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Public Perceptions of Synthetic Biology Solutions for Environmental Problems

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This study explored public attitudes towards developing synthetic biology solutions for environmental problems: 1) invasive pest management, 2) endangered species conservation, 3) bioremediation of waterways, and 4) coral reef restoration. A sample of 4,593 Australians were surveyed online. Results showed that public support for a synthetic biology solution was highest for the bioremediation of waterways using an engineered pseudo-organism. Genetically engineering endangered species, invasive pests and coral received comparatively less support than bioremediation, however, support was still moderate to high for these other applications. More proximal behavioural intentions were also rated moderately to more favourably. Our findings underscore the importance of engaging with those who are likely to be impacted by the synthetic biology solution if it were introduced. At this local level, we can then obtain a better understanding of how people are likely to respond to the synthetic biology solution, which can inform how the solution is developed, and when, where, and how it might be implemented in the future.

Keywords: public perceptions, technology acceptance, public attitudes, environmental conservation, synthetic biology

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INTRODUCTION

Synthetic biology has the potential to address a range of critical problems facing society, including reducing the spread of pests and disease, enhancing food production, and restoring biodiversity in the natural environment. While expanding rapidly as a distinct field of science, it is still a nascent industry with a predicted long-term timeframe of up to and over 10 years for many of its applications (Fraser and Gray, 2020). Given its relatively new and emerging status, regulators and other governing bodies in Australia are still in the process of conducting various consultations and review processes regarding how synthetic biology techniques and technologies should be appropriately regulated (The Third Review of the National Gene Technology Scheme, 2018). Such regulatory systems are primarily set up to anticipate risks (rather than benefits), and to provide a framework with accountability for responsible decision-making. In Australia, it is considered that the existing risk framework and regulatory regime (e.g., Australia's Gene Technology Scheme) are adequate for current applications of synthetic biology (Gray et al., 2018; The Third Review of the National Gene Technology Scheme. 2018). Similarly, in the international area, existing risk assessment frameworks are considered sufficient for near-term applications of synthetic biology (Scott et al., 2015). Yet, regulatory agencies in Australia are well aware of the need to innovate and are proactively identifying potential areas of legislation change to keep pace with the developments in the scientific field (Department of Health, 2018; The Third Review of the National Gene Technology Scheme, 2018). It is envisaged that future changes to the legislation may enable a more tailored, flexible, responsive, and efficient approach to assessing actual risk, enabling more streamlined assessments and the potential for commercialisation (Australian Academy of Science, 2018). For example, all Australian Governments have agreed to pursue an Action Plan aimed at updating the National Gene Technology Scheme over the 2018–2023 period, and one of the listed priorities is to design a framework to regulate the release of gene drive organisms (one of many synthetic biology applications).

Concomitant with the development of appropriate regulatory frameworks is the need for researchers to engage in socially responsible research practice when developing synthetic biology solution. A socially responsible researcher would carefully consider societal (and other various publics) concerns, perspectives, and likely impacts, when making decisions about the technology (including even whether the technology should be developed at all). Inclusive deliberation and ongoing engagement with affected or interested publics is considered part of socially responsible research practice (Owen et al., 2013; Stilgoe et al., 2013; Owen and Pansera, 2019), something which the synthetic biology community has recognised as an essential part of developing the industry in Australia and are actively investing in (Gray et al., 2018; Carter and Mankad, 2021). In concert, dedicated social science studies can be designed to shape these conversations and address important questions about human behaviour and decision-making in this unique context of future benefits that may be spatially distant, high uncertainty and potential risk. For example, social science studies can incorporate targeted discussion points on key issues (e.g., risk and risk management, regulation, benefit sharing, uncertainty and unintended consequences, social norms) and utilise experimental methods, to understand the key drivers of decision-making, and public acceptability. Indeed, such work broadens the analysis from one that is purely biophysical, yielding scientific results about technical and ecological efficacy, to one that is systems-focussed, essentially addressing broader social, ethical, and moral dilemmas, concerns and issues associated with whether and how the solution should be deployed. The desire for triple bottom line impacts and the combination of both biophysical and public engagement research means that we will be able to not only answer the question of "Can we do it?" but also the questions of "Why should we do it?" and "How should we do it?". The current study therefore sought to contribute to, and start, this public engagement exercise by first exploring what people think about a range of synthetic biology solutions for conservation purposes and whether they would be supportive of further development of these technologies.

