness strategies need appropriate tailoring to different community and cultural groups across Australia, as well as an understanding of key barriers to change. The messenger is also an incredibly important element of awareness raising. Community leaders – whether they be of scientific, sectoral, or cultural groups – will be key in establishing legitimacy, efficacy of key messaging, and driving change.

Australian Collaboration in Action: AAMRNet

A key recommendation from MTPConnect and Biointelect's 2020 'Fighting Superbugs' report was a call for expanded collaboration across the sector through the formation of an Australian AMR Network. The Australian Antimicrobial Resistance Network (AAMRNet) was formed in response. AAMRNet is a multi-stakeholder expert group in the human health space that collaborates to share knowledge and resources, to create domestic and international alliances, and to educate and advocate for AMR.

The AAMRNet now has 15 consortium members and has made several submissions to Australian parliamentary enquiries such as approval processes for novel pharmaceuticals and medical technology. Initiatives like AAMRNet are key to build on and expand across sectors to drive further collaboration and action in the fight against AMR.

Part III

Enabling technologies

Five key enablers were identified to overcome the major barriers to mitigating and managing AMR, particularly using One Health approaches. These are in the domains of:

- data
- standards
- commercialisation
- implementation
- education.

This chapter will explore each of these enablers in more detail and present a pathway to unlocking the potential of the technology-based solutions presented in this report.

3.1 Data

One of the four major challenges to tackling AMR identified in this study is the absence of high quality, joined up data to inform the design of appropriate solutions. As well as data, addressing AMR requires health informatics – how health information is captured, transmitted, and used in healthcare delivery – to inform the development or use of targeted interventions. However, Australia's healthcare system has been described as 'data-rich, but information-poor' (Health Informatics Society of Australia, 2018). This means that while a variety of data is gathered, it is not necessarily being translated into useful insights. For the data collected to be useful in addressing AMR, consistent approaches to data collection, data curation, data quality, and interoperability are needed.

> "We only use a small proportion of all data we collect. We're sitting on an iceberg of 'dark data' that's not being utilised."
> – Interview respondent

Achieving the reality of a fit-for-purpose data infrastructure to address AMR requires:

- Coordinated and robust data policies that incorporate best practice principles.
- Interoperability between data sets from different sources and sectors.
- Strategic approach to data collection analysis – setting priority questions and ensuring the data you are collecting can be used to answer them.

Each of these features is discussed in the following sections.

3.1.1 Robust policies and best practice principles

The FAIR (Findable, Accessible, Interoperable and Reusable) principles provide a framework for data but do not sufficiently acknowledge nor address issues with historical contexts and power differentials associated with use and sharing of data for health and medical research. Supplementing the FAIR principles with the CARE (Collective benefit, Authority to control, Responsibility and Ethics) principles which were developed for Indigenous Data Governance ensures a more strategic and holistic approach to addressing data ownership, sovereignty, and governance (Carroll et al., 2021).

Food Agility CRC's Best Practice Data Policy: A potential foundation to build on?

The Australian Food Agility Cooperative Research Centre (CRC) released a ‘Best Practice Data Policy’ in 2020, outlining how it will lead the way in data management for collaborative research in agriculture technology and analytics innovation.

This policy sets out a framework for how data will be handled in the Food Agility CRC, and the projects that Food Agility invests in. Different parties (originator, collector, provider, user, holder, sharer, or third party) establish a contract that clearly sets the data collection and sharing conditions according to the needs of the contracting parties. Details referring to data sharing feature in a dedicated and exclusive section of the contract where possible. The policy also clearly differentiates between three different data types: raw data, transformed data and new data.

Data service providers (the people who store or process the data) in this framework have a responsibility to protect the data and must have data protection protocols that prevent unauthorised access. Third parties sub-contracted as service providers must uphold the same security standards and must be authorised in the contract as approved third parties. Anyone dealing with personal data must be adhering to the Privacy Principles set out under the Australian Privacy Act, 1998 (Cth). Data should be anonymised where possible, and records are required to be kept about permissions for access and breaches. Data policies such as this provide a foundation that can be adapted and built upon by other sectors.

3.1.2 Interoperability of data sets

In the current landscape, AMR data lack interoperability resulting in data silos – data that is held by one group and has limited accessibility for others for research and operational purposes (discussed further in section 2). These silos persist across health services, educational institutions, and sectors that are linked through a One Health approach. If connected and made fit-for-purpose for analysis and use, data can save lives and livelihoods. The evolution of public health responses to the COVID-19 pandemic demonstrated how high quality, interoperable data sets can inform effective action. The early sequencing and sharing of the SARS CoV-2 viral genome, as well as subsequent sharing of the genomes of worrying variants, was a prime example of this. Based on this information, the scale and pace of international COVID-19 vaccine research and distribution were unprecedented.

Establishing standards in data, for AMR testing, and technology is the most effective way to create a comprehensive picture of AMR as it prevents data silos from forming. Common data models – creating a standardised and modular way of collecting data – support data interoperability, such as the Systematised Nomenclature of Medicine (SNOMED). This set of global standards for healthcare terms is a positive step in this direction and is an example of an initiative that could be expanded beyond healthcare and into other sectors (SNOMED, 2022)

Traditionally, data linkage, the process of connecting and merging disparate data sets has been used to connect data silos. Data linkage is a powerful tool yet doesn’t always result in a perfect or complete match, particularly if health data is not collected in a standardised way. Artificial intelligence (AI) and machine learning (ML) will be critical technologies as they can overcome this issue to bridge data sets, especially for formats that are difficult to manage such as unstructured texts and textual data. For example, multinational producers of medical equipment have been incorporating AI- and ML-powered solutions into their workflows for some time. These technologies assist in drug management by monitoring prescribing behaviour, dispensing operations, and staff behaviour to identify and manage risky practices (Latinovic & Chatterjee, 2019). The ability of AI and ML to take unstructured or semi-structured data and provide actionable insights will be a key technology to capitalise on the wealth of data collected across time. These technologies have to be closely managed so they are applied in an ethical fashion, avoiding biases encoded in algorithms, risks to patient safety, and weaknesses in cybersecurity.

3.1.3 Strategic approach to data collection and analysis

Setting priority questions to guide usage of high-quality data is the logical next step in a One Health approach to addressing AMR. One such priority question that integrated One Health sensing and surveillance systems can help address is tracking AMR bacteria in animals and humans, and how they move through the environment. This will support the development of holistic mitigation and management strategies that allow interventions to be applied in a way that eliminates issues at the source. Such data can also improve the understanding of zoonoses – diseases that can be transferred between humans and animals – and the pathways by which resistance spreads. Zoonotic diseases represent critical threats to global health security if left unaddressed by contributing to increased rates of infection, antibiotic use and resistance emergence. A major obstacle to understanding, predicting, and controlling zoonoses is that data describing transmission between humans and animals is often incomplete or not available (Asokan & Asokan, 2015). Prioritising the collection and analysis of reliable, timely, and complete data is needed to understand and manage zoonotic episodes and to convince policy-makers to invest in sustainable solutions to AMR.

3.2 Standards

Technology-based solutions provide clear pathways to better prevention, detection, diagnosis, and treatment of AMR. Yet there is a dire need to establish appropriate One Health standards for data collection and sharing if these technologies are going to be able to be leveraged across all One Health domains. A set of agreed standards to guide data collection and technology used to store and share it helps to ensure consistency, quality, and build trust across organisations and the general public. A set of standards can define technical requirements for designing and manufacturing equipment, safety and efficacy criteria for a new healthcare consumable or details for the collection and management of data.

> "We need both data and technology standards. And we need to make a concerted effort to internationally harmonise them. The current pace is glacial."
> – Interview respondent

A standardised approach to data collection and management within – and across – sectors is key to enabling a collaborative approach to problem solving and value creation. Investing in the establishment of common, agreed standards, and harmonising between currently existing standard-sets, will be essential to unlocking domestic and international collaboration across sectors. Each of these features is discussed in the following sections. The development of standards should be undertaken in such a way that they are fit-for-purpose and achievable (Figure 11). Standards should also be easy to access and interpret to maximise their utility.

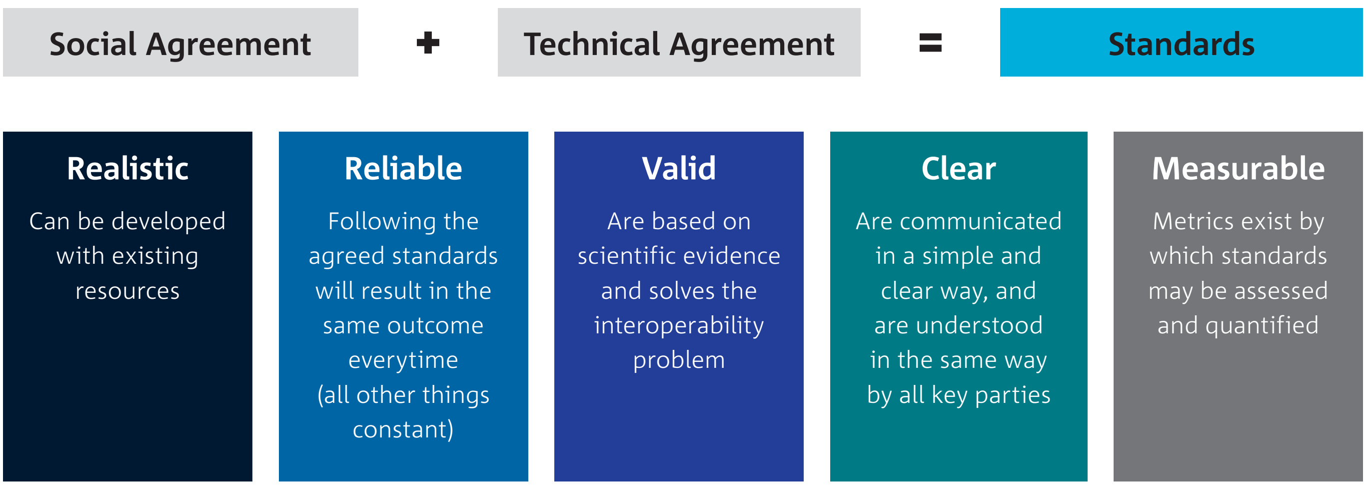
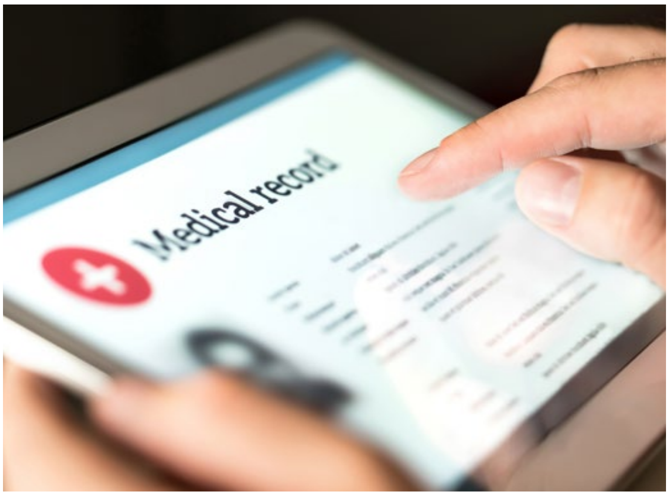


Figure 11: Framework for developing standards (ATSE expert interviews; Wisconsin Hospital Association Quality Centre, 2012)

Standards in data, technology, and product testing are key to driving understanding and innovation in the mitigation and management of AMR. Harmonisation of standards and regulation is also critical, in Australia and beyond, if they are to fulfil their potential as a bridge between sectors that comprise a One Health approach and a catalyst for innovation and bringing new AMR solutions to market.



3.2.1 Enabling One Health collaboration through a common set of standards across sectors

Tackling AMR from a One Health perspective requires a variety of stakeholders who often rely on different processes and information systems to work collaboratively. A harmonised set of rules and definitions, both at the micro and macro level, is needed to make this possible. Consultations and expert interviews highlighted data and technical standards are the most important requirement for enabling collaborative work towards managing AMR. Data standards ensure all parties use the same language and approach to collecting, sharing, storing, and interpreting information. In healthcare, data standards are critical to interoperability which enables health systems to exchange data regardless of domain or software provider. Technology standards set the specifications for the technology that is used to collect data, and to streamline sharing and analysis across different data sets. A leadership structure that recognises the benefits of shared information is also needed, particularly one that incentivises the adoption and implementation of data and technology standards to improve AMR outcomes.

3.2.2 Enabling international collaboration by harmonising standards across countries

"We can't create financially viable products without international regulatory alignment."
– Interview respondent

A common set of standards can also support a streamlined, collaborative and coordinated approach to working with international counterparts towards management of AMR. Without standardisation across countries, time-consuming and expensive evaluation procedures need to be conducted in each target market country to obtain approval in international markets. This increases costs of research, development and ultimately health care. A common set of standards for regulatory approval, and harmonisation between sets of standards, will ensure safe and efficacious products and treatments are available where they are needed as quickly as possible. Developing a framework of global standards would help create products that can be made available to both domestic and international markets.

International Harmonisation in the Veterinary Industry

An example of harmonised technical requirements can be seen in the veterinary industry with the International Cooperation on Harmonisation of Technical Requirements for Registration of Veterinary Medicinal Products (VICH). VICH is a trilateral (EU-Japan-USA) program that sets technical standards for veterinary medicinal products. It provides a basis for wider international harmonisation of registration requirements. The APVMA has adopted VICH guidelines on data requirements for chemistry, human safety, environmental safety, anthelmintics, and good clinical practices and has observer status on VICH. However, to ensure maximum impact a much wider harmonisation is required. Global uptake of something along the lines of the VICH standards in other sectors would go a long way to ensure more effective collaboration, coordination, and integration of solutions.

3.2.3 Building trust and shared understanding

Adopting a set of common standards is key to building trust through consistency, quality, transparency, privacy, and security. Products or services developed according to a set of standards for approval, production and delivery are often more easily trusted for their quality, safety, or compatibility. The rise of electronic medical records in human health is providing a basis to build on, supplemented by fast healthcare interoperability resources (FHIR) standards to support with interoperability between healthcare organisations. Expanding these platforms, systems and standards across sectors, with appropriate standards for sharing and use of these data by industry, researchers, consumers, and policymakers is critical to a collaborative, collective approach to tackling AMR.

3.3 Commercialisation

Commercialisation of research discoveries towards the market is driven by their potential to respond to a current or emerging need. To reach the market, research discoveries need to move through a pipeline that assesses proof-of-concept utility, safety, and efficacy. Data collected during this phase informs the regulation process and funding strategies. Technologies and products that successfully navigate this process are ready for market, but then must deliver commercial value and returns (Figure 12). Each stage of product development carries risks and barriers that must be navigated and overcome. ATSE's research and consultations have revealed that many Australian AMR technologies encounter blockages at almost every stage of the pipeline, preventing or delaying their entry to the market (Figure 12).

Standards for antibiotic susceptibility testing: Highlighting differences in testing between CLSI and EUCAST

Antibiotic susceptibility testing (AST) of clinical isolates is critical for guiding treatment and monitoring antimicrobial resistance (AMR). Despite the importance of AST for clinical infection management and AMR surveillance, the methodologies and benchmarks of the two most widely used systems in the world, the Clinical and Laboratory Standards Institute (CLSI) and the European Committee for Antimicrobial Susceptibility Testing (EUCAST), are far from consistent. The CLSI is more common in the USA and many other regions of the world outside of Europe. While EUCAST is the favoured standard in the European continent. The WHO's Global Antimicrobial Resistance Surveillance System (GLASS) recommends both systems (Cusack, Ashley, Ling, Roberts, et al., 2019).

The differences that occur between these systems are far from trivial. The concentration of antibiotic used to define whether an infection by a particular isolate is likely to be treatable in a patient – known as the clinical breakpoint – deviates substantially between CLSI and EUCAST. This results in a substantial impact on susceptibility interpretation of clinical isolates, with EUCAST recommendations often yielding lower susceptibility rates. As well as having impact on clinical interpretation of results, these differences also have material consequences when comparing data from larger AMR surveillance projects (within and between nations utilising various methods) or over the time period in which a change in methodology is implemented (Cusack, Ashley, Ling, Rattanavong, et al., 2019). Clinical breakpoints that are globally standardised would help in better interpretation and more timely action. And for those entering the product development space, it is important to bear discrepancies such as these in mind to ensure products are being prepared for the jurisdictional demands of the proposed market.

Idea generation	• Lack of funding available for fundamental AMR research • Lack of understanding of how to navigate the end-to-end commercialisation process
Solution development and screening	• Lack of fit-for-purpose testing standards and infrastructure • Lack of pre-clinical/clinical facilities to obtain key efficacy data • Challenges in accurately quantifying the cost:benefit ratio of a solution
Technology transfer	• Difficulties translating research and lab findings to real-world settings • Challenges scaling research to a viable, marketable solution • Scaling solutions including pre-clinical to clinical phases
Engaging industry	• Difficulties in demonstrating solution efficacy via pre-clinical and clinical data • Difficulty demonstrating superiority as lack of agreed gold standard comparators • Lack of collaboration between different stakeholders
Regulation	• Complex navigation of multiple regulators, particularly for novel solutions and mechanisms of action • Lack of domestic and international regulatory alignment and harmonisation • Lengthy, complex and expensive regulation pathways
Commercial value and returns	• Lack of international regulatory harmonisiation make it challenging for products to access global markets • Lengthy, expensive processes make it challenging to recoup R&D costs

Figure 12: Challenges faced in commercialisation of solutions. Framework adapted from (AAMRI, 2018)

The key barriers that emerged include:

- Lack of funding and investment across the commercialisation pipeline.
- Lack of infrastructure, support, and access for pre-clinical testing.
- Limited transparency in navigating the R&D pipeline.

Each of these features is discussed in the following sections, along with the importance of keeping equity front-of-mind as the market is influenced.