From very first principles, we can already gather from prior research that awareness and knowledge of synthetic biology is relatively low among the general population (Gaskell et al., 2010; Hart Research Associates, 2013; Pauwels, 2013; Ancillotti et al., 2016; Akin et al., 2017; Cormick and Mercer, 2017). A survey of the Australian public also has revealed that awareness and knowledge of synthetic biology is substantially lower than that observed for other biotechnologies (Cormick and Mercer, 2017). For instance, in terms of knowing enough to explain it to a friend, the technologies can be prioritised as follows: cloning of animals (23% know enough to explain it to a friend), genetic modification or GMOs (22%), gene editing (13%), biotechnology (12%) and synthetic biology (7%). And in terms of never having heard of the technology, the technologies can be prioritised as follows: synthetic biology (51% never heard of it), gene editing (32%), biotechnology (27%), genetic modification or GMOs (17%), cloning of animals (10%). Thus, awareness and knowledge of synthetic biology lags behind that of other biotechnologies.

The few public opinion studies conducted, predominantly in Europe and the U.S., have also revealed that it is not the details of the synthetic biology technology that seem to matter to people, but it is how synthetic biology is used or applied that really matters. Support is higher for synthetic biology applications that have clear practical utility, addressing important problems such as communicable diseases, energy shortages and environmental pollution (Bhattachary et al., 2010; Gaskell et al., 2010; Hart Research Associates, 2013; Pauwels, 2013; Ancillotti et al., 2016). In contrast, people tend to react negatively to applications that they perceive serve a non-essential purpose, such as accelerating the growth of cows and pigs, improving memory and learning capacity, or engineering aquarium fish to glow (Bhattachary et al., 2010; Gaskell et al., 2010; Hart Research Associates, 2013; Pauwels, 2013; Pew Research Center, 2018). Findings from these public opinion studies suggest that people seem to prioritise and value health and environmental applications of synthetic biology.

In the current study, we focussed on what the public thought of using synthetic biology technologies to address problems in the environmental management or conservation domain. While there exists a wide range of environmental problems facing the world, we collaborated with synthetic biologists in our research institution to develop four case study problems that they anticipated could be addressed by the application of synthetic biology solutions in the future, and that was a focus of their current research. These problems included water pollution, coral reef loss, invasive animal pest impacts, and endangered species extinction. These problems are not only recognised as significant problems facing Australia, but also the world. **Table 1** provides a list of the synthetic biology solutions intended to address each of these problems and a review article discussing how genetic and other biotechnological solutions may address such environmental conservation problems.

Our research builds on existing public perceptions research on synthetic biology in several ways. First, it compared public responses across several synthetic biology applications, not just one—and it did so in a specific rather than general manner. This comparison will therefore reveal which environmental applications of synthetic biology may be deemed publicly acceptable. Second, in addition to presenting a definition of synthetic biology, we presented more detailed information about the technology's application, the problem it seeks to address and current alternative solutions. This was done *via* a *Technology Storyboard*, a PowerPoint presentation that provided text-based explanations, supported with visual diagrams. Given that the average person may not be aware of synthetic biology, the

TABLE 1 | The synthetic biology technologies surveyed.

Synthetic Biology technology	Environmental problem	Relevant research reviews
Gene editing endangered species of animals to increase genetic diversity (*n* = 1,148)	Endangered species are under threat of extinction	Segelbacher et al. (2021)
Gene editing invasive animal pest species to bias sex determination (*n* = 1,149)	Invasive animal pests are a threat to biodiversity and agricultural productivity	Segelbacher et al. (2021)
Genetically engineering coral to enhance thermal tolerance (*n* = 1,148)	Rising sea-surface temperatures causing coral bleaching and coral loss	Anthony et al. (2020)
Genetically engineering a pseudo-organism (a tissue-engineered self-limiting organism) to break down pollution in waterways (*n* = 1,148)	Pollution in waterways	Rylott and Bruce, (2020)

provision of information about the environmental problems and current solutions was considered essential to helping people make sense of the broader context. Third, we probed people's "willingness to interact with," or how "bothered" they would be if, the technology was introduced in their local area. While still hypothetical, these more "proximal" behavioural intentions may provide a closer representation of how people might respond if the synthetic biology solution is introduced into society. Fourth and finally, because scientists can use different techniques to modify genes, we also examined people's support for research that uses the following techniques: 1) adds a gene from the same species of organism, 2) adds a gene from a different species of organism (i.e., transgenics), 3) removes a gene from an organism, and 4) changes an existing gene within an organism. The answers to these questions may then inform synthetic biologists on which technique they should or could opt for if they indeed have a choice.

MATERIALS AND METHODS

Participants

4,593 members of the general public participated in this study by completing an online survey. Imposed quotas ensured that the sample was representative of the Australian population on age, sex, and state of residence. There were 2,119 males (46.1%) and 2,465 females (53.7%) (9 selected "other"). A range of ages were represented (18–24 years: 12.5%; 25–34 years: 15.6%; 35–44 years: 17.4%; 45–54 years: 17.6%; 55–64 years: 16.0%; 65 years and over: 21.0%). A range of educational levels were represented (Year 10 or below: 9.4%; Year 12: 14.5%; Certificate: 14.7%; Diploma/Advanced Diploma: 14.5%; Bachelor degree: 26.2%; Graduate Diploma/Graduate Certificate: 6.4%; Postgraduate degree: 14.2%). Most were employed (61.4%) or looking for work (5.0%) with the remainder not in the labour force (24.3%) or selecting "other" (9.3%).

Procedure

Participants were recruited *via* an external third-party research agency with each participant receiving a token incentive for participation. The survey was conducted across a 3-week period from November to December 2018. To participate in the survey, respondents were required to be an Australian resident and over the age of 18 years.

A standard introductory email was sent to potential participants, inviting them to take part in an online survey. Once participants clicked on the link to the survey, an information page was displayed explaining the general purpose of the study and inviting them to participate by completing a survey. Those that agreed to participate provided consent by ticking a checkbox and continuing with the survey. Demographic information (age, gender, postcode, state of residence) was collected at the commencement of the survey to monitor and achieve quotas.

At the start of the survey, participants were provided with the following definition of synthetic biology as is typical of survey-based research (e.g., Gaskell et al., 2010; Cormick & Mercer, 2017):

- Synthetic biology is a new field of research bringing together genetics, chemistry and engineering. It allows scientists to design and build new biological organisms, so that they may perform new functions.
- Synthetic biology can use DNA to create new characteristics, or remove certain functions, in plants, animals, and other organisms (e.g., bacteria, fungi, algae). Additionally, a pop-up box also provided the following definition of DNA (for those who hovered over the word "DNA"):
- DNA are molecules that carry genetic instructions used in development, general functioning and reproduction of all living things.

Participants were randomly assigned to receive information and questions about one environmental problem and the associated synthetic biology solution. Thus, after the general synthetic biology definition, participants were asked whether they had heard of "gene editing of animals," "genetically engineering coral" or "genetically engineering pseudo-organisms" depending on which survey they had been randomly assigned (0 = No, 1 = Yes). For those who had heard of it before, they were then asked, "How much would you say you know about it?" (1 = no knowledge, 2 = a little knowledge, 3 = some knowledge, 4 = a lot of knowledge, 5 = extensive knowledge).