3.3.1 Investment, funding, and financial incentives

A lack of funding and investment across the commercialisation pipeline was the leading obstacle reported through ATSE's consultation. Most domestic funding for AMR is through the Australian national funding bodies like National Health and Medical Research Council (NHMRC), Australian Research Council (ARC), and Medical Research Future Fund (MRFF). However, these bodies service the research sector better than the start-up sector and most early-stage start-ups must instead rely on private equity investors.

Access to international funding for AMR has also been variable, and opportunities exist to increase engagement, collaboration, and obtaining or pooling funding with international counterparts. The established agreements between the Australian Government and other agencies (e.g., WHO) and countries could be used as a base to build new AMR agreements. Adaptation of international initiatives to test AMR solutions, such as the establishment of a CARB-X accelerator in Australia should also be considered to support commercialisation.

In terms of domestic financial incentives, the key financial incentive noted by respondents is from the R&D tax incentive. Specific 'push' and 'pull' financial incentives should be designed to stimulate AMR R&D in Australia to bridge the gap between idea generation/proof of concept and the latter stages of development (Figure 13).

Coordination of funding was also called out by stakeholders as a key barrier to AMR related R&D, as was the complicated regulatory environment and the lack of dialogue between those that conduct the R&D, the regulators, funding bodies and other financiers. Commercialisation pathways differ depending on the nature and domain of the product.

For example, Australian domestic vaccine development in the primary production sector would require additional support due to market characteristics (e.g., smaller market size) that make it tougher to commercialise outputs. Commercialisation incentives should be curated in a case-specific manner that utilises a balance between push and pull incentives so that both funding inputs, as well as rewarding outputs, are achieved.

3.3.2 Infrastructure support and access

For those outside of academia or industry, there is a prohibitive lack of affordable, accredited laboratory spaces available to test new ideas. This makes gaining agreement for pre-clinical and clinical testing even more challenging, as without indicative evidence a solution works, busy practitioners are less likely to agree to allow product testing in their settings. Investment in, and increased access to, product and clinical testing facilities for early-stage start-ups is a major area that should be developed. Staff at these facilities should be provided with the skills to support start-ups as they navigate the steps required to test and validate new AMR solutions.

Push incentives

Focus on cultivating partnerships between government and companies

Examples include:

- Tax credits and grants (to help address financing constraints)
- Public private partnerships
- Access to intellectual property
- Minimal disincentives
- Regulatory clarity
- Contracting flexibility
- Sufficient and sustained funding
- Market access pathway

Pull incentives

Focus on market sustainability

Examples include:

- Advanced market commitments (i.e., legally enforceable price commitments that are conditional on demand), procurement guarantees
- Patent extensions
- Data protection
- Liability protection

Figure 13: Push incentives vs pull incentives: How they impact the commercial landscape

3.3.3 Pipeline transparency and process navigation

Another critical element of an aligned and collaborative R&D pipeline is process and resource transparency. This can be facilitated by digital platforms that provide stakeholders with visibility of the end-to-end commercialisation process, where bottlenecks emerge, and what is coming to market. This will ensure researchers and financiers avoid duplication of work effort and investment. Information on the availability of funding sources and a centralised location to support awareness of application deadlines would benefit planning and managing resources, particularly for early-stage start-ups. Positive steps towards such systems, such as the Global AMR R&D hub's dynamic dashboard, have been developed and provide opportunities to be built upon. This platform goes part of the way to meeting this need for transparency and visibility by continually collecting and presenting information on AMR R&D investments, products in the pipeline, and financial incentives available. Building on these platforms to meet the needs of the commercial sector will support the sector, funding bodies, and regulators alike to better understand the R&D commercialisation landscape.

3.3.4 Ensuring equity

As solutions are supported through the commercial pipeline and into the market, it's also important to maintain healthcare equity. The incidence and impacts of AMR and communicable diseases can disproportionately impact remote and marginalised communities, where access to quality healthcare and socioeconomic status can act as barriers to accessing these products. Treating priority AMR solutions as a public good is a critical factor in increasing equitable and universal access and achieving better healthcare outcomes.

3.4 Implementation

Across ATSE's consultations, a lack of planning for implementation and change management was noted as a key barrier to AMR solutions achieving optimal impact. It was noted that stakeholders frequently knew 'what' needed to be done to better mitigate and manage the impacts of AMR, but faced challenges in implementing the changes. That is, determining 'how' to make the change to a process, system, or service was identified as vital to ensuring that approaches to addressing AMR move from an idea to an integrated part of a service system.

> "We need to make a business case for change management. Physical systems are tangible. Change management/human systems aren't. But look at the major technology deployments that failed – they usually fell down around change management planning."
> – Interview respondent

Different skill sets are required across the process from developing an idea to implementing it. The development phase may require additional capabilities in technical problem solving related to an area of deep subject matter expertise, whereas helping a solution to be accepted in a new setting or market may require expert capabilities in communication, education, and change management. The following section will explore two key areas needed to get solutions where they are needed: implementation planning and change management.

3.4.1 Implementation planning for impact

There is a need to support individuals and entities through the paradigm shift required to adapt to this new way of operating. Challenges encountered during implementation of One Health solutions include:

- A fragmented and disconnected governance of human health, animal health, and the environmental health.
- A lack of clarity about the definition, concept, and scope of the One Health approach.
- Under-recognition of the solution's economic benefits.
- A lack of agreement among stakeholder groups on the best way forward, and insufficient training activities (Johnson et al., 2018).

Robust implementation planning that clearly articulates the changes, impact, strategy, governance structures and roadmap to reach the desired future state is key to success. The plan needs to consider the technology, process, and 'human' elements of shifting to a different way of doing things and should be accompanied by best-practice change management.

3.4.2 The need for change management

Change management practices can assist the process of incorporating change into existing systems. They provide a framework to support the systematic understanding of barriers to change and provide tools and techniques to maximise the chances of successful implementation (Figure 14).

While change management may not always proceed in a linear, step-by-step way, a guiding framework supported by strong and credible leadership is key to ensuring foundational activities have taken place to support successful, sustainable changes.

3.4.3 Change management in a One Health context

In the context of AMR, implementation and change management will require collaboration and buy-in from numerous stakeholder groups across industries and sectors. This can be difficult as solutions in one sector may be seen as detrimental in other sectors (for example, restricting the use of certain antibiotics to use in human health raises challenges for infection management in animal health). Therefore, it is important to understand the system-wide impacts of making change, and gain agreement on who pays for the costs incurred to have these solutions. Fostering a culture that enables productive and respectful conversation, stewarded by good leadership, will be critical to progressing these collaborative activities.

The framework for implementation of One Health programs should include political commitment, policy formation, sustainable finance, program development, knowledge exchange, institutional collaboration, capacity enhancement, civil society involvement, and active community participation.

> "A key question we need to solve is how we tackle the operationalisation of One Health."
> – Interview respondent

Highlight urgency	Highlight urgency by convincing people of the importance of making change
Form a guiding coalition	Form a multidisciplinary team with a wealth of cognitive diversity to drive change forward
Create a vision	Create vision statement and strategic initiatives to guide the coalition
Form a team, rally and communicate	Share information, encourage strategic risk-taking, and work cross-functionally to help change management
Remove barriers and enable action	Remove inefficient processes and hierarchies providing the freedom necessary to work across silos and generate real impact
Generate short-term wins	Recognise, collect and communicate wins early and often to track progress and energise effort
Sustain acceleration	Be relentless after the first succeses. Leverage credibility from sucesses to improve systems, structures and policies
Further cultural and institutional change	Articulate connections between new behaviours and organisational success, making sure they continue until strong enough to replace old habits

Figure 14: Kotter's eight-step process for leading change (Kotter, 2014)

3.5 Education

Education and raising awareness about AMR issues and management strategies is critical to successfully implement solutions and drive change. This was highlighted as a critical area of need during ATSE's consultations, particularly for the general public. This is consistent with objective 3 of Australian's National AMR strategy which highlights the need for '*greater engagement in the combat against resistance*' (Australian Government, 2019). Strategies that educate and raise awareness are critical enablers to increase levels of engagement around the issues presented by AMR.

This section will explore key elements that should be considered when developing education strategies, including:

- Evidence-based approaches to behaviour change.
- Employing 'citizen science' to educate and empower.
- The importance of tailored and targeted messaging.

3.5.1 Evidence-based approaches to behaviour change

Evidence-based approaches that employ behaviour change theory have been called for to tackle issues with antibiotic prescribing practices, which are known to fuel the proliferation of AMR (McKernan et al., 2021a). A novel and successful approach to support good AMS practices is the application of nudge theory, which focuses on designing the environment around decision points to optimise for preferred outcomes. Nudge theory has been used in the UK and Australia to reduce antibiotic prescriptions by doctors with a track record of high antibiotic prescription rates. Personalised letters were sent from their Chief Medical Officer informing them of their prescribing rate relative to their peers, which then led to a reduction in their antibiotic prescriptions (WHO, 2018). Gamification is another approach to nudge theory, which leverages the principles of game design to engage, motivate and reward individuals. This strategy has been used to help drive standardised decision-making, data input, and in-situ education and training (Table 1).

There is also an opportunity to deploy a similar approach to gamification to raise awareness on the differences between antibacterial, antiviral, antifungal, and antiparasitic agents among the public. These approaches can support a base-level patient understanding of why one would not be prescribed an antibiotic if they had a viral infection, supporting GP recommendations and patient dosing adherence. Fundamental to all behaviour modification strategies is an understanding of the key motivations and drivers of key stakeholder groups, and the incentives that will be effective in achieving the desired change.

> "For clinicians it often comes down to 'how do I put a meal on the table for my family'. If someone wants to be prescribed an antibiotic, and they don't get one, they will go elsewhere."
> – Interview respondent

Table 1: Antimicrobial stewardship strategies employing gamification

GAME	COUNTRY	TARGET	DESCRIPTION
The Chancellor	Saudi Arabia	Dental students	Educational scenario-driven virtual boardgame (Aboalshamat et al., 2020)
GASDA	Nigeria	Surgeons	Gamified decision-support smartphone app (UCL, 2019)
Flu.O	France	Doctors and nurses	Educational scenario-driven smartphone app (Callaghan, 2016)
On Call: Antibiotics	UK	Clinicians	Acute care scenario driven game (Castro-Sánchez et al., 2014)
AntibioGame®	France	Medical students	Educational case-based game (Tsopra et al., 2020)

3.5.2 Employing 'citizen science' to educate and empower

Citizen science offers another effective tool to educate and engage the public as well as contribute to the understanding of and incidence of resistance. Citizen science projects are when the public participates in scientific activities such as data collection, analysis, and dissemination. One such example of a citizen science project is 'Swab and Send'. Launched in 2014 this program engages students and the public in the active collection of samples to be analysed for antimicrobial resistant bacteria in the environment. Such a program not only collects important data sets to be used in antimicrobial research but engages and educates the public about AMR (Redfern et al., 2020; Hubbard et al., 2020). A similar tactic has been used before in Australia, with scientists and citizens in Melbourne and Sydney joining others around the world to take a 'microbial selfie' of public transport systems, taking samples that are analysed to provide a snapshot of the invisible microbes many people interact with every day (Smith, 2016). In addition to these techniques being great methods for hands-on, experiential learning, they can also be used to provide important data that has the capability to be fed in via open-source systems and provide a sense of empowerment and shared responsibility for understanding and managing AMR.

"Let's look to the lessons from COVID-19. If we can target our messages correctly, we can get the public to understand concepts like variants of concern. That only happened because enough journalists communicated in clear, consistent, persistent messaging. We can do this with better science communication [around AMR]."
– Interview respondent

Further education of the public around the challenges associated with AMR can lead to an empowered populous able to engage in civilian-led change. When USA fast food chain Chipotle Mexican Grill transitioned to antibiotic-free meat and accompanied the shift with a marketing and education campaign, they saw a significant increase in sales. This has led to an increase in demand for antibiotic-free products, providing additional financial support and incentive to the agriculture industry to reduce the quantity of antibiotics they use in production and food-producing animals (Aubrey, 2012).

3.5.3 The importance of tailored and targeted messaging

Targeting education and awareness campaigns in an appropriate way across sectors is key to achieving this objective, and there is a wealth of experience to draw upon as a result of the COVID-19 pandemic and from AMS practices. AMS practices guide the appropriate administration and use of antimicrobials, and good stewardship strikes the optimal balance between prescribing effective treatment and avoiding unnecessary risks.

The way people interact with antimicrobials varies greatly depending on their social and cultural backgrounds. Antimicrobial consumers also vary greatly in terms of their health status and age, who they provide care for, and the tactics they may employ to manage and treat infections. These different ways of interaction pose differing risks of exposure to resistance (Schermuly & Davis, 2022). Education and awareness of the issue needs to be done in a way that is relevant for the individual's specific health, socioeconomic, and cultural circumstances. Research also demonstrates that the education strategy for AMR should also incorporate language that is easily understandable, avoiding the use of complex scientific language as not all individuals can comprehend it (M. Davis et al., 2021; M. D. M. Davis et al., 2020).

Lessons from COVID-19 have also highlighted the importance of ensuring messages are not only translated into multiple languages but that this is done in a way that is culturally relevant and via channels that are trusted and appropriate (Karidakis et al., 2022) An integrated preventative education strategy that includes several stakeholders would be most effective. Public education messages to tackle COVID-19 are a good foundation to build on and raise awareness of antibiotic resistance, utilising an educational resource that is easy to understand for people without a scientific background and of different cultural and linguistic backgrounds.

Show me your personality and I'll speak your language

"Would you use the same marketing strategy to sell a Volvo to a nurse as you would to a doctor? Of course not! So why are you surprised that hand hygiene compliance rates are worse among doctors than nurses?"

This was the exasperated cry from an advertising consultant on hand hygiene which spurred an Australian research group to team up with a marketing company to create tailored messages to influence a range of behaviours, including antimicrobial prescribing. In the study, different clinician groups (i.e., specialist doctors, junior doctors and nursing staff) were profiled using an evidence-based personality profiling tool to understand key drivers of behaviour. This information was then used to create custom messaging. A specialist doctor who is driven to make informed decisions based on the best available evidence was provided messaging of "Antimicrobial prescribing should be rational, with a clear indication, duration, and expected outcome". Whereas junior doctors driven by concerns regarding career progression and meeting the expectations of leaders were provided the messaging "Making efforts to prescribe antibiotics appropriately shows your potential". The tailored-messaging approach resulted in an improvement in desired clinician behaviours, demonstrating the value of a segment-driven messaging approach (Grayson et al., 2015).

Part IV

Potential solutions and sector technology readiness

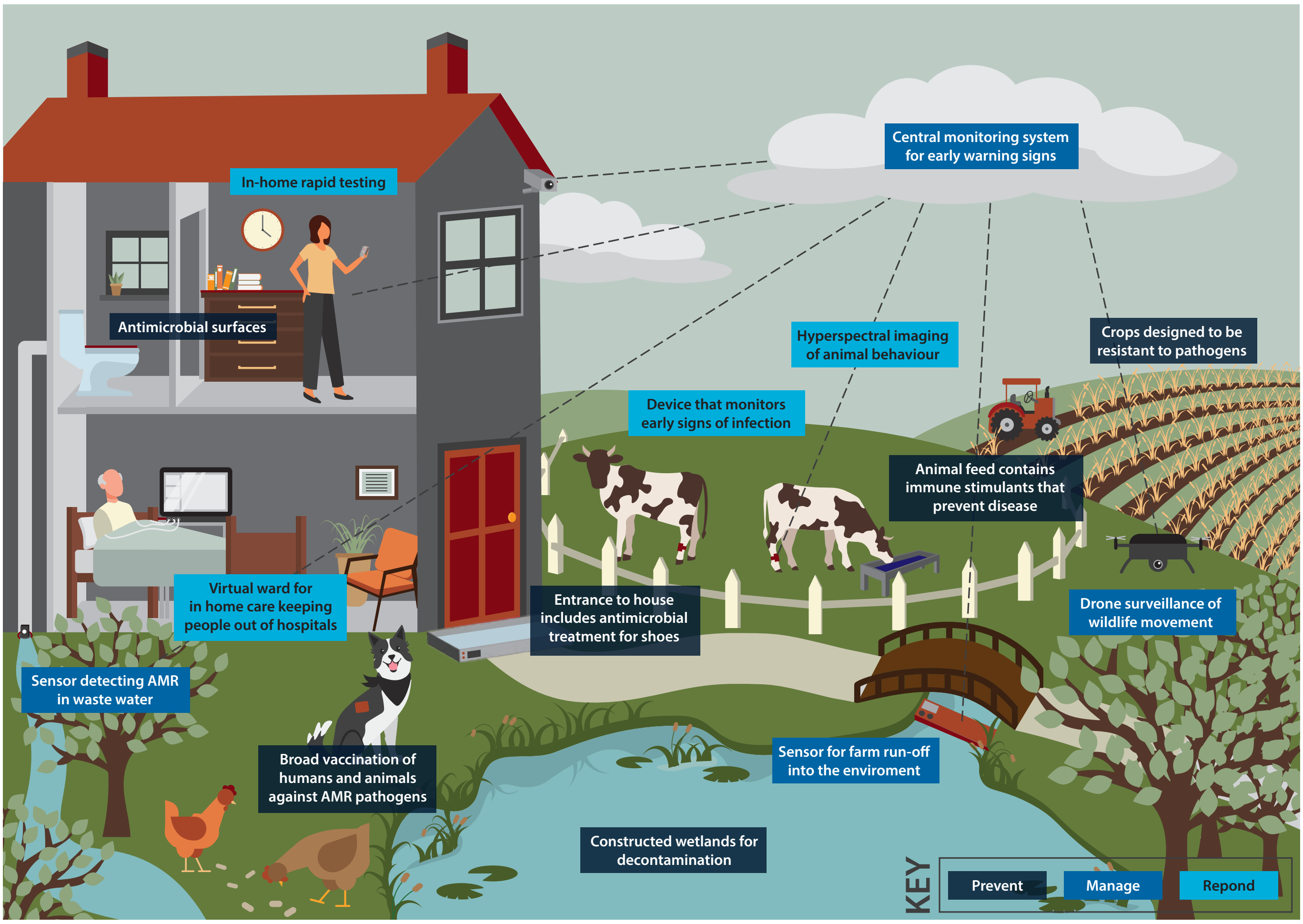


Figure 15: Connected culture: a technology-powered, human-driven future for AMR

Four technology-based solutions have been selected based on stakeholder viewpoints and their ability to help mitigate and manage the spread of AMR over the next decade (Figure 16). Along with the challenges presented by the COVID-19 pandemic has come an awareness of the impact of communicable diseases, increases in vaccination infrastructure and POC diagnostic capability, and an increased understanding of the importance of public health surveillance. These will be key to adopt, adapt or further develop to address the challenges outlined in part II of this report.

This chapter analyses each of the identified technology-based solutions against the five readiness parameters below and provides a score between the range of 0 (not ready) to 4 (ready), along with reasons for the rating:

- Infrastructure readiness
- Skills availability
- Social and ethical readiness
- Economic and commercial feasibility
- Policy and regulatory readiness.

Quantitative and qualitative analysis was performed to generate the final readiness assessment ratings. Industry was strongly represented in the technology readiness survey at 50 per cent (%) of respondents, followed by academia (39%), other (23%), and government (15%; note respondents could represent more than one sector). In Figure 6, Australia's readiness to adopt, adapt, or further develop the potential solutions outlined has been assessed across a range of axes. This provides a snapshot of where Australia is ready to embrace these solutions, and where more work is needed. The following section of the report will explore each solution against the readiness parameters in more detail.

Integrated sensing and surveillance systems

Integrated surveillance and sensing technologies and environmental sensors to monitor AMR across sectors.

Point-of-care diagnostics

Simple, affordable and action-oriented point-of-care diagnostics to enable timely diagnosis and treatment of infections.

Vaccination technologies

A data-driven, risk-based approach to vaccine production, leveraging new and emerging vaccination technologies.

Design for prevention: High risk-settings

Designing our farms, hospitals, and other high-risk settings to prevent the spread and growth of AMR organisms by deployment of antimicrobial surfaces, air sterilisation technologies, and engineering solutions.

Figure 16: Key technology-based solutions to adopt, adapt or further develop to address the key challenges associated with AMR

Table 2: Readiness indicator scale and readiness assessment

	Infrastructure readiness	Skills availability	Social and ethical readiness	Economic and commercial readiness	Policy and regulatory readiness
Integrated sensing and surveillance systems	◔	◑	◑	◔	◔
Point-of-care diagnostics	◑	◕	◕	◑	◑
Vaccination technologies	◑	◑	◕	◑	◕
Preventative design: High-risk settings	◔	◕	◑	◔	◔

KEY

Not ready		More work required		Ready
○	◔	◑	◕	●

4.1 Integrated surveillance and sensing systems

Surveillance systems can be either active or passive. Active surveillance generally involves public health personnel either actively collecting data on a pathogen, or contacting institutions such as animal health laboratories, clinics, or water monitoring programs to obtain that data. This is generally a more targeted approach, where the primary purpose of collecting the data is to examine trends and answer key questions relating to AMR or antibiotic use. A passive system relies on self-reporting from organisations with relevant data collected for purposes other than examining AMR or antimicrobial use which may reveal insights into these areas, even if it wasn't the original intent. Examples of these data being leveraged in Australia for this purpose can be found in Table 3.

Table 3: Examples of active and passive AMR surveillance initiatives in Australia

Active surveillance	• Australian Group on Antimicrobial Resistance (AGAR) • Critical Antimicrobial Resistance Alert (CARAlert) system • National Antibiotic Prescribing Survey (NAPS) • National Notifiable Disease Surveillance System (NNDSS) • National Neisseria Network (NNN).
Passive surveillance	• Australian Passive AMR Surveillance (APAS) • National Antimicrobial Utilisation Surveillance Program (NAUSP) • Pharmaceutical Benefits Scheme (PBS) datasets for antibiotic use • Data feeds from Sullivan and Nicolaides Pathology (SNP) for AMR.

Most surveillance systems around the world do not gather data in the same way which makes it hard for organisations and systems to be able to exchange, compare and use each other's data sets (data interoperability). Data is also often incomplete and inconsistent across regions. This can be caused by a lack of coordination and policy, inadequate or absent data or technology standards, and the continuing development and deployment of new sensing and surveillance technologies. For example, most environmental bacteria cannot be cultured in the lab, which means the detection of resistances and understanding of the underlying mechanisms cannot be easily achieved. Genomic technologies have made it possible to identify bacterial material, rather than rely on lab culture, yet there are still major hurdles in identifying new resistance mechanisms or determining the extent that known resistance mechanisms are active in unculturable microbes (Allen et al., 2010a).

When collecting data, surveillance systems that are automated have several advantages over techniques that rely on individuals self-reporting data. Automation speeds up and simplifies reporting while causing minimal disruption to daily operations. According to a 2018 study of clinical diagnostic laboratories across Europe, the common hurdles to automated reporting into national surveillance systems were technological and financial (Leitmeyer et al., 2020). Other impediments to automated monitoring are data interoperability and the protection of confidential information. Establishing an integrated One Health sensing and surveillance network and an accompanying strategy addresses these key challenges and is significantly cheaper than a non-integrated system (Rostal et al., 2018).

To move towards an integrated One Health surveillance system, the Australian Government Department of Health commissioned a study to explore what this might look like in Australia. The options paper (2021) resulting from this study outlines key requirements for such a system, shown in Figure 17, including governance, surveillance and data management, coverage and capacity, capability, and the authorising environment (Allen + Clarke Consulting, 2021).

From a technology and infrastructure perspective, successful surveillance systems must be accurate with known error rates, integrated and incorporate sensing technology that is cost-effective, reliable, and deployable at scale. Integrated One Health sensing and surveillance systems are estimated to provide a cost saving of approximately 10 – 35% over non-integrated systems (Rostal et al., 2018). With this type of surveillance in place, a robust understanding of the routes pathogens and resistance genes take through the ecosystems can be obtained.

Surveillance and data management	System coverage and capacity	Enabling capabilities	Governance	Authorising environment
Surveillance design Data collection Data storage and access Analysis Dissemination	Priority organisms Geography sector Population and equity Activity and practice Usage and prescription Time and frequency	Data stewardship Surveillance dissemination and communication Coordination and legislation	Strategy and leadership Roles and responsibilities Engagement and coordination Monitoring and evaluation	Funding model Inter-governmental agreements Enabling legislation

Figure 17: Key requirements for a One Health Surveillance system (Allen + Clarke Consulting, 2021)

As discussed in the challenges section of this report, AMR surveillance does take place in Australia, yet is inconsistent in its establishment and maturity across and within human, animal, and environmental domains. At an environmental level, sensing and surveillance are key to developing early warning systems to adapt to, mitigate and manage the impacts of AMR during extreme weather events such as flooding or drought, and during health crises like pandemics and epidemics. Data from integrated sensing and surveillance systems can power data-driven decision support tools to highlight the areas of a hospital that are harbouring harmful pathogens and most need sterilisation, or to monitor levels of antibiotics making their way into the environment. Data can also support the development of 'digital twins' – digital models of physical environments – that enable the prediction of the impacts of AMR to design appropriate interventions. Robust surveillance is key to understanding how AMR moves through the world and to guide data-driven decisions on the best place to focus investment into solutions.

4.1.1 Readiness measures

Survey respondents noted that the technology required to develop integrated sensing and surveillance systems is now available, yet there is a lot of work still required to make these work in practice. Centralised One Health leadership and oversight were called out as key to facilitating coordination, prioritisation, and operationalisation of such a surveillance program. Areas such as awareness and understanding of the criticality of such systems, the need for investment, and the need for robust data policy, standards, and infrastructure were also cited as key to enabling data interoperability, security, and trust. However, the consensus was that it is critically important and worth the effort to overcome these barriers to be able to have data on the size and impact of AMR so early warning systems can be developed to drive targeted interventions and to monitor the impact of AMR mitigation and management programs.

4.1.2 Infrastructure readiness

The theme across consultations is that technology is not the largest challenge to achieving integrated sensing and surveillance systems. It is the ability to overcome the myriad barriers to executing such a large-scale infrastructure project (Figure 18). Australia is a large, geographically, and climatically diverse country. A pragmatic prioritisation of areas to monitor, as well as ongoing funding to establish the technological infrastructure, are key elements in unlocking infrastructure readiness.

From a digital infrastructure and systems perspective, Australia has a strong base to build from as there is already a culture of collecting data across sectors. To capitalise on this starting position the current state of data relating to AMR needs to move towards integrated, One Health sensing and surveillance systems. For example, AGAR – a collaboration between scientists and clinicians from microbiology labs around Australia – collects, analyses, and reports on specific pathogens. This initiative could be strengthened by broadening geospatial coverage, with a wider range of hospitals participating. Surveillance blind spots in critical areas, such as HOTspots featured in AURA reporting, are a great step towards addressing these critical surveillance data gaps. Yet there is much to be done in order to integrate microbiology data with clinical outcomes across Australian states and territories to enable more holistic surveillance.

	Infrastructure readiness	Skills availability	Social and ethical readiness	Economic and commercial readiness	Policy and regulatory readiness
Integrated sensing and surveillance systems	◔	◑	◑	◔	◔

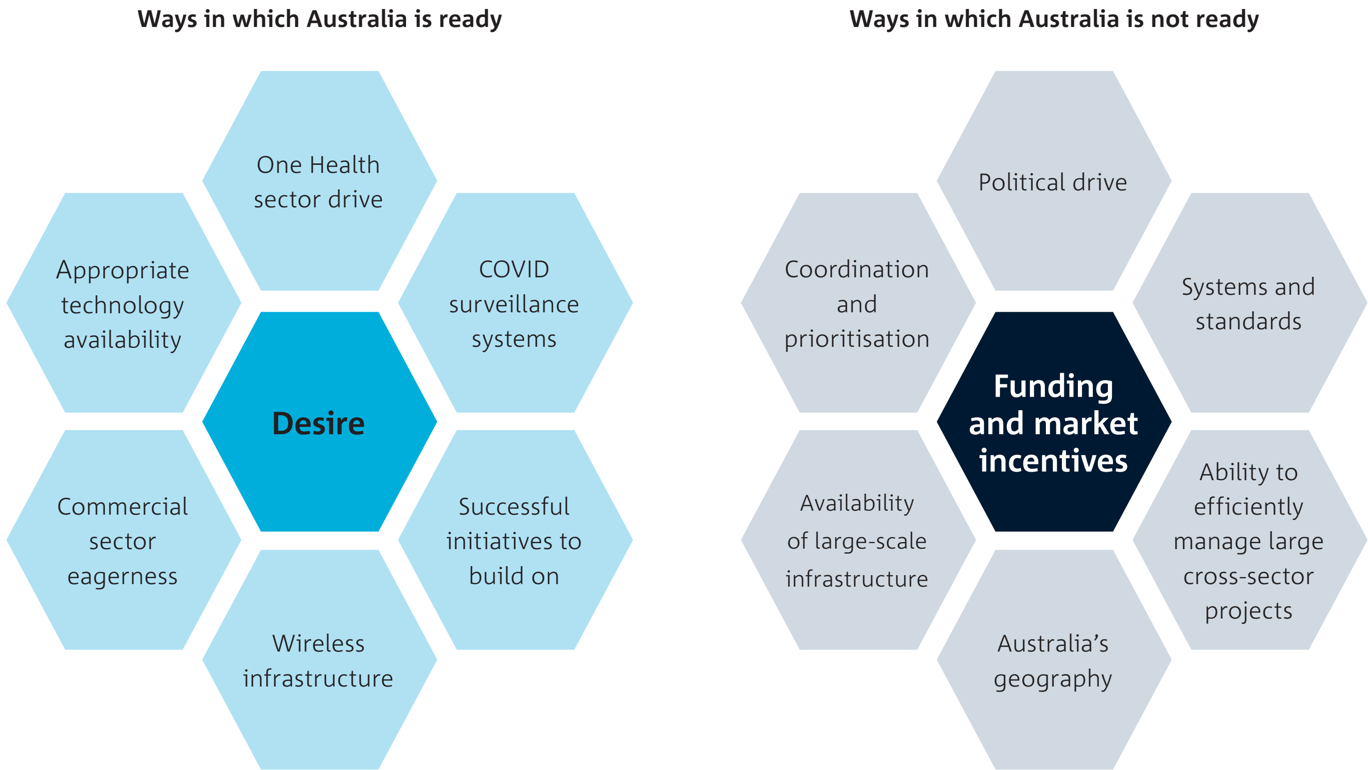


Figure 18: Key consultation themes on the ways Australia is and is not ready from an infrastructure perspective

Data and research are key to understanding the drivers of AMR. Infection ecology, comorbidities, and environmental and socio-economic drivers such as geography, climate, and cultural and structural determinants of health will need to be considered to create a more complete picture of AMR, how it moves through the environment, and its impacts on humans, plants, and animals. A recognition of the gap in knowledge between health, environmental, and agricultural domains has resulted in the funding of a new CRC that is attempting to resolve this disparity (CRC SAAFE, 2022). A key consideration in establishing the AMR monitoring program will be how to enable collaboration across all sectors, and how to support data interoperability.

A continual theme that emerged across consultations is that a lot of the technology required has been developed but is stuck in the commercial pipeline or struggles to access the marketplace (see barriers in Figure 18). Table 4 outlines some current and emerging technology approaches that can be considered for monitoring and surveillance.

4.1.3 Skills availability

Survey respondents highlighted there was a need to uplift the product development and research translation competencies in the workforce, particularly to support ushering myriad technologies into the markets where they are needed. It was acknowledged that Australia has the basic skills available to implement and operate integrated sensing and surveillance systems, however the individuals with these skills are not always included in discussions regarding the establishment of integrated surveillance systems. This omission can lead to difficulties in understanding the challenges and opportunities associated with these technologies to fully and appropriately scope what is possible into an implementable vision.

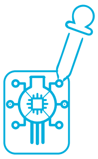
Table 4: Key technology approaches for sensing and surveillance

Drone surveillance

Can be equipped with optical or biochemical sensing and surveillance technologies

Omics technologies

Can provide detailed information on proteins (proteomics), metabolites (metabolomics) or genetic (genomics, transcriptomics) information in a sample.



Microfluidics

Can incorporate entire lab workflows into small, ‘smart’, rapid tools.

Quantum dot sensors

Highly energy efficient semi-conductor nanoparticles which can emit signals used for very sensitive and selective detectors.

Hyperspectral sensors

Uses broad light-based techniques to detect biofilms and other spectrally distinct materials.

Aptamer-based sensing

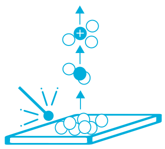
Genetic-based tools used to probe for structure-based features, generally on a surface of a bacterial cell.

Nanophotonic biosensors

Utilises nanoscopic light-based sensors to identify and interrogate bacteria.

Thin film transistor sensors

Can detect DNA amplification via pH change to detect ARGs.



Mass spectrometry

Techniques such as MALDI-TOF separate and analyse molecules to provide a spectral analysis and specific identification.

4.1.4 Societal and ethical readiness

Societal and ethical readiness is underpinned by awareness, and while there are still major hurdles to overcome in terms of societal awareness of AMR, the COVID-19 pandemic has supported understanding of the concepts and criticality of surveillance around communicable diseases. Regular reporting of COVID cases identified using PCR (Polymerase Chain Reaction) and RAT (Rapid Antigen Tests), along with public reporting of COVID-19 results from wastewater monitoring and acceptance of genomic pathogen surveillance, have helped pave the way for understanding how these technologies work and why they are important. Australia has a golden opportunity to continue to build on this awareness amongst the public and with policy-makers to help continue to develop the trust, and to drive the changes required to lead to cultural and political reform.

4.1.5 Economic and commercial feasibility

Survey respondents highlighted that the commercial feasibility and incentives are not in place to drive forward change in this area. Political and societal awareness and will are required to support the prioritisation of funds for AMR surveillance, and while Australia has some strong capabilities in specific areas of technology, large-scale collaborative programs that involve various commercial parties across sectors are challenging to construct. To make a monitoring program like this viable, data science approaches need to move beyond research activities into the commercial arena, and technology and data standards are required to support interoperability (and avoid the costly activity of retrospective data alignment and linkage). There are also efforts required to align differing stakeholder interests and drivers, data and technological maturity, and coordinate ways of working across sectors.

4.1.6 Policy and regulatory readiness

There was a strong call for policy and regulation across the board, especially in the areas of data privacy, data and technology standards, and regulatory harmonisation (particularly with international bodies). This will be key to unlocking data interoperability, global markets, and maintaining the trust of sectors and citizens, particularly as collecting data without a clear and transparent plan for interpretation and use carries the risk of generating fear and mistrust. There was also a call for more standardisation in testing methods and result turnaround times, and clear mandates and enforcement around participation in surveillance programs. Strong leadership in this area – with subject matter expertise and business and industry credentials – will be needed to guide and inform policy-makers and regulators, and to coordinate groups, priorities, and drivers across sectors.

4.2 Point-of-care diagnostics

In 2015, the WHO published a Global Action Plan that emphasised the need for 'effective, quick, and low-cost diagnostic technologies for guiding the optimal use of antibiotics in human and animal medicine' (WHO, 2015). This need was reiterated in the 2018 O'Neill report, where rapid diagnostics were positioned as one of the biggest potential game changers in the battle against AMR (Collier & O'Neill, 2018).