Participants then received additional information—by way of a "technology storyboard" which was a PowerPoint-style presentation that people could view at their own pace—so that people would be more informed about the technology's

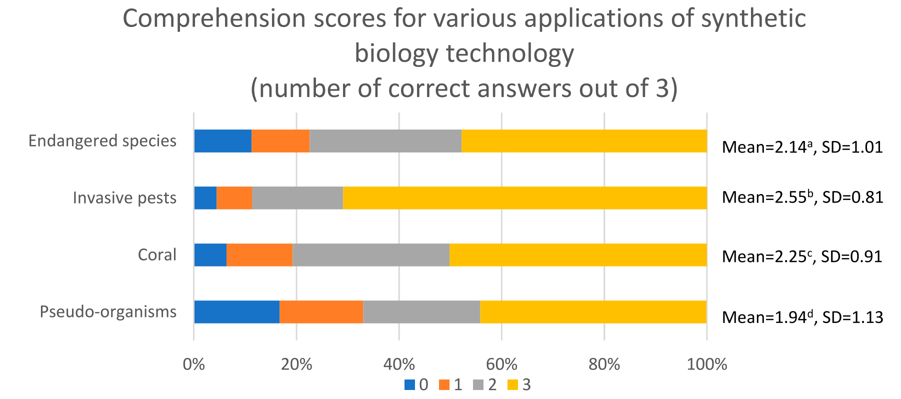

FIGURE 1 | Comprehension scores for the various applications of synthetic biology technology (based on the information supplied in the technology storyboards). Notes: Different superscripts (a, b, c, and d) denote statistically significant differences between the means.

application and the problem it sought to address. This included information about the problem, current methods for addressing the problem, and the potential benefits of introducing a synthetic biology solution. Pictures were also included to support the textual information. These technology storyboards were developed by the authors in collaboration with the synthetic biologists who are developing the technologies, as well as science communication specialists (to view the technology storyboards, see https://research.csiro.au/synthetic-biology-fsp/public-attitudes/).

After viewing the technology storyboard, participants were also asked several questions, designed to measure a range of psychological and social factors (e.g., attitudes, emotions, social norms) including behavioural intentions (e.g., support for development of the technology), comprehension, and general communication needs (e.g., information needs). Additional demographic information was requested at the end of the survey.

Comprehension of the information contained in the technology storyboard was assessed with 3 true- or false-style questions. For example, for invasive pests, the 2 true questions were: "Invasive pests include wild rabbits, feral cats and wild dogs (among others)" and "Gene editing could involve modifying genes so that animals only produce male offspring"; and the 1 false question was: "Gene editing of invasive pest species aims to increase the population of invasive pests". Two true questions and 1 false question were similarly designed to assess comprehension for the other technologies. Analysis of the comprehension scores revealed that, on average, participants correctly answered 2 out of the 3 true-false questions (see **Figure 1**).

In addition to our knowledge questions (previously described), the variables of interest for this paper included:

Support for development of the synthetic biology technology which was measured with a single question: "Overall, based on the information provided and your own general knowledge, to what extent would you support the development of this technology?" (1 = would not support to 5 = would strongly support).

Behavioural intentions associated with each synthetic biology technology was assessed by presenting participants with a question relevant to the application of the technology in the field.

- Coral: "To what extent would you be willing to visit parts of the Great Barrier Reef (GBR) where genetically engineered coral has been introduced?"
- Endangered species: "To what extent would it bother you if your local land management authority used this technology to help endangered species in your local area?"
- Invasive pests: "To what extent would it bother you if your wildlife conservation authority used this technology to manage invasive pests in your local area?"
- Pseudo-organisms: "To what extent would you be willing to swim in a waterway where this new technology had been used to remove pollution?"; "To what extent would you be willing to eat seafood caught from a waterway where this new technology had been used to remove pollution?"; and "To what extent would you be willing to drink from a waterway where this new technology had been used to remove pollution?".