Point-of-care (POC) diagnostics can reduce AMR by reducing inappropriate antimicrobial use and pathogen spread. There are now numerous tests that detect specific resistances associated with a pathogen (e.g., diagnostics from T2 Biosystems). These technologies enable tests to be taken and results to be received at the same place. However, given the low cost of antibiotics compared with the high cost of the new tests these will often not be used due to financial constraints. This highlights the broader challenge around the societal (tragedy of the commons) vs the individual health cost of antibiotic use. This means that the benefits of understanding regional resistance rates at a community or population are lost along with the opportunity to better manage resources, reduce waste, and ensure availability of effective antimicrobials at a local level.

For a patient, POC tests allow a faster turn-around to obtain results and guide specific and appropriate treatment regimens, reducing the administration of inappropriate use of broad-spectrum antibiotics. In a human health context, the ability to use POC testing in the home can also reduce the need for to attend health care clinics and lower unnecessary antibiotic use, thereby further reducing the spread of pathogens and AMR. In animal health, it can improve the diagnostic and treatment capabilities of farmers to reduce the need for unnecessary animal culling (Figure 19).

Normal test procedure
Attend appointment/Site visit by veterinarian
Take sample
Process sample
Transport sample
Prepare sample for analysis
Analyse sample
Document and send results
Patient/animal owner receives results (phone or second appointment)
Patient/animal receives diagnostically relevant treatment

Point-of-care test procedure
Attend appointment/obtain POC test
Take and process sample
Receive and report results
Patient/animal receives diagnostically relevant treatment

Figure 19: POC testing procedures reduce the time taken to receive appropriate treatment

The ideal POC test should be simple and effective, supporting their ability to be performed in a clinic, on a farm, or at home. The tests can be all-in-one systems, like pregnancy tests or RATs, or portable devices that can be used to process a sample, like those used to measure glucose or cholesterol in blood. The REASSURED criteria in Figure 20 have been developed to provide a best-practice framework for developing POC diagnostics with a view to equity, advocating for tests to be available at the places that need them the most. In addition to health care settings, this means regional, rural, and remote communities that may have limited testing infrastructure and expertise, and settings relating to animal health where location and cost can make obtaining veterinary care and testing prohibitively expensive. Tests should also consider environmental impacts, minimising the generation of unnecessary waste wherever possible.

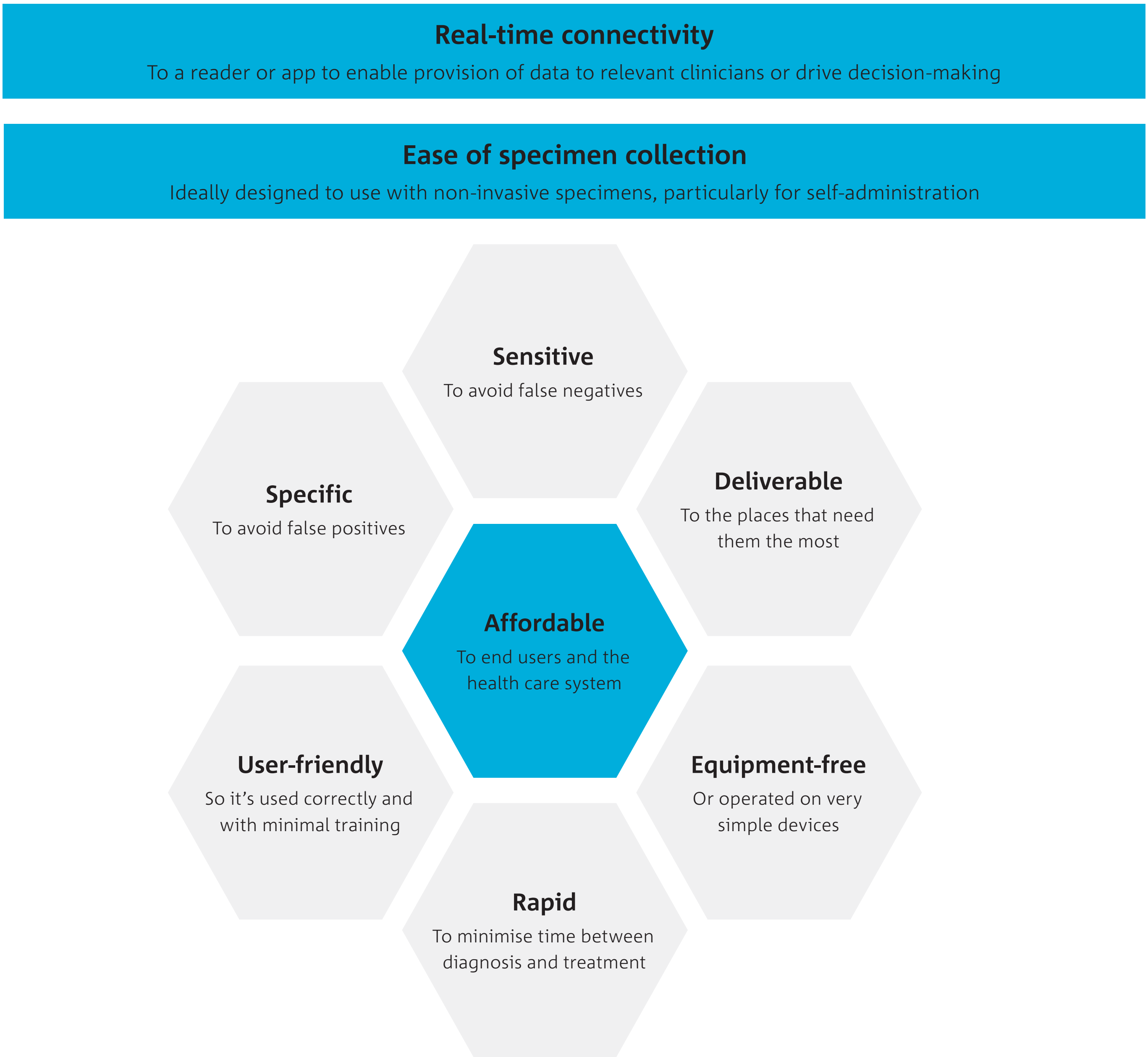


Figure 20: REASSURED criteria for developing optimal POC diagnostic technologies (Land et al., 2019)

In Australia, there is a limited variety of POC tests available and in regular use, particularly for AMR. A range of tests are now in development or coming to market for in-home sexually transmitted infection testing, leveraging mechanisms from antigen-detection mechanisms to quantum dot technologies (Radetec, 2019; Test Kit Labs, 2014). Small, portable devices that analyse nucleic acid have also demonstrated the ability to detect AMR in wastewater and stormwater could be a potential solution for applications in healthcare and primary production settings. These systems require expertise in sample preparation and analysis which will limit their ability for wide-spread use (Białasek & Miłobędzka, 2020; Leggett et al., 2020). While POC tests are a key weapon in the diagonstics arsenal against AMR, it is also important they are used strategically, and it is acknowledged where they are fit-for-purpose and where more extensive testing may be required.

In the spirit of 'keeping it simple' a first positive step on the path to increased consumer awareness around AMR may be starting with tests that enable in-home testing for bacteria vs viruses, coupled with decision-support apps to enable result reporting and providing 'next best action' analytics for patients. As products that can rapidly differentiate between bacteria and viruses come to market – for example ImmunoXpert, which can detect in 100 minutes and FebriDx which can detect in 25 minutes – there is an opportunity to look to these technologies as key interventions to reduce antibiotic use, the transmission of pathogens and AMR in health care settings and to educate the general public about the differences between bacteria and viruses, as well as how they are managed (NIHR, 2022).

4.2.1 Readiness measures

A key recommendation that emerged from the analysis is: start simple and build from there. Survey respondents noted that while several barriers still exist for POC AMR diagnostics, progress on these technologies is being made. The science and technology needed to make POC diagnostics work are at our fingertips, and COVID-19 has brought rapid testing into the home. There are still a few issues to be addressed including answering the question of who pays for tests, particularly those performed at home, with a view to maintaining equity.

Many of these technologies are still getting 'stuck' on their way to market, so commercialisation barriers need to be addressed, necessitating strong leadership and solid collaboration to continue to drive these. Surveillance and data management associated with POC tests will also be a key factor for consideration.

4.2.2 Infrastructure readiness

With COVID-19 RATs becoming more common due to the pandemic, these tests have joined other at-home testing that have been available for some time, such as pregnancy tests and blood glucose testing. These tests are increasingly being coupled with digital infrastructure to support decision-making and data collection and have paved the way for the addition of testing for other communicable diseases, as well as to further explore precision medicine and end-to-end patient care. POC diagnostics for AMR – rather than the pathogens themselves – are relatively immature and there are only a small handful of companies with this capability at present. While Australia has started putting the first steps in place to move towards rapid POC diagnostics for communicable diseases and AMR, there is still work to be done to ensure there is available data to understand the current and emerging threats that need to be addressed. This will ensure that R&D efforts are focused on priority problems, and the areas in Australia where it can have the largest positive impact. There must also be assistance to administer these tests safely and effectively – whether it be by oneself, a clinician, a veterinarian, or other – to understand the results, be able to report results and support management.

4.2.3 Skills availability

There is a long history, and general acceptance, of the use of POC diagnostics for blood glucose monitoring, pregnancy tests and more recently for COVID-19 diagnosis. Development of future tests should follow the REASSURED principles to ensure they are simple and effective. Respondents reflected that Australia's diagnostic industry has possessed the capability to design and deliver these products for domestic and international markets for some time, but reporting and integrating results into the medical system, which itself is fragmented across states, territories, and federal, needs work and will need to be well managed.

	Infrastructure readiness	Skills availability	Social and ethical readiness	Economic and commercial readiness	Policy and regulatory readiness
Point-of-care diagnostics	◑	◕	◕	◑	◑

4.2.4 Societal and ethical readiness

Point-of-care diagnostics for communicable diseases have become prevalent and accepted during the COVID crisis. While the development of additional in-home POC diagnostics may require more work with decision-support apps, or remote healthcare and laboratory services to interpret and manage results, there is broad societal exposure, acceptance, and readiness for these technologies. With the use of devices to monitor health and wellness becoming more commonplace, such as the Fitbit fitness trackers, the Oura wellness ring, and various pregnancy monitoring devices, the commercial sector has also supported the establishment of privacy and security protocols for the collection and management of health data, along with developing consumer trust, that can be built upon and leveraged (Benedetto et al., 2018; Maijala et al., 2019; Ryu et al., 2021).

4.2.5 Economic and commercial feasibility

While Australian companies such as Universal Biosensors and SpeeDx have POC devices and rapid tests – including for AMR – available, a large number of diagnostics are still in the laboratory phase and haven't yet been able to make it to market (SpeeDx, 2022; Universal Biosensors, 2022). It was noted that Australia is too small a market to be the only focus for the deployment of technology and lacks the domestic commercial demand required to support commercialisation of these technologies, highlighting the need for international regulatory harmonisation. Priority settings (i.e., primary production, veterinary, healthcare clinics, and hospitals) are also not always provided with the funding or processes required to support POC diagnostics and build them into their workflows. For in-home testing, there is also the question of who pays for tests and how access is provided for all Australians, particularly the most vulnerable.

> "COVID has shown us we can rapidly develop diagnostics, immunisations and therapeutics – we can do this for non-COVID challenges too."
> – Interview respondent

4.2.6 Policy and regulatory readiness

As discussed previously, consumer health technologies and COVID-19 testing has been supported by prompting changes to policy and regulatory frameworks, data management practices, and building the trust required to deploy POC technologies. These can serve as a starting point for data management protocols, yet there is still work to do around data privacy protection, ownership, and transparency of use to drive momentum and maintain trust in this space. This will be particularly important if citizens are to be encouraged to report their data to large-scale surveillance databases. The policy settings also need to ensure in-home POC diagnostics do not fuel inequity by pushing cost and responsibility onto the public. Respondents commented that the technology is usually ready well before clinical practices are ready to accept them, and regulatory systems are currently struggling to keep pace with the technologies being developed.

4.3 Vaccination technologies

Vaccination programs are a key weapon in the arsenal against AMR. In the spirit of 'prevention is better than cure', they help prevent infection in the first place, reducing disease burden in populations, and consequently lowering antibiotic use. Vaccines also reduce the number of infected individuals who are spreading pathogens containing AMR throughout communities. Consequently, the development of vaccines against pathogens with complicated resistance profiles and those which have a high frequency of severe illness will be a key positive step towards managing AMR.

> "Any organism you can't reliably keep out of farm, you need to vaccinate against."
> – Interview respondent

Traditional vaccination technologies often contain a part of the microbe it is targeting, training the immune system to respond to that pathogen. If the microbe is later introduced to the body, the immune system will create antibodies that latch onto the microbe and mark it for destruction. This is the key mechanism that is exploited in autogenous vaccines, also referred to as 'custom vaccines'. In autogenous vaccination, the specific microbe that is believed to be causing illness is isolated and a vaccine is generated against that pathogen (Figure 21). These are more often used in animal industries, and as part of an informed veterinary health program, have several advantages in terms of intellectual property, efficacy, and flexibility (Barnes et al., 2022).

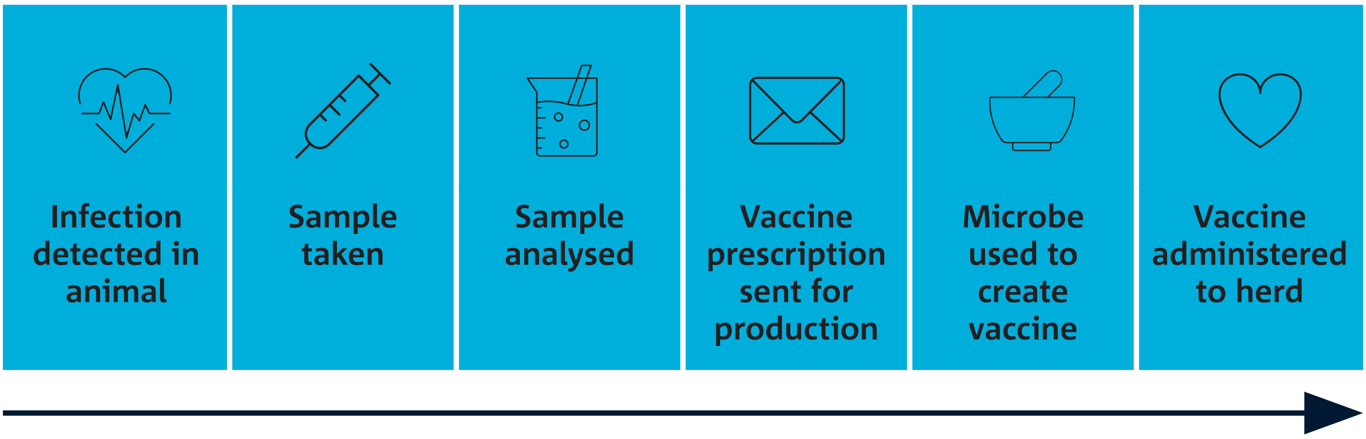


Figure 21: The process for autogenous vaccine production in agricultural settings

Vaccines that are mRNA-based work differently by leveraging the body's own ability to make proteins that are then used to induce an immune response. mRNA vaccines work by administering mRNA – messenger RNA that contains the instructions for a host to create a particular protein that can stimulate an immune response to the microbe of interest. One example is the COVID-19 mRNA vaccines which contain genetic information for the spike protein that enables the virus to attach to the host cell in the human body. Cells produce copies of the protein, and the immune system responds to the presence of this foreign protein and creates antibodies against it. The immune system is then trained to recognise that protein in the future. An advantage of mRNA vaccines is that they cause the body to create small parts of the pathogen which eliminates infection risks to the recipient.

4.3.1 Readiness measures

In a lot of ways, Australia is at a point to embrace broader vaccination programs more readily, both for humans and animals. The COVID-19 pandemic has supported this by generating greater awareness around the critical role vaccines play in managing communicable diseases, and by driving the prioritisation of spending on vaccine production infrastructure. This increase in infrastructure and production capability will also necessitate a focus on ensuring an available skilled workforce to maximise these investments to their full capacity. There is a disparity in attention, funding, and production of vaccines for human health vs animal health which, from a One Health perspective, will need to be addressed to create a greater focus on the risks associated with zoonotic infections. Barriers to developing vaccines include the ability to progress solutions beyond proof-of-principle, and limited returns on investment for vaccination technologies compared to other non-vaccination projects – a factor that is often fuelled by small Australian market shares for a particular vaccine product, making investment non-viable (Janse et al., 2021). Work is still required to usher vaccines through the commercial and regulatory pipeline, particularly international regulatory harmonisation to enable new products to access global markets. Assessing which animal vaccines will give the largest overall return on investment will be key to moving towards equity of access to vaccines across sectors.

	Infrastructure readiness	Skills availability	Social and ethical readiness	Economic and commercial readiness	Policy and regulatory readiness
Vaccination technologies					

4.3.2 Infrastructure readiness

Imported vaccines are not always optimised for the strains that are most important locally, and not all vaccines can be imported due to biosecurity restrictions. Retaining and growing vaccine development and delivery capabilities in Australia will be key to a comprehensive and appropriate vaccination strategy. Australia has some infrastructure for full GMP onshore vaccine development (i.e., CSL and Seqirus), however, delivery capacity is limited and there is a need for additional fill and finish, and pre-clinical testing capabilities. The COVID-19 pandemic has demonstrated Australia's readiness for new vaccination technologies (i.e., RNA vaccines) and their integration into national infrastructure. There have also been recent investments in onshore autogenous viral vaccine manufacture infrastructure (i.e., Apiam) which will focus on serving the primary production sector to fill the gap where there are few, or no, commercial vaccines available (RDV, 2022). Embracing these technologies will be key to supplementing existing vaccination production infrastructure to deliver a diverse portfolio of vaccines in Australia.

4.3.3 Skills availability

There will also be a need for applied scientists and clinicians with translational experience in enabling new vaccines to make it to market and to the human and animal patients that need them, and for regulators to continue to keep pace with new and emerging technologies. As mRNA vaccine development is nascent in Australia, it will take some time to develop a strong R&D capability and local commercial capabilities around the burgeoning infrastructure. As such, there will be a need to ensure skilled workers can be developed and attracted in alignment with infrastructure development. The current workforce skilled in more traditional vaccine technologies will be critical to retain and continue to develop to the evolving vaccine landscape and skill requirements.

4.3.4 Societal and ethical readiness

In primary production and veterinary settings, vaccination is a well-accepted strategy, yet vaccine availability and cost are key barriers to adoption. There has been extensive awareness-raising around the key role vaccination plays in maintaining a healthy society because of the COVID-19 pandemic. Mandatory vaccination programs have propelled information-seeking and education around vaccines and how they work. Yet public sentiment around the ethics of such mandates may also pose a barrier, as those who received vaccines begrudgingly or against their preferences may be polarised against receiving future mRNA vaccines. There is still more to be done in education around vaccination, in particular, its role in mitigating and managing AMR.

> "Vaccine inequity is a concern. When AMR gets worse, it will get worse in developing countries and will impact us all – we are currently gently walking towards a cliff edge."
> – Interview respondent

4.3.5 Economic and commercial feasibility

Strong leadership in AMR and medical countermeasures has been called for to provide direction, oversight, and prioritisation of products as they move from discovery to delivery. Vaccines for animals and livestock have lagged behind human applications, with R&D investment and economic feasibility for new vaccines being key factors. More traditional vaccine technologies here in Australia, in particular live vaccines (that can be administered by adding them to drinking water, in eyedrops, or injecting them into eggs) can be prohibitively expensive to develop and produce – particularly if the product doesn't have access to a larger market share beyond the domestic market. Next-generation vaccines, such as mRNA vaccines, may be too expensive for herd and flock vaccinations unless there are further improvements in large-scale administration techniques and cost reduction – cost-effectiveness is a critical factor. Treating AMR solutions as a public good and extending that to the livestock sector as a way of acknowledging the inextricable link between primary production settings, environment, and human, is a key path forward to breaking zoonotic cycles.

4.3.6 Policy and regulatory readiness

To support vaccine development, particularly in the cost-sensitive primary production animal sector, international regulatory alignment and harmonisation will be required to support new products coming to market. This harmonisation and alignment should come with incentives that take into consideration the different market structures (e.g., market sizes) present. Strides made by harmonisation initiatives such as the VICH trilateral program could be leveraged by expanding to additional countries or being used as a model by other sectors. Initiatives such as these will support Australia with having fit-for-purpose veterinary products and will mean producers can look beyond the needs and regulatory hurdles of the EU and USA to have a financially viable product.

"There is a lot of red tape to navigate, and the animal space is regulated like we're creating human vaccines. The red tape increases every year. So, when we tell people the cost and time involved with developing a new vaccine, they often walk away because it's too hard and too expensive."
– Interview respondent

In Australia, there are clear procedures when it comes to vaccination technology regulation via the TGA. However, stakeholders noted the processes can be complicated, protracted, and onerous to manage which slows development. There can also be conflicts and duplications between regulatory processes, highlighting an opportunity for additional domestic harmonisation and alignment.

Investments in capacity and capability for Australia's regulators will be key if they are to keep pace with the next generation vaccines and emerging technologies. This will be critical to ensure processes are streamlined for current needs, while simultaneously looking forward to anticipating future needs. This will be key to making sure that regulatory processes are not major bottlenecks and barriers for AMR solutions. Permits for autogenous vaccines are less stringent than other vaccine types, with the greater focus being placed on demonstrating product safety (over efficacy). One Health vaccine policy and program development will be critical to ensuring investment and rollout are developed in a way that considers how AMR moves between human, animal, and environmental reservoirs.

4.4 Prevention through design: High-risk settings

A key strategy for managing AMR is to prevent infections in the first place (Figure 22). Prevention is a critical component to reducing use of antimicrobials and includes vaccination as well as attention to ensure surroundings and processes are designed in a way that reduces spread and proliferation of pathogens and AMR. This is particularly critical in high-risk settings such as farms, hospitals, and other known AMR-proliferation 'hot-spots'.

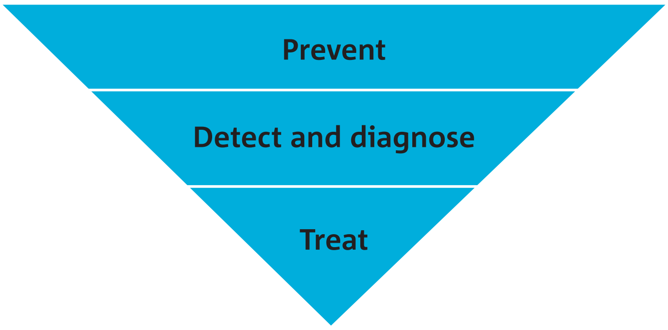


Figure 22: A strong focus on prevention is key when designing high-risk settings

Hospital-acquired infections alone account for over 80,000 infections per year in Australia, with the primary infection types being urinary tract infections (UTIs), *Clostridium difficile* infections, and surgical site infections (Mitchell et al., 2017). It is suspected that these numbers only reflect around half of the actual infection numbers due to an absence of – or incomplete – data. In alignment with the adage 'what gets measured, gets managed', obtaining more complete data on the movement of microbes within hospitals and healthcare settings will support with better management of the AMR risks associated with these transmission pathways.

In primary production settings, high-risk areas and methods of microbial use and AMR spread vary from clinical settings. Recent estimates suggest that 73% of antibiotics sold globally are for agriculture for a variety of therapeutic and non-therapeutic uses, and there has been a history of overuse in these settings (Figure 23; van Boeckel et al., 2019). Australia has been taking actions to restrict antimicrobial use for growth promotion purposes and drugs of critical importance, positioning itself as a world leader in minimising antibiotic use in farm animals (Australian Government, 2017). As the number of treatment options in farmed animals is reduced, it increases the criticality of preventing AMR spread via vaccination and design.

Therapeutic use

- Treatment of disease
- Control of disease spread (metaphylaxis)
- Prevention of disease (prophylaxis)

Non-therapeutic use

- Growth promotion

Figure 23: Key antibiotic uses in farmed animals (van Boeckel et al., 2019)

There is an opportunity to curb infection rates in areas of high transmission and high-risk, such as surfaces, air, and equipment, by embracing emerging technologies that reduce the number of bacteria at these interfaces. Surface modification for antimicrobial resistance presents the opportunity to reduce or eliminate the microbial load on surfaces that would otherwise serve as sites for cross-contamination or microbial proliferation. These can include solid-air interfaces such as door handles, computers, tables, and textiles, as well as solid-liquid interfaces like taps, drains, showers, and toilets where the biofilm formation can present additional challenges to sterilisation (Adlhart et al., 2018).

Biomimicry – the process of looking to nature to help problem solve – holds hope for surface modification in these settings. The application of discoveries such as bacteria-inhibiting patterns of shark skin, or the microbial-piercing properties of insect-wing nano-needles on high-risk, high-contact surfaces, can help tackle microbial spread (Lee et al., 2020; Linklater et al., 2021). Other nanotechnology-based interventions such as nano-thin layers of black phosphorous as an antibacterial/antifungal coating and silver nanoparticles have also demonstrated the ability to kill microbes and disturb biofilms (Lara et al., 2020; Shaw et al., 2021). These technologies can make an impact both in healthcare settings, and beyond (i.e., door handles, railings, agricultural equipment, etc.). However, applications in one setting should also be evaluated for potential negative impacts in another.

> "Tech is sexy. Treatment is sexy. But we need to focus on prevention and educate people on the disincentives – if you don't change your behaviour, our drugs won't work anymore. And technology doesn't move the needle on its own – we need to focus on the workforce and workflows."
> – Interview respondent

Antimicrobial coating technologies such as the shark skin-inspired patterns are also being used in invasive medical devices which are often associated with high levels of hospital-acquired infections like catheter-associated UTIs, intubations associated with pneumonia infections, and central line-associated bloodstream infections (Rumbaugh, 2020). Hydrophobic materials are used for invasive medical devices due to their anti-fouling properties (Faustino et al., 2020). Biofilms are a key site for intervention when tackling AMR. As such, these lend themselves to novel approaches for management. In orthopedics, approaches such as electrical stimulation and using laser-generated shockwaves to enhance biofilm detachment, and applying electromagnetic fields to augment conventional antibiotic treatments, have been explored as intervention strategies with high degrees of success (Ercan et al., 2011; Kizhner et al., 2011; Pickering et al., 2003).

It is critical that there is data and evidence on where the highest levels of risk are, and that there is a data-driven, prevention-focused, technology-enabled approach to designing and retrofitting high-risk settings. This will be a key element in mitigating and managing the impacts of AMR now and into the future.

4.4.1 Readiness measures

Moving the emphasis from a 'treatment focus' to a 'prevention focus' was welcomed by respondents, and there was agreement that Australia should be embracing emerging technologies and design principles that reduce AMR prevalence, particularly in high-risk settings. There was acknowledgement that prevention through design is taking place in many spaces, such as biosecurity practices in agricultural settings and infection management and control practices in healthcare settings. These processes – along with pockets of activity where sectors are exploring novel technologies in this space – can be built on and applied across sectors. It was noted that there is quite a bit of work still to do from a policy and regulatory readiness perspective, and there will be a tension for regulators to manage in enabling new preventative technologies to come to market in a timely manner, while still ensuring efficacy and safety of these products. Australia's policy and regulatory settings in this area will be key to unlocking economic, commercial, and infrastructure readiness.

4.4.2 Infrastructure readiness

Embracing emerging technologies to support preventative design in high-risk settings does occur across all sectors relevant to AMR management, though they are often focused on pathogen control rather than AMR control, and therefore may not be optimised to manage AMR. The COVID-19 pandemic is a reminder of just how important targeting pathogen transmission pathways are in managing infectious diseases (Murply, 2020).

As new sterilisation and surface coating technologies are being developed, a lack of testing infrastructure, testing standards, and complicated regulatory process make it challenging to obtain the clinical data and evidence required for a 1) strained health care system and 2) fiscally conscious primary production sector to invest in these new solutions. This evidence is also key to ensuring the solutions do not exacerbate the problem. Nanosilver surface coatings introduced for a range of purposes in medical care due to their antibacterial properties resulted in adverse health reactions and an increase in bacterial resistance, with a lack of regulation making them difficult to track and manage (SCENIHR, 2014). AMR surveillance data will be key to rational and prioritised design, and to assess the impacts these interventions are having on prevalence and spread. As telehealth and COVID-19 'virtual wards' continue to change the way the sector and consumers think about digitally enabled healthcare, this system-wide perspective to moving out of hospitals and into homes can also help ease the burden on infrastructure, reduce transmission through the community and clinics, and provide comfort and familiarity to patients while they are unwell (Thornton, 2020).

	Infrastructure readiness	Skills availability	Social and ethical readiness	Economic and commercial readiness	Policy and regulatory readiness
Preventative design: High-risk settings					

4.4.3 Skills availability

The skills required to develop and deliver products to support detection, mitigation, and management of AMR in high-risk settings are readily available. Ensuring there is a supply of skilled engineers to design and deliver designs that prevent the spread of pathogens and AMR, both in new buildings and retrofit of high-risk settings, will be key. Another theme that emerged through consultations is ensuring that regulators and policy-makers have the skills required to keep up with the new and emerging technologies and pre-empt what comes next to keep a clear path for products to get where they are needed.

4.4.4 Societal and ethical readiness

From a societal perspective, awareness of the growing threat of AMR is still low. Concerted efforts will be required for individuals and organisations to see the imperative of investment and policy to manage AMR and will be key to driving actions that can be taken at a local level. These could include awareness that AMR risks are associated with unprocessed animal manure being placed on household gardens to grow vegetables. Or a better understanding of 'hot spots' in the home and office where AMR can spread, such as intimate contact with companion animals or high-touch surfaces such as door handles. It also extends to a raised awareness of the impact that overuse of household antimicrobial/cleaning agents (which are often unregulated) are having on the issue.

Awareness of the problem and support with understanding actions that individuals can take to play their part in curbing AMR will be crucial to culture change and an empowered citizenship. In the spirit of building on what is working, lessons and processes from biosecurity practices, such as on-farm biosecurity planning, may be useful for supporting other settings in understanding the issue and making management strategies (Farm Biosecurity, 2022).

4.4.5 Economic and commercial feasibility

Funding models and financial incentives need to consider the way AMR moves through sectors, focusing on prevention and elimination at the source wherever possible. From the general population to businesses, farmers to clinicians, there is a need for data and evidence around the widespread impacts and transmission pathways of AMR, and the benefit of solutions. This also includes information and awareness raising on the cost of inaction. These factors will be critical to generating market share and widespread adoption. Credible research into the efficacies of new technologies is essential, and 'gold standards' for measuring these types of technologies are currently lacking or absent and require development – particularly as more novel and innovative solutions are developed. The animal sectors are particularly cost-sensitive, and there will be a question of where the money will come from to invest in AMR-sensitive design and retrofit of high-risk areas. The TGA has a strong reputation as a regulator both domestically and internationally, yet there are still challenges with moving many Australian AMR technologies to market. A 'whole of system' approach is required, which would be supported by central, One Health-focused AMR leadership and oversight.

4.4.6 Policy and regulatory readiness

As Australia looks to the policy settings required to make changes to the design of infrastructure investments, there is a pressing need to ensure policy-makers understand the scale and breadth of the issue and potential solutions available, which further highlights the criticality of education, awareness raising and collaboration in the political sphere and beyond.

> "There needs to be grass-roots awareness of AMR, plus the finances available to drive change. Without money, there is no mission."
> – Interview respondent

Novel technologies each may have different mechanisms of action, and it is not always clear which regulatory pathway they should go down. And when a solution is travelling along the regulatory path, it is not always a smooth ride. Providing support and expert guidance from both a sector-specific and One Health perspective will be key to supporting AMR technology achieve regulatory approval. There will be a tension to manage between not over-regulating the environment to enable goods to get where they are needed, being clear and specific enough on what is required to come to market and providing evidence of efficacy and safety of a product (i.e. HEPA air filters just need to show they remove 99.99% of pathogens to achieve certification, regardless of the size of the space or how much air has passed through it previously). There is also a need for regulators to be continually aware of the emerging challenges and technologies that are making their way to them so they can anticipate market needs and not be the rate-limiting factor in bringing solutions to market. Developing policy for the design and retrofit of high-risk settings is one path forward and should include integrated AMR monitoring and surveillance systems to better track and manage the incidence of AMR and provide data on better ways to predict and prevent proliferation in these settings.

4.4.7 An expanded view of prevention through design: Urban planning and the environment

The COVID-19 pandemic is a reminder that cities are not designed to limit the spread of pathogen transmission. As the impacts of climate change impact global temperatures affect the availability of clean water and contribute to extreme weather events, these factors also impact on AMR prevalence and transmission in cities and beyond. In taking a holistic view of AMR, it is important to consider how it moves through the environment and how cities and surroundings are planned to manage this.

When released into the environment, antibiotics can impact the natural, healthy processes that usually take place in nature. The continued exposure of microbes to antibiotics can also further contribute to resistance in these bacteria. Of antibiotics administered, a high proportion is generally excreted unaltered or as active metabolites (Bansal, 2019). In areas where consumption rates are high, such as clinical settings and agriculture, this can lead to high rates in connected waterways and ecosystems which can become key sites for the exchange of antibiotic resistant genes (ARGs).

Studies exploring resistance gene transmission in slaughterhouse workers have demonstrated working in these conditions is a key factor in ARG transmission, and this transmission extends beyond livestock to wildlife and companion animals (van Gompel et al., 2020; Allen et al., 2010; Rusdi et al., 2018). Wastewater treatment plants are particular hotspots for antibiotic and ARG accumulation, and evidence shows that these sites are not particularly effective at the elimination of antibiotics or ARGs (Sabri et al., 2020). To combat this issue, some countries are exploring constructed wetlands as a cost-effective method for removing contaminants from the environment, including both antibiotics and ARGs (Liu et al., 2019). Bacteriophage (phage) technologies – particular viruses that occur naturally and only attack bacteria – also hold promise as method for environmental decontamination and use in this setting may pave the way for greater public awareness and acceptance of these technologies in human use (Issabekov et al., 2022). As mentioned previously, environmental monitoring and surveillance are key to understanding and managing the continued emergence of AMR.

An inter-species battleground: Phage technologies as a weapon in our AMR arsenal?

Phage technologies provide the ability to harness nature to engage in inter-species battle and pit microbes against microbes. Phage are viruses that infect and destroy bacteria but are harmless to humans, plants and animals. They have high specificity for particular bacterial species – including those that are multi-drug resistant – and can be used as a single phage to tackle a single bacteria, as a cocktail to increase the likelihood of being effective against a bacterial strain of interest or to tackle multiple bacteria simultaneously, or in concert with antibiotics for optimised treatment (Nikolich & Filippov, 2020a).

While phage technology was described by Félix d'Hérelle over a century ago and embraced by a small number of countries, global adoption has been slow and there are a number of challenges that will need to be overcome to realise its implementation. A strength of phage treatments is their high specificity for particular bacterial strains. Yet this can also pose a challenge as it increases the importance of a specific and accurate diagnosis of infection, and can result in phage technologies that are region-specific, creating challenges for scaling these therapeutics to a global market (Nikolich & Filippov, 2020b). There is a need to increase the stability of phage cocktails (including at room temperature) to maintain treatment potency (Jault et al., 2019). Research is still learning about how phages interact with – and accumulate in – mammalian tissues, including the brain (Barr, 2017; Huh et al., 2019). And there is the additional challenge of public sentiment, particularly towards viruses after the COVID-19 pandemic. Yet this technology holds promise as an important tool to have in our toolkit against AMR, particularly in setting where it can act to disrupt biofilms and where other treatments are no longer effective.