Support for different gene modification techniques was measured in the final section of the survey, which was prefaced with the following lead-in sentence: "In this part of the survey, we'd like to ask you about your feelings towards different synthetic biology techniques in general". To measure support for different gene modification techniques we asked participants: "To what extent would you support research that. . .

- . . ..changes an existing gene within an organism?
- . . .removes a gene from an organism?
- . . .adds a gene from the same species of organism?
- . . .adds a gene from a different species of organism?

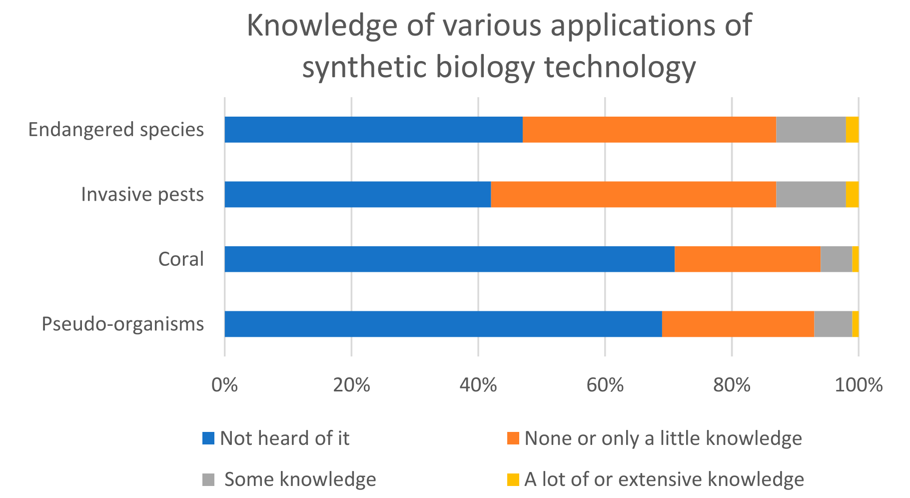

FIGURE 2 | Knowledge of various applications of synthetic biology technology.

Analytic Method

Survey data was imported into the statistical data analysis program, STATA/MP 17.0 (StataCorp, 2021). The data was reviewed for missing values, and all data manipulation and coding, and descriptive and inferential analysis was performed in STATA/MP 17.0.

Simple t-tests were conducted to compare means across the different technologies. In addition to assessing the statistical significance of effects by comparing the p-value to the conventional alpha (α) = 0.05 threshold, Cohen's d was calculated to determine the size of an effect. Cohen's d reflects the difference between the means in standard deviation units.

- Cohen's d = 0.2 (i.e., 0.2 of a standard deviation difference between the means) was considered a small effect
- Cohen's = 0.5 (i.e., 0.5 of a standard deviation difference between the means) was considered a moderate effect
- Cohen's d = 0.80 (i.e., 0.8 of a standard deviation difference between the means) or greater was considered a large effect.

RESULTS

Awareness/Knowledge

When provided a definition of synthetic biology, we found that in our sample of 4,593 Australians, 54% had "no knowledge," 29% had a "little knowledge," 14% held "some knowledge," 2% held "a lot of knowledge," and 0.5% held "extensive knowledge".

Similarly, when it came to each of the synthetic biology applications, awareness/knowledge was low (see **Figure 2**). Most had not heard of genetically engineered coral (71%) or pseudo-organisms (69%). A little less than half (47%) had not heard of gene editing of endangered species and 42% had not heard of gene editing of invasive pests. Across all applications, less than 20% reported some or extensive knowledge, with just 5% claiming a lot or extensive knowledge. Thus, the majority (>87%) were either entirely unaware, or aware but with only little knowledge.