As well as waterways playing a role in the spread of antimicrobial resistance, soil is a major reservoir for ARGs. In countries where water availability is low and demand is high, water is often re-used for irrigation and other primary production purposes leading to the further spread of antibiotics, pathogens, and ARGs between the environment, animals, and humans (Slobodiuk et al., 2021). This water reuse further contributes to rising antibiotic levels in both ground and drinking water, and these practices are a particular challenge in developing countries and areas sensitive to climate change-induced water scarcity (Burke et al., 2016; Deng et al., 2016). AMR doesn’t respect state and country borders. Coordinated international activities, alignment, and oversight are critical to tackling this global health problem comprehensively and equitably.

Changes to our climate and rising baseline temperatures have also been shown to accelerate the bacterial growth and the spread of resistance (B. Chen et al., 2013). Higher temperatures are a crucial predictor of pathogenic bacterial growth rates and are thought to contribute to an increase in bacterial carriage in both people and animals. Ambient temperature has been identified as the most important contributor to the establishment of resistance in a study of resistant isolates collected throughout Europe over a 16-year period (Burnham, 2021; McGough et al., 2020). Designing our expanding cities with a sensitivity to hot-spots, changes in proliferation rates, and the impacts of extreme weather events such as floods and fires, will be key to mitigating against the climate-change associated cross-contamination risks.

4.4.8 Expert perspectives

When asked about preventing the spread of AMR through urban design, survey respondents called for better environmental monitoring and surveillance to improve our understanding of where Australia's largest current and emerging challenges are, so environments can be designed with them in mind. This information, and recommended courses of action, will need to be communicated to the public, policy-makers, and infrastructure developers (who can exhibit a large degree of influence over planning processes and decision-making).

Australia being a vast and geographically diverse country will necessitate the development of local, place-based management strategies. Such strategies require a coordinated approach from both the public and private sector allowing for central oversight and coordination. Clear communication of the evidence and impetus for change will need to take place in the context of the pressures and opportunities presented to major stakeholders, and clear leadership and direction around the authorising environment, key policies, and societal and environmental ethics will need to be considered as Australia continues to move towards designing surroundings that prevent and manage the spread of AMR.

This paradigm shift in how cities are planned has already begun in Australia with the establishment of strategies for cities that are 'smart', climate resilient, and water sensitive (CRC, 2022; PIA, 2021; Samira Sarraf, 2020).

Off the back of the COVID-19 pandemic, there is an opportunity for other communicable diseases – and AMR – to leverage and influence these strategies to ensure Australia is designing our cities and surrounds with prevention and wellness in mind. Strong, central leadership and coordination will be required to achieve these aims. For all these forward-thinking strategies to be successful, it will be critical Australia has the right skills needed to plan, design, and deliver the large-scale infrastructure projects that lie ahead. Community awareness will be key to obtaining buy-in for our major infrastructure developments and to driving continual change. It was commented that the cost-benefit ratio will be key to highlight in gaining traction (which necessitates data for robust and trusted quantification) and changes in this area are more likely to be adopted at the planning and development phase, rather than driving a retrofit agenda due to prohibitive costs.

Part V

Future scenarios

This portion of the report, explores what the world may look like in 2050 based on the actions Australia does, or does not, take now to manage AMR. This report contains several action areas which will reduce the incidence of AMR in humans, animals, and the environment by increasing the number of AMR products making their way to market, particularly those with a prevention-focus or that help rapidly identify a pathogen, leading to better diagnosis and treatment of infections. They will lead to comprehensive, interoperable data and action-oriented insights to respond to risks and improve health outcomes. And all of this will be powered by educated, empowered, enabled, and aligned citizens and sectors.

Two scenarios are presented in this section. In one scenario, the cost of inaction will be explored, drawing insights from expert analysis. This will be the scenario of maintaining the 'status quo' and is written as a narrative inspired by desktop research. The second scenario explores what the world might look like if Australia rallies around AMR management, living up to the nation's technology-powered, human-driven potential to solve this looming crisis.

Each of the decisions that have been made up until this point has taken the world to where we are today, and the choices that are now made will determine what the world will look like in the future (Figure 24).

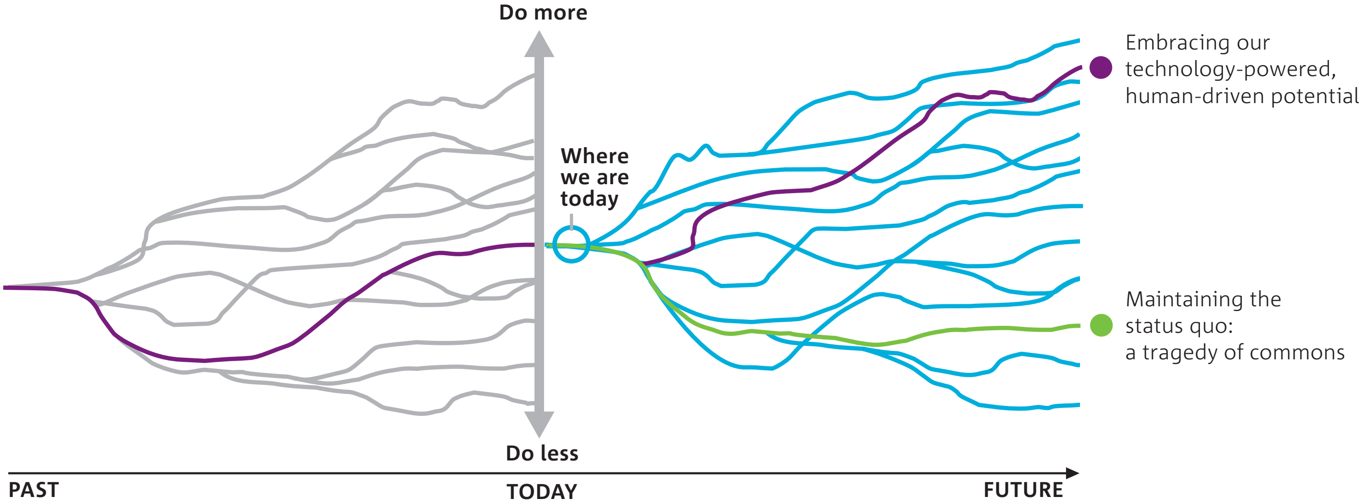


Figure 24: Our choices have led us to where we are. The question is, where to next?

In solving the challenge of AMR from a One Health perspective, multiple sectors must come together and problem-solve collaboratively. As discussed, new and collaborative models of problem solving have challenges to overcome in how solutions are implemented – particularly in the areas of funding, coordination, and prioritisation. However, they also bring myriad strengths as they support understanding problems and solutions from a systems-thinking perspective, borrowing ideas and innovations from different sectors as what works is built upon, and, evolved and iterated.

New, multi-faceted problems necessitate new, multi-faceted solutions. In a white paper released by MIT University in 2011, a 'convergence' model of science and research was called out as a powerful catalyst to revolutionise advances in biomedicine, as well as other scientific disciplines (MIT, 2011). Under this model, multiple disciplines such as life sciences, physical sciences, and engineering come together with their unique perspectives to solve some of our most complex challenges in transdisciplinary ways (Figure 25).

In the spirit of convergence, a multi-disciplinary roundtable of 22 diverse scientists, artists, futurists, and technologists was held in May 2022 to explore what our world could look like in 2050 if Australia rallied around solving AMR without constraints. The objective was to bring together

new and creative ways of thinking to spark conversation and innovation, and to balance the bleak outcomes of this global challenge against an inspiring, collaborative, sustainable, and technologically enabled better future. One where disciplines and sectors come together to collaboratively build a healthier, more equitable world. Key ideas from the session are reflected in the 'technology-powered human-driven' narrative. To begin, the report starts with the scenario of the 'status quo'.

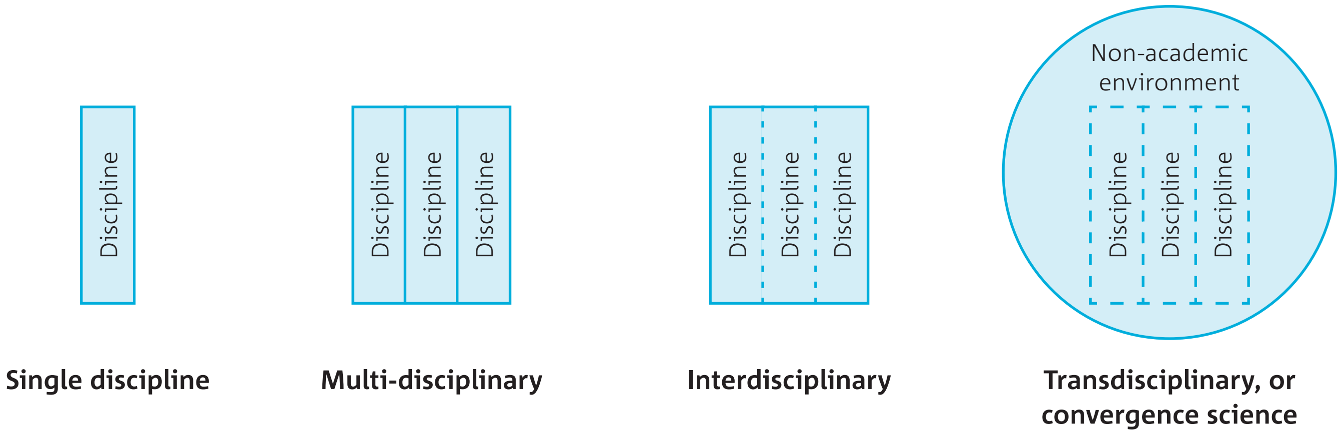


Figure 25: New, multi-faceted problems necessitate new, multi-faceted solutions

5.1 Maintaining the status quo: a tragedy of commons

It is 2050, and we missed our opportunity to get on top of managing the challenges humanity faces from AMR, and are now living in a post-antibiotic world. In economic theory, the 'tragedy of the commons' is used to describe systems in which individuals act in their interest instead of acting to help the common good. The overconsumption, misuse of antimicrobial drugs, under-investment in antimicrobial resistance solutions, and the ultimate depletion of the public health systems efficacy of antimicrobials as a treatment solution have led to the 'tragedy of commons'. While significant funding is still being poured into finding the next 'miracle drug', new therapeutics that have been able to mitigate AMR have not made it to market in the last 25 years and anything that does manage to make it to market is so prohibitively expensive it is only available to a select, wealthy few.

While technology and understanding of health have significantly advanced, surgeries that used to be routine are now incredibly rare because the risks associated with acquiring a secondary infection usually do not outweigh the benefits of the procedure. Policy and financing choices by governments and development partners have resulted in weak public-health systems across the world, enabling the undetected spread of pathogens, including drug-resistant strains. This is putting an enormous financial burden on the healthcare system as we shift from treating diseases to managing symptoms. Drug-resistant infections are now costing the health system more in terms of person-hours needed to treat them and extended hospital stays, and drugs are more expensive and less well-tolerated than ever before. The cost of AMR containment measures is now at US$9 billion annually in low- and middle-income countries. About half of this amount is for investments in, and operation of, core veterinary and human public-health systems. Lifespan has been in steady decline, along with a marked decline in quality of life, with healthcare costs skyrocketing by 25%. Extreme stigma surrounds any communicable disease.

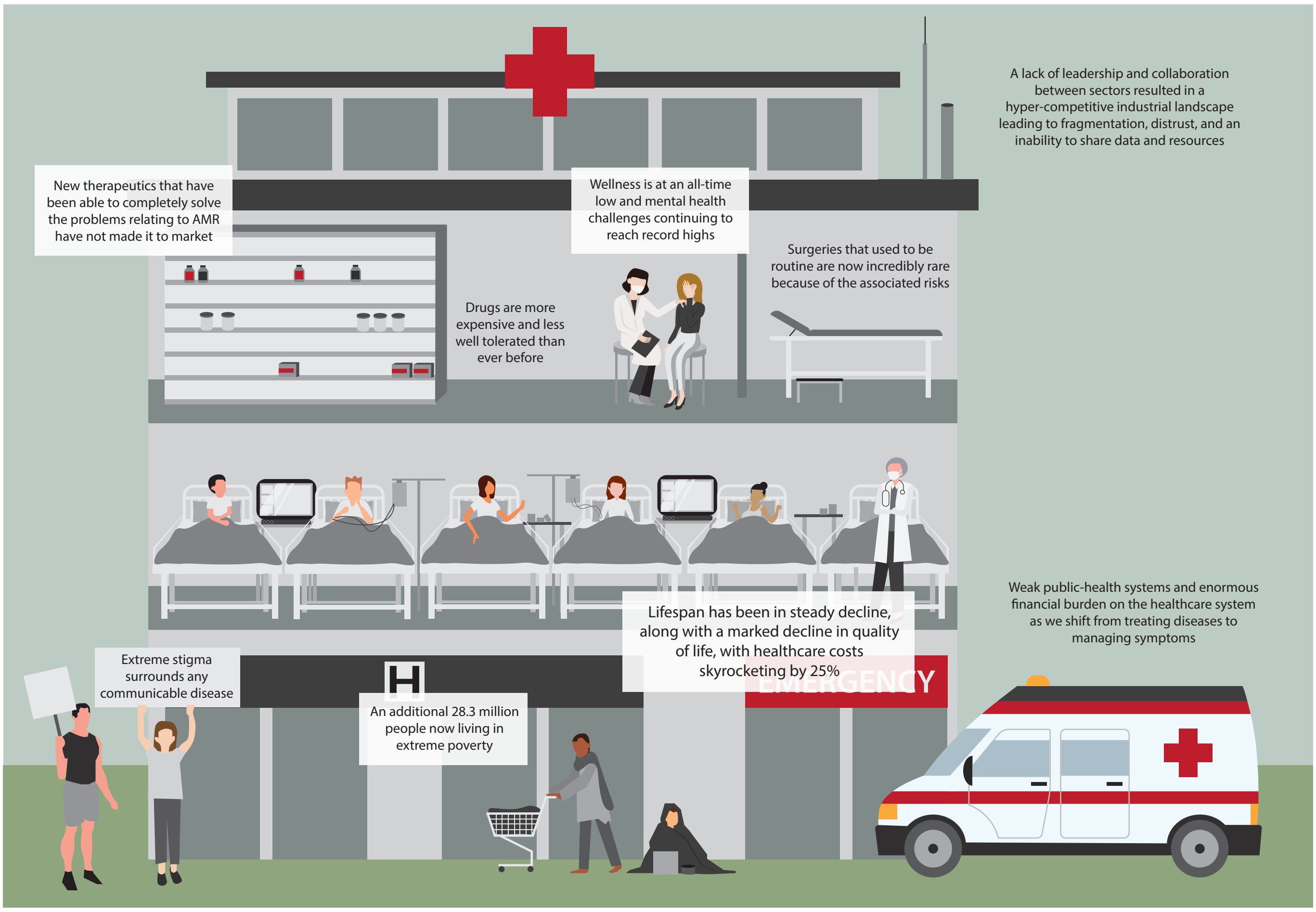


Figure 26: A portrait of our potential future if we maintain the status quo

The Sustainable Development Goals for 2030 – such as ending poverty, ending hunger, ensuring healthy lives, reducing inequality, and revitalising global development partnerships – have not been achieved. Developing countries have been hardest hit by the crisis, losing 5% of their Gross Domestic Product (GDP) and an additional 28.3 million people now living in extreme poverty. Livestock production has also declined, with meat being rare and risky to eat. Global livestock production is now in decline by at least 2.6% per year, and up to 7.5% some years. Again, this has been most markedly felt in low-income countries.

A lack of leadership and collaboration between sectors resulted in a hyper-competitive industrial landscape, with individuals and entities only focusing on their needs in isolation. This has led to fragmentation, distrust, and an inability to share data and resources in a way that would benefit the greater good. The global costs associated with AMR skyrocketed as we lost our final effective antibiotics and are now at US$100 trillion in lost economic output. Global GDP has been cut by 3.8% annually and the volume of global real exports has also fallen below base-case values by 3.8%.

Unlike the financial crisis way back in 2008, there are no prospects for a cyclical recovery in the medium term, as the costly impact of AMR persists. The increasing need for health services is also putting more pressure on public spending for health, which, coupled with decreasing trade and livestock production, is driving a public deficit. The huge health burden placed on society sets back the progress made in previous decades and disproportionately affects the poorest regions and people.

Society suffers as our productive workforce continues to decrease in size, and the costs borne by society are not only monetary but psychological as well with wellness at an all-time low and mental health challenges continuing to reach record highs. The constant risks of getting sick and the high costs of treatment continue to lead to a level of anxiety that has fundamentally changed social functioning for the worse. A global sense of hopelessness persists and it is difficult to see how we can reverse the impacts of the cumulative decisions that have led us into this continual state of decline.

Key reports that inspired this section include:

- 2050 Scenarios: four plausible futures (ARUP, 2019)
- Tackling drug-resistant infections globally: Final report and recommendations (O'Neill, 2016)
- OUTBREAK consortium: One Health antimicrobial resistance economic perspective (UTS, 2020)
- Global burden of bacterial antimicrobial resistance in 2019: a systematic analysis (Murray et al., 2022b)
- Averting the AMR crisis: What are the avenues for policy action for countries in Europe? (Anderson et al., 2019)

Table 5: Key results from reports informing the 2050 scenario

PROJECTED MODELS	HUMAN LIVES LOST	CUMULATIVE GDP LOSS BY 2050 (US$)
RAND model (Taylor et al., 2014)	11 to 444 million adults, cumulative	$5.8–$125 trillion
KPMG model (KPMG, 2014)	200 to 700 million, cumulative	$5–$14.2 trillion
Jim O'Neill report (O'Neill, 2016)	10 million a year by 2050	$60–$100 trillion

5.2 Embracing our technology-powered, human-driven potential

It is 2050, and after concerted and successful public and political awareness campaigns to help people understand the impacts of AMR, we now live in harmony with the microbes in our surroundings and have a more nuanced understanding of how they can help or harm us. Lessons from global challenges such as the COVID-19 pandemic and subsequent outbreaks have been harnessed, and we are now better collectively finding solutions to complex problems. This is accompanied by an understanding and expectation that large, long-term challenges often need long-term solution pathways that are accompanied by collaborative, fit-for-purpose, sustainable funding, and policies designed to keep us happy and well. New technologies that help us manage the challenges associated with AMR are appropriately prioritised and ushered into the market where and when they are needed most, and antibiotics are now used only as a last resort, only in the minimum quantities they are needed.

In our daily lives, our diets have shifted significantly to be more plant-based and incorporate lab-grown meats, which has reduced the intensive farming practices of the past. Consumers have a greater awareness of the biological processes taking place in their bodies, with personalised wellness-focused, genomic-based food and exercise plans now commonplace. In our supermarkets, goods now contain digital tokens which contain information on microbes, antibiotics, or ARGs present in our produce. Where this information is not available, our lifestyle-assist devices (which also act as our telecommunication devices) can provide a quick scan for key food safety and nutrition information. This can be cross-referenced against our genomic-eating plans and data from biosensors residing in our gut to inform what we should eat to maintain wellness and prevent illness based on our current bio-snapshot.

Digital certificates also provide metrics on the impact producing that food had on the well-being of the environment and animals, from how well animals were treated to the emissions associated with the end-to-end logistics of the product. Other consumer goods, such as cleaning products, also come with digital certificates that provide information on how effective a product is and its impact on the environment. As we now have sensing technologies integrated into our homes, our lifestyle-assist devices support us with selecting the best product to manage only the problem microbes in our environment, and we use these in the minimum doses required which saves us money, reduces product consumption, and supports with maintaining a healthy microbiome in the home.

Figure 27: Our lifestyle-assist devices are powered by interoperable data from our home and personal data collection systems to help guide wellness-focused decision-making

The design of our homes now incorporate sensing technologies and self-management of microbial risks. Areas that are at the highest risk for microbes that will make us unwell have been designed to minimise microbial loads via antimicrobial technologies and automated cleaning, such as with safe aerosols that also balance the good bacteria in your surroundings. Data is collected and reported on what is detected, and the interventions your smart home has taken, to keep you safe and well. These are presented in a dashboard on your lifestyle-assist device so you can see the infection type that has been prevented and the ‘well’ hours you have been given as a result. Trusted data policies mean we are comfortable with this data being fed into broader surveillance systems that monitor what is moving through our environment and community, and we can opt-in to receive periodic updates on the positive impacts our data-sharing has had on our community and research, which is powered by advanced automated analytics to provide insights.

We are now better at knowing the difference between helpful and harmful microbes by the sensing and detecting devices we have installed in our homes, particularly in our air sterilisation units. Our scanning goggles (which we also use for entertainment purposes) and surface sprays that change colour in response to the presence of dangerous pathogens also help us visualise any dangerous microbes lurking in our homes. We are much better at cleaning discriminatorily, guided by our lifestyle-assist devices. Areas of our homes that were previously areas linked with sickness also now have technologies to keep us well. Sensors and neutralising technologies are embedded in our toilets and drains to detect and disarm harmful microbes and compounds before they make their way into our waterways.

Even the humble toothbrush is now designed to keep us healthy, linked to our lifestyle-assist device, it guides us to brush to dislodge any biofilms around our teeth, gives us readouts of our oral microbiome, and even sterilises itself after use.

The technologies to sense and detect microbes, ARGs, and antibiotics that live in our homes are also connected to our lifestyle-assist device and feed in key information on our state of wellness, our health, and rate of antibiotic metabolism/treatment profile, and connect to trusted databases shared with clinicians. This enables end-to-end tracking of illness and recovery and guides precision dosing of antibiotics and other drugs we take. However, the need to take antibiotics is now very rare, as our environments are designed to reduce infections. Additionally, our systems-thinking approaches to health and wellness have demonstrated that for some diseases, toggling factors to increase wellness in one part of our system is as effective – or more effective – than directly targeting disease with drugs.

Going into medical clinics and hospitals for diagnosis and treatment of infections is also incredibly rare, thanks to the shift to in-home, digitally-powered platform development and wearable sensors that support with assessment, testing and treatment. This has reduced the community spread of pathogens and has also reduced strains and costs that used to be associated with the healthcare system. Because of the extensive, specific, and trusted data we have available, standard dosing practices are rare and precision dosing is the norm. Data gaps that previously existed in pregnant women, children, marginalised populations, or people with contraindications have been bridged due to this data. All hospitals have been designed with, or retrofit with, integrated sensing and surveillance systems which have in turn informed how hospitals are designed to minimise harmful microbes and guide targeted cleaning regimes.

The ingestible biosensors used in humans are also available in animals and are commonly used in pets to maintain wellness in our companion animals. Animals, including wildlife, farmed animals, and pets, are commonly surveyed for movement and microbes. Our sensing and surveillance systems in high-risk areas of the environment are commonly equipped with early warning systems connected to advanced, automated analytics that help the environment remediate itself. Data from our homes and yards also feed into aggregated neighbourhood datasets that provide insights into the pathogens in an area, as well as the incidence and severity of infections. This data is used to drive local policies to maintain neighbourhood wellness and is also available in public dashboards that are used by real estate agents and property buyers, with areas with higher wellness rankings fetching higher prices. It is common for this data to be used by school groups too for practical hands-on learning and problem-solving activities.

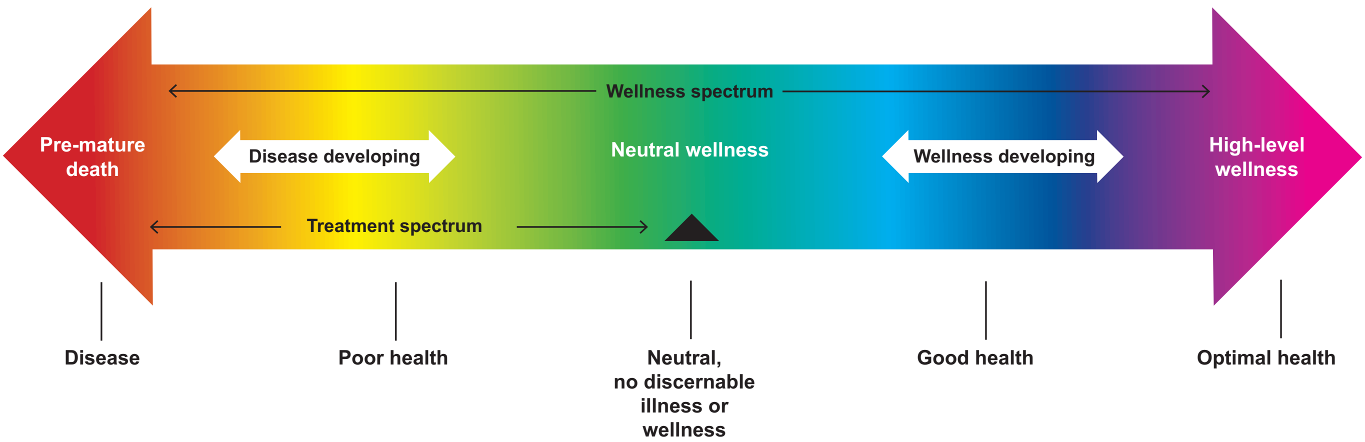


Figure 28: Society has undertaken a paradigm shift, moving the focus from treatment to wellness promotion

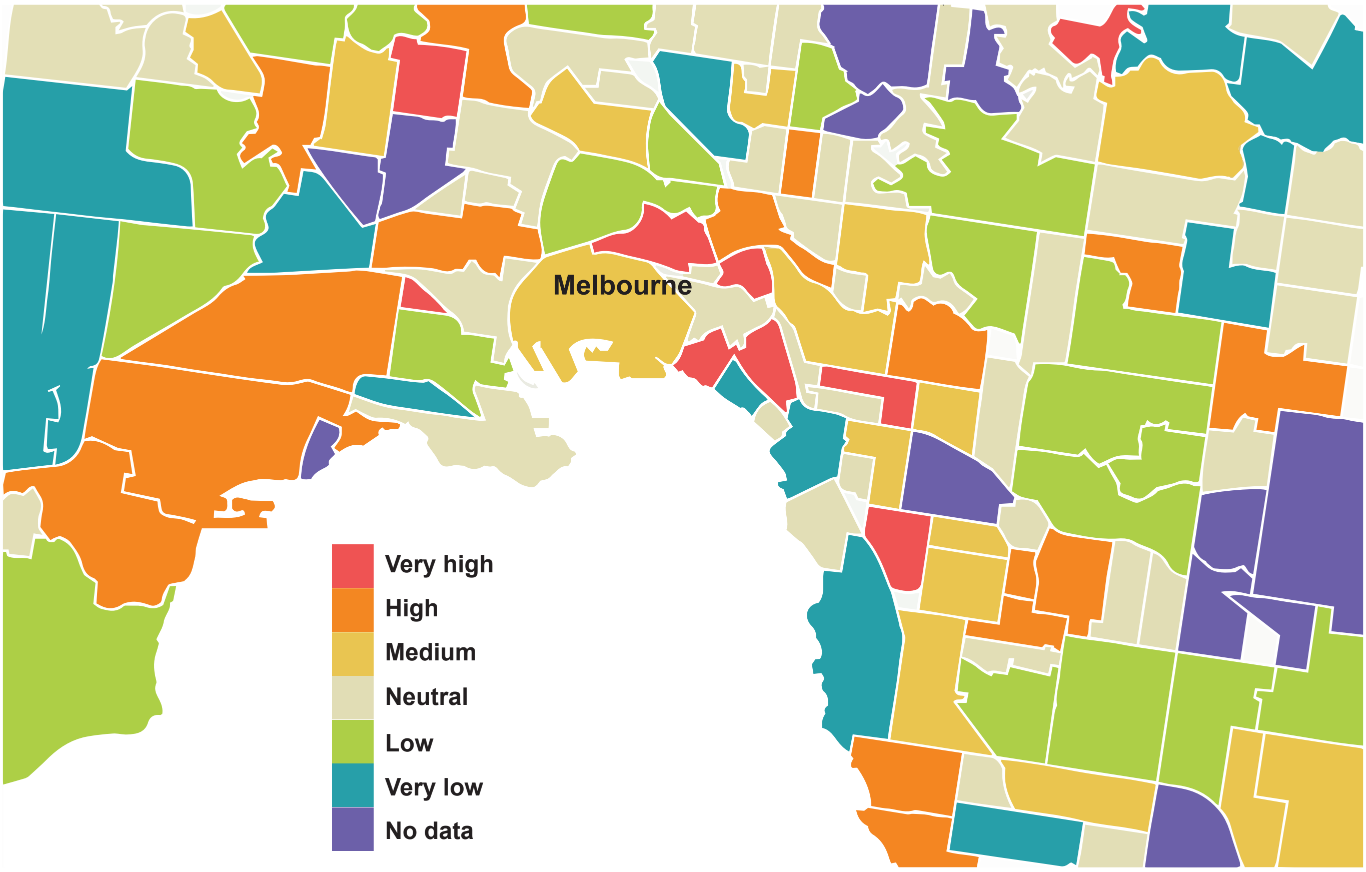


Figure 29: AMR surveillance and sensing data feeds into publicly available dashboards that are used for a variety of purposes, from education to informing 'wellness' indicators and property prices

The intensive meat production practices of the past have almost disappeared due to decreased demand, with primary producers transitioning to sustainable practices focused on lower-quantity, higher-quality, higher-wellbeing produce. Farmers also derive income from the government by participating in bioremediation activities and engaging in alternative energy production. Where meat production on farms still occurs, widespread vaccination programs have resulted in most pathogens being eradicated, so infection is rare. Ingestible biosensors that track animal health and wellness are commonplace. These biosensors enable early detection of unhealthy balances of microbes and a 'next best action' to prevent infection spread in an individual or herd. Monitoring of animal health and wellbeing extends across the entire lifecycle of the animal, including times they are in transit, to ensure wellbeing is paramount and guarded.

The AMR-preventing, wellness-focused technologies we use on our farms, in our homes, and in our clinical settings are now ubiquitous, applied in the places they are needed ranging from our schools and offices to our communal infrastructure and public transport. Through better detection and prevention, we are less likely to need to treat illnesses and infections. And when we do need to treat, it is tailored, data-driven, and only as long as it is needed. Consumers understand what their choices mean for them, their communities, and overall well-being.

5.2.1 Sounds far-fetched... but is it?

While elements of the above may seem like science fiction, a lot of the technologies that would be needed to make it a reality are already here, in some form or other. Some examples include:

- Consumer technology products such as Apple Health now have the functionality to scan your prescription medications, reminding you when you need to take them and pooling this data with other biometric and health information (Wetsman, 2022).
- Genomic analysis and personalised eating plans are now available in Australia from a range of companies such as myDNA and Vital Health (myDNA, 2022; Vital Health, 2022).
- In America, the Aquaculture Stewardship Council is using new technology to enable consumers to track the seafood they are looking to buy back to the farm of origin with >95% accuracy (Nelson, 2021).
- After the Japanese Fukushima nuclear disaster in 2011, some citizens took to supermarkets with their own personal detection devices to assess radiation levels in food. They also took environmental readings and fed them into local open-source platforms to crowdsource information on radiation levels in their community and environment (Reiher, 2016).
- Lab-based meats are making their way from concept to high-end cuisine as celebrity chef Neil Perry serves a lab-cultured meat menu with products created by Sydney start-up Vow (Palmer-Derrien, 2020).
- Companies such as Mother Dirt are now creating ranges of probiotic-focused substitutes for toiletries such as deodorant, skincare, and haircare that focus on increasing the populations of wellness-promoting microbes (Mother Dirt, 2022).
- Ingestible biosensors such as MyTMed have been developed to monitor the medications taken via a 'digital pill' that enables two-way data transmission using cloud technology. Data is available to the individual and their clinician (Chai et al., 2016).
- All-natural products, such as those from Australian-based MicroSafe, are now approved for use that can rapidly disinfect and sanitise a range of microbes as quickly as – or faster than – conventional products and techniques (MicroSafe, 2022).
- Smart in-home air and surface sterilisation technologies such as those from Australian-based Steribright and PuriflOH coming to market to enable autonomous cleaning in our households (PuriflOH, 2022; Steribright, 2022).
- Smart toothbrushes such as those from Philips are now available that automatically select the optimal brushing mode and intensity, link up to your smartphone to track and guide your brushing practices and have UV sterilisation charging compartments (Philips, 2022).
- Sensing and surveillance technologies with high levels of sensitivity are currently in use in areas of high importance for biosecurity purposes, such as the BioFlash system by Smiths Detection, which can identify different variants of COVID-19 present in airports (Smiths Detection, 2021).
- German policy has seen a diversification in income streams for primary producers by providing farmers with financial incentives to process their animal manure and convert it into biogas (Thrän et al., 2020)
- The concept of toilets that detect and neutralise antibiotics may not be too far off, as proof-of-concept products emerge from the iGEM (international Genetically Engineered Machine) competition to tackle antibiotics that make their way from our bathrooms into our waterways (ASTWS-China, 2019).
- 'Virtual ward' models of care that enabled patients to stay at home and receive monitoring and treatment during the COVID-19 pandemic have been shown to be safe, effective, and support with reducing further community and clinical disease transmission (Ferry et al., 2021).
- Drone technologies have been earmarked for a range of purposes, from patient sample logistics and delivery, monitoring and surveillance, and have even been used to examine the microbiome of whale breath (Apprill et al., 2017; Poljak & Šterbenc, 2020).

While these technologies may be at our fingertips, they are still small-scale and fragmented, and will require a coordinated, cohesive strategy to bring desired elements of this scenario into reality.

Part VI
Conclusion

The findings of this report have brought together expert opinions from extensive consultations and desktop research to identify and explore Australia's key challenges that need to be addressed if the nation is to improve how AMR is prevented and managed. Key solutions and their enablers have been identified to provide a pathway to more positive health and economic outcomes in Australia, and beyond, as introduced in the project framework (Figure 6, page 60).

Australia's readiness to adopt, adapt or further develop the potential solutions outlined was assessed across the range of axes in Table 2 (page 61), providing a snapshot of where the nation is ready to embrace these solutions, and where additional work is required. Along with the challenges presented by the COVID-19 pandemic has come an awareness of the impact of communicable diseases, increases in vaccination infrastructure and POC diagnostic capability, and an increased understanding of the importance of public health surveillance. This leaves Australia well positioned to be able to leverage these lessons and to apply them to the area of AMR.

Research and stakeholder consultations revealed a consistent and common theme: Australia has a lot of technology at its fingertips to prevent, detect, mitigate, and manage AMR, but the nation needs to be better at helping solutions through the research translation and commercialisation pipeline. This is critical to ensuring they arrive where they are needed most. There is also a need for Australia to continue to develop its ability to solve these challenges from a One Health perspective, with central leadership and coordination being called out as a key requirement for successful national AMR management. Moving the emphasis from a 'treatment focus' to a 'prevention focus' was welcomed by respondents, and there was agreement that Australia should be embracing emerging technologies and design principles that reduce AMR prevalence, particularly in high-risk settings.