Support for Research Using Different Synthetic Biology Genetic Techniques

Support depended on the genetic technique (see **Figure 3**); it was highest for adding a gene from the same species of organism (with 28% indicating support by scoring "4" or "5" and 27% indicating less or no support by scoring "1" or "2") and lowest for adding a gene from a different species (where 19% indicated support by scoring "4" or "5" and 41% indicated less or no support by scoring "1" or "2"). Interestingly, most people (ranging from 40% to 46%) tended to select the mid-point response for each technique. Although statistically significant differences were observed between different techniques, non-trivial effect sizes were only found between "adds a gene from different species of organism," and all other techniques: "change an existing gene within an organism" (Cohen's d = 0.38), "removes a gene from an organism" (Cohen's d = 0.32), and "adds a gene from space species of organism" (Cohen's d = 0.44).

Support for Development of Synthetic Biology Technologies

Individuals were asked the following question after viewing the technology storyboard: "To what extent would you be willing to support the development of this technology?" (**Figure 4**). Our results showed significant differences in support across the different applications, however, the effect size or proportion of variability in support explained by the different technologies was negligible (R^2/η^2 = 0.02, CI 0.01:0.03, F (3,4589) = 31.34, p = 0.000).

Pairwise comparisons (with Tukey's method to control familywise error rate at 0.05) revealed that people were more supportive of genetically engineered pseudo-organisms (65%) compared to genetically engineered coral (59%) (Tukey t =

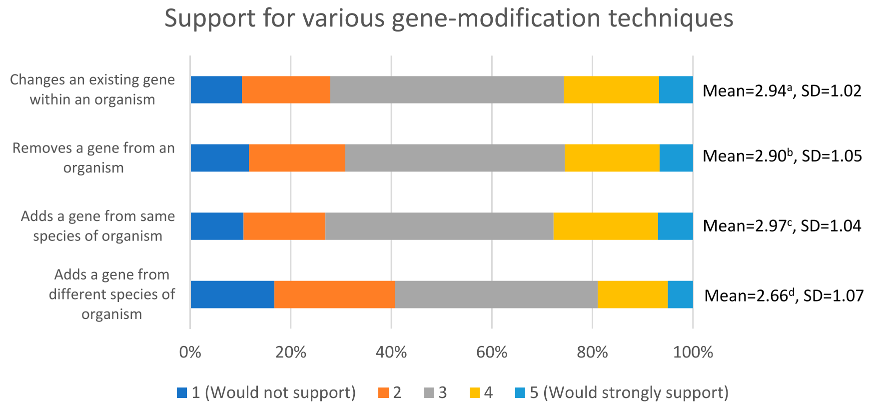

FIGURE 3 | Support for different gene-modification techniques. Notes: Different superscripts (a, b, c, and d) denote statistically significant differences between the means.

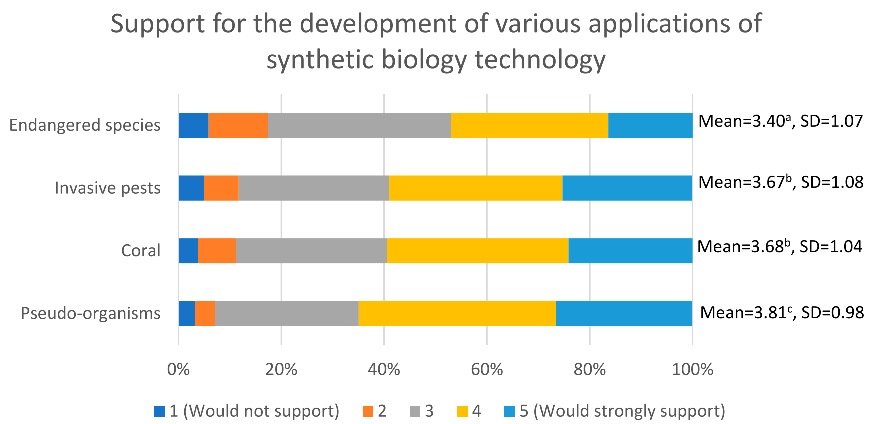

FIGURE 4 | Support for the development of various applications of synthetic biology technology. Notes: Different superscripts (a, b, c, and d) denote statistically significant differences between the means.