Challenges

Lack of trusted and complete multi-sectoral data to inform decision-making and drive behavioural change to mitigate the impact of AMR

Climate change accelerating the emergence and spread of AMR across sectors

Lack of new technologies and treatments for prevention, detection, diagnosis, and treatment of AMR coming to market

Lack of awareness, understanding, accountability, and responsibility to improve AMR outcomes

Enablers

Data

- Interoperability
- Common data model
- Artificial Intelligence and Machine Learning

Standardisation

- Technology
- Data
- Regulation

Commercialisation

- Infrastructure
- Translation
- Funding

Implementation

- End-to-end planning
- Change management
- Continual improvement

Education

- Behaviour change
- Citizen science
- Equity

Potential solutions

Integrated surveillance and sensing systems

Integrated surveillance and sensing technologies and environmental sensors to monitor AMR across sectors

Point-of-care diagnostics

Simple, affordable and action-oriented point-of-care diagnostics to enable timely diagnosis and treatment of infections

Vaccination technologies

A data-driven, risk-based approach to vaccine production, leveraging new and emerging vaccination technologies

Prevention through design

Designing our farms, hospitals, and other high-risk settings to prevent the spread and growth of AMR organisms by deployment of antimicrobial surfaces, air sterilisation technologies, and engineering solutions

Outcomes

Comprehensive data and action-oriented insights to respond to risks and improve health outcomes

Reduced incidence of AMR in environment, plants, humans, animals

More solutions to manage communicable diseases – particularly AMR – in the market

Educated, empowered, enabled and aligned citizens and sectors

Figure 6: Project framework highlighting potential solutions and enabling technologies to mitigate and manage AMR

Table 2: Readiness indicator scale and readiness assessment

	Infrastructure readiness	Skills availability	Social and ethical readiness	Economic and commercial readiness	Policy and regulatory readiness
Integrated sensing and surveillance systems	◔	◑	◑	◔	◔
Point-of-care diagnostics	◑	◕	◕	◑	◑
Vaccination technologies	◑	◑	◕	◑	◕
Preventative design: High-risk settings	◔	◕	◑	◔	◔

KEY

Not ready		More work required		Ready
○	◔	◑	◕	●

6.1 Themes

In addition to the recommendations presented in the project framework (Figure 1), four key themes emerged throughout the project.

6.1.1 Build on what is working

There are a range of solutions that are working in certain sectors domestically and abroad that can be expanded to enable better AMR management, or that can act as launch pads for solutions. Australia should seek to celebrate its successes to date, and to focus on progress over perfection as the nation continues to take prioritised and sustainable steps towards an ideal future state.

6.1.2 Embrace collaborative, transdisciplinary problem solving

Large, interconnected problems can necessitate different ways of thinking and problem solving. Collaborative, transdisciplinary approaches to problem solving such as One Health, convergence science, and systems-thinking methodologies will be key to fast-tracking innovation by sharing solutions across sectors, sparking ideas across groups, and understanding the impacts that interventions will have on the broader system.

6.1.3 Place equity at the heart of strategies

AMR is a global issue, and does not respect geographic, sector, or industry boundaries. It is critical that holistic approach to mitigating and managing AMR is taken, ensuring solutions are developed and delivered equitably across sectors, citizens, and with a view to international coordination and alignment.

6.1.4 Remember the human element

Bringing together multiple stakeholder groups with competing priorities, drivers and needs is a big task. Activities such as education, awareness raising, and shifting the emphasis from a treatment-focus to a prevention-focus can require a large degree of trust, change management and time. The sociotechnical elements of solution deployment can't be overlooked and must be factored into planning and implementation of solutions .

6.2 Recommendations

Australia has the potential to be a strong global contributor in technologies to combat AMR, and should aspire to be a world-leader in its management. Through integrated surveillance and sensing systems, and the establishment of One Health data standards and data sharing models to enable the generation of comprehensive data and action-oriented insights to respond to risks and improve health outcomes. These data can be used to develop evidence-informed, risk-based strategies to produce new vaccines, leveraging Australia's burgeoning vaccination infrastructure to reduce the incidence of AMR in humans and animals.

Vaccination strategies, coupled with embracing new technologies for minimising pathogen and resistance spread through prevention-focused design principles, will help Australia reduce the incidence of AMR in humans, plants, animals, and the environment. By removing the barriers to AMR solution commercialisation and implementation, Australia will be supported to ensure the nation has more solutions to manage communicable diseases – and the continued rise of AMR – in the market. By increasing the development and use of point-of-care diagnostics, coupled with education on the issues and risks associated with AMR, the timely diagnosis and treatment of infections can be increased while creating educated, empowered and aligned citizens and sectors.

To help Australia achieve these critical outcomes, two high-level recommendations have been developed with the report's key themes in mind. Along with the supporting research and policy priorities presented, these recommendations will propel Australia forward in improving how the nation prevents, mitigates, and manages the impacts of AMR. The recommendations are intended as guidelines for government, funding agencies, sectors that comprise a One health approach, and the research community to meet the needs and expectations of diverse Australian communities, and to build practical research agendas to address questions about how to tackle the rising challenge of AMR.

Recommendation 1: Establish centralised coordination and leadership for AMR management to align and coordinate domestic and international activities across human health, animal health and environmental health sectors.

Establish national, central, and credible coordination and leadership to provide alignment, governance, and oversight across Federal, State and Territory governments and sectors that comprise a One Health approach. This will be key to resolving the lack of awareness, understanding, accountability, and responsibility to improve AMR outcomes, and to tackle the impacts of climate change that can accelerate the emergence and spread of AMR across sectors. This leadership should:

Recommendation 1.1. Provide national, multi-sectoral representation and coordination.

Lead coordination across sectors that comprise a One Health approach, and State and Territory governments, providing equitable leadership, strategic prioritisation, and central oversight on AMR in Australia.

Recommendation 1.2. Drive the development of an enabling policy, regulatory, financial, and commercial landscape.

Work across sectors to understand the challenges, drivers, and barriers to progress. Drive progress through advocacy, influence, and strategic partnerships.

Recommendation 1.3. Ensure long term AMR strategy is accompanied robust implementation plans, and reporting and review.

AMR is a complex, dynamic, and evolving issue. Australia's strategy and planning practices should be accompanied by clear, robust, and responsive implementation planning. Progress against the implementation plan should be measured, reviewed, and used to inform ongoing activities.

Recommendation 1.4. Integrate AMR management into urban and environmental planning practices

Lead the integration of AMR management into Australia's future city and town planning practices. Leadership should work closely with State and Territory governments to inform and influence current and emerging strategies for 'smart', climate-resilient, and water-sensitive cities, and should inform building regulations.

Recommendation 1.5. Lead on AMR messaging, awareness, and education.

Empower stakeholders from sectors, politics, and the public by leading the development of appropriately tailored education and awareness strategies that rely on clear, consistent, and compelling messaging.

Recommendation 2: Streamline and optimise the commercialisation process to support Australian AMR solutions entering the market.

This could be achieved by the Australian and State Governments, in collaboration with the private sector and industry associations, providing pathways to market and support for new AMR prevention and mitigation technologies. This will be critical to deploying new technologies and treatments for the prevention, detection, diagnosis, and treatment of AMR so they can benefit public health and the national economy. This includes:

Recommendation 2.1. Establish central AMR oversight to track and manage AMR funding and solutions.

Establish central visibility of the process to bring AMR solutions to market which allows for product tracking and management, available funding at each stage, and to support with the identification and proactive management of process bottlenecks.

Recommendation 2.2. Create a streamlined process for expediting AMR solutions.

Leverage lessons from COVID-19 solutions and orphan drug designation programs to create fast-track processes to bring priority AMR solutions to market.

Recommendation 2.3. Advocate for international alignment, collaboration, and harmonisation.

Continue to prioritise regulatory harmonisation across Australian and international regulators. This will help reduce the time spent on duplicative or complex processes and will unlock global markets.

Recommendation 2.4. Support regulator capacity and capability to bring AMR solutions to market.

Ensure regulator capacity and capability is appropriately resourced to ensure they do not become a process bottleneck, and that they are connected with AMR solutions consumer and producer needs to continue to regulate safe and effective products in the market in a timely manner.

Recommendation 2.5. Leverage strategic partnering approaches across sectors as a practicable delivery solution.

Continue to invest in strategic, transparent, and mutually beneficial strategic partnerships between sectors, and the public and private domains, to prioritise Australian solution development and delivery.

6.3 Policy priorities

The high-level recommendations outlined are key to efficient and effective management of AMR, and to supporting a viable marketplace for Australian innovations and economic prosperity. These high-level recommendations are supported by the following policy priorities, which emerged through research and consultation as being critical to achieve sustainable, systemic, and equitable impact against AMR.

6.3.1 Establish robust One Health data policies and standards

A coordinated and robust data policy needs to be implemented that incorporates FAIR and CARE principles. There needs to be a shift in focus away from data linkage as a solution, and towards data standardisation and common data models, in the healthcare system and beyond. Establishment of integrated sensing and surveillance systems should be prioritised by leveraging technology as much as possible to automate collection, integration, analysis, and interpretation into actionable insights.

6.3.2 Establish fit-for-purpose, sustainable funding models and financial incentives

Long-term sustainable solutions need long-term sustainable funding. Fit-for-purpose funding models that are designed with One Health collaboration and outcomes in mind need to be developed. Funding models should be designed with a range of push and pull incentives to stimulate AMR R&D in Australia. Funding solutions for containment of antimicrobial resistance is a high-yield development investment with estimated returns far outweighing costs (World Bank, 2017).

6.3.3 Treat priority AMR solutions as a public good

AMR solutions need to be viewed as a public good which would increase accessibility, impact, economies of scale, and equity. Support for technologies that reduce spread of AMR needs to be prioritised, particularly to enable these to make it into households and community settings. This will assist with reducing transmission, driving public awareness of AMR, and will provide tools to combat AMR that empower citizens.

6.4 Research priorities

Australia has a strong research sector, with significant expertise, experience, and capacity to investigate and develop best practice solutions to Australia's biggest challenges. The following research priorities were identified during consultations as important for successful mitigation and management of AMR.

6.4.1 Fundamental AMR research

A more complete picture of AMR, how it moves through the environment, and its burden on society is needed. Increasing investment for AMR research is critical to better understanding, mitigation, and management. While fundamental research does not pursue immediate commercial objectives, findings of fundamental studies are key to understanding the mechanisms of AMR, future impacts of the issue and design interventions, and pave the way for innovations and practical solutions. There needs to be more support and push for research into understanding the fundamentals of AMR from a One Health lens.

6.4.2 Point-of-care diagnostics

Research and development into priority POC diagnostics across human health, animal health and environmental health sectors is essential to create the required public health tools needed to detect and diagnose AMR, particularly in humans and animals. The current R&D pipeline for new AMR-related health technologies must also be strengthened to address priority diseases at risk of resistance, particularly those in the national interest. Tests developed should be developed in alignment with best practice (i.e., REASSURED criteria), and should focus on fitness-for-purpose, be fast and affordable, and results should be reliable and give the minimal information required to take the 'next best action'.

6.4.3 Vaccines

Research and development into vaccines for priority organisms – particularly resistance strains of national relevance and prevalence – needs to take place. This should leverage the range of current, and emerging, vaccination infrastructure available in Australia. Australia's R&D agenda should be supported by evidence-based decision making. Vaccination programs should take the needs, priorities and risks associated with the individual/sector into account to ensure vaccines make it where they are needed the most to minimise the incidence of ARG transmission, zoonosis, and infection.

Australia is at a critical juncture in the approach to mitigation and management of the devastating impacts of AMR, and how the country works with international counterparts to tackle this global crisis. Strong and decisive action is required if Australia is to slow the rate of AMR and realise the healthy, sustainable, equitable, technology-powered future that is well within the nation's reach.

Shortened forms

Further definitions and details can be found in the Glossary.

SHORTENED FORM	EXPANDED FORM
AAHMS	Australian Academy of Health and Medical Sciences
AAMRNet	Australian Antimicrobial Resistance Network
AGAR	Australian Group on Antimicrobial Resistance
AI	Artificial Intelligence
AM	Member of the Order of Australia
AMR	Antimicrobial Resistance
AMS	Antimicrobial Stewardship
AO	Officer of the Order of Australia
APAS	Australian Passive AMR Surveillance
APVMA	Australian Pesticides and Veterinary Medicine Authority
ARC	Australian Research Council
ARG	Antibiotic Resistance Genes
AST	Antibiotic Susceptibility Testing
ATC	Anatomical Therapeutic Chemical
ATSE	Australian Academy of Technological Sciences and Engineering
AURA	Antimicrobial Use and Resistance in Australia
BF	Becton, Dickinson and Company
CARAlert	Critical Antimicrobial Resistance Alert
CARB-X	Combating Antibiotic Resistant Bacteria Biopharmaceutical Accelerator
CARE	Collective Benefit, Authority to control, Responsibility and Ethics
CDC	Centers for Disease Control and Prevention
CLSI	Clinical and Laboratory Standards Institute
COVID-19	The 2019 novel coronavirus
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DNA	Deoxyribonucleic acid
EPA	Environmental Protection Authority
EU	European Union
EUCAST	European Committee for Antimicrobial Susceptibility Testing
FAHMS	Fellow of the Australian Academy of Health and Medical Sciences
FAO	Food and Agriculture Organization
FARE	Finable, Accessible, Interoperable and Reusable
FHIR	Fast Healthcare Interoperability Resources
FTSE	Fellow of the Australian Academy of Technological Sciences and Engineering
GLASS	World Health Organization's Global Antimicrobial Resistance Surveillance System
GP	General Practitioner

SHORTENED FORM	EXPANDED FORM
HISA	Health Informatics Society of Australia
HIV/AIDS	Human Immunodeficiency Virus/Acquired Immunodeficiency Syndrome
IACG	UN Interagency Coordination Group
iGEM	International Genetically Engineered Machine
JPIAMR	Joint Programming Initiative on AMR
ML	Machine Learning
MRFF	Medical Research Future Fund
MSRA	Methicillin-resistant *Staphylococcus aureus*
mRNA	Messenger ribonucleic acid
NAPS	National Antimicrobial Prescribing Survey
NAUSP	National Antimicrobial Utilisation Surveillance Program
NHMRC	National Health and Medical Research Council
NNDSS	National Notifiable Disease Surveillance System
NNN	National Neisseria Network
OIE	Office International des Epizooties
PBS	Pharmaceutical Benefits Scheme
PCR	Polymerase Chain Reaction
POC	Point-of-care
PSM	Public Service Medal
R&D	Research and Development
RAT	Rapid Antigen Test
REASSURED	Real-time connectivity, Ease of specimen collection, Affordable, Specific, Sensitive, User-friendly, Rapid, Equipment-free and Deliverable.
RNA	Ribonucleic acid
SNOMED	Systematised Nomenclature of Medicine
SNP	Sullivan and Nicolaides Pathology
STI	Sexually Transmitted Infection
SDGs	Sustainable Development Goals
TATFAR	Transatlantic Taskforce on Antimicrobial Resistance
TGA	Therapeutic Goods Administration
VOCJ	International Cooperation on Harmonisation of Technical Requirements for Registration of Veterinary Medical Products
WHO	World Health Organization
UN	United Nations
USA	United States of America
US$	United States Dollar
UTI	Urinary Tract Infection

Glossary

TERM	DESCRIPTION
Antibiotic Resistance Genes	Mobile genetic elements (bits of DNA) that can pass between microorganisms via horizontal gene transfer, even from dead to living cell. These bits of DNA can contain information that helps microorganisms be resistant to antibiotics.
Antimicrobial Resistance	Antimicrobial Resistance (AMR) occurs when microbes including bacteria, viruses, fungi and parasites, acquire resistance to the drugs designed to kill them. This growing resistance is largely due to our overuse and misuse of antimicrobials, such as antibiotics, in human and animal medicine (CSIRO, 2022)).
Autogenous vaccines	Autogenous vaccines, also referred to as 'custom vaccines', are generated by isolating a microbe believed to be causing an illness from an infected animal and generating a vaccine against that particular pathogen. It is more commonly used veterinary practices.
Biosecurity	Biosecurity is a critical part of the Australian government's efforts to prevent, respond to and recover from pests and diseases that threaten the economy (DAWE, 2021).
Biomimicry	Biomimicry is learning from and then emulating nature's forms, processes, and ecosystems to create more sustainable designs Click or tap here to enter text.(Biomimicry 3.8, 2022).
Convergence science	A method of transdisciplinary problem solving where multiple disciplines (i.e. life sciences, physical sciences and engineering) come together with their unique perspectives to solve complex challenges.
Digital twin	A virtual replica of a physical system that can be used to understand and model scenarios to anticipate outcomes.
Gamification	Gamification leverages the principles of game design to engage, motivate and reward individuals, and this strategy has been used to help drive standardised decision making, data input and in-situ education and training.
Herd immunity	Herd immunity occurs when a significant portion of a population becomes immune to an infectious disease and the risk of spread from person to person decreases due to decreased incidence and transmission.
Interoperability	Interoperability is the ability of different information systems, devices and applications to access, exchange, integrate and cooperatively use data in a coordinated manner, within and across organisational, regional and national boundaries, to provide timely and seamless portability of information and optimise the health of individuals and populations globally (HIMSS, 2022).
Microbiome	A community of microorganisms that can be found living together in a particular habitat, such as an area of the environment or in humans and other animals.
Nudge theory	Nudge theory focuses on carefully designing the environment around decision-points to optimise for preferred outcomes.
One Health	One Health is a collaborative, multisectoral, and transdisciplinary approach that works at local, regional, national, and global levels. The approach has the goal of achieving optimal health outcomes by recognising the interconnection between people, animals, plants, and their shared environment.
Systems thinking	A holistic approach to problem-solving that explores the ways different part of a system inter-relate and overall dynamics in solution design.
Zoonosis	A zoonosis is an infectious disease that has jumped from a non-human animal to humans. Zoonotic pathogens may be bacterial, viral or parasitic, or may involve unconventional agents and can spread to humans through direct contact or through food, water or the environment. They represent a major public health problem around the world due to our close relationship with animals in agriculture, as companions and in the natural environment (World Health Organisation, 2020)

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Contact us
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amrmission@csiro.au
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