2.86, $p = 0.02$) gene-edited invasive pests (59%) (Tukey t = 3.14, $p = 0.01$), and gene-edited endangered species (47%) (Tukey t = 9.39, $p < 0.001$). Endangered species received the least support, with approximately 17% reporting less or no support for the development of the technology. Although statistically significant differences were observed between the means for different technologies, non-trivial effect sizes were only observed between endangered pests and all other technologies: invasive pests (Cohen's d = 0.25), pseudo-organisms (Cohen's d = 0.40), and coral (Cohen's d = 0.27).

Behavioural Intentions

We sought to understand people's reactions to the deployment of synthetic biology in the field. For coral, we asked: "To what extent would you be willing to visit parts of the Great Barrier Reef (GBR) where genetically engineered coral has been introduced?" (**Figure 5**). Most (72%) expressed willingness to visit the GBR (scoring "4" or "5") while around 11% expressed unwillingness (scoring "1" or "2"), and 25% selected the mid-point.

For endangered species (and invasive pests), we asked: "To what extent would it bother you if your local land management authority (wildlife conservation authority) used this technology to help endangered species (manage invasive pests) in your local area?" (**Figure 6**). Results revealed that participants were significantly more bothered by local implementation of the technology to help endangered species compared to managing invasive pests [t (2,295) = 1.63, $p = 0.05$]. However, the effect size was trivial (Cohen's d = 0.07). Around half the sample indicated that they would not be especially bothered with the introduction of these technologies in their local area (scoring "1" or "2") whereas, just under 20% indicated that they would be bothered (scoring "4" or "5") and around a third reported mid-point scores.

For pseudo-organisms, we asked: "To what extent would you be willing to (swim in, eat seafood caught from, drink from) a waterway where this new technology had been used to remove pollution?" (**Figure 7**). T-tests revealed that more people were willing (scoring "4" or "5") to swim in water treated using pseudo-organisms (around 40%), than they were to drink water treated

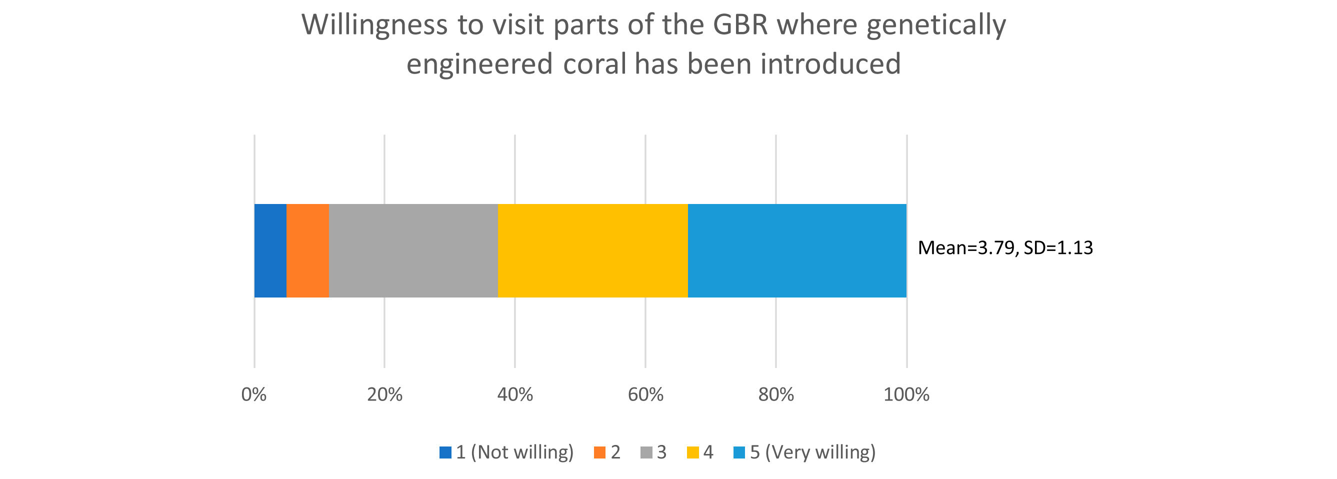

FIGURE 5 | Willingness to visit parts of the GBR where genetically engineered coral has been introduced.

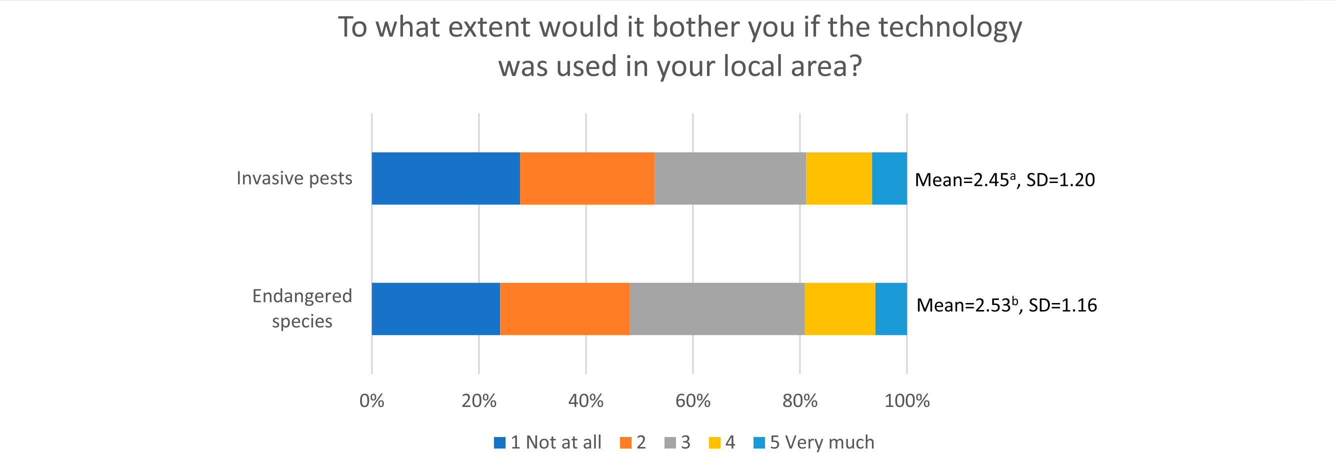

FIGURE 6 | Extent of "bother" if the synthetic biology technology was used in the local area. Notes: Different superscripts (a, and b) denote statistically significant differences between the means.

using pseudo-organisms [t (1,147) = 15.34, p = 0.000, Cohen's d = 0.45] or eat seafood (around 30%) (t (1,147) = 13.10, p = 0.000, Cohen's d = 0.39). People were also more willing to eat seafood sourced from waterways treated using pseudo-organisms than to drink the water from treated waterways [t (1,147) = 2.50, p = 0.006], however, this difference was trivial (Cohen's d = 0.07). 23% were not willing to swim in the water (scoring "1" or "2"), whereas almost 40% were not willing to eat seafood or drink the water (scoring "1" or "2"). Roughly one-third selected the mid-point of the scale.

DISCUSSION

The purpose of this study was to compare public acceptability of synthetic biology solutions to four different environmental management or conservation scenarios. We found that most Australians held little to no knowledge of synthetic biology, which is consistent with previous research (Cormick and Mercer, 2017). We also found that public awareness and knowledge of specific synthetic biology technologies was low. The majority of participants were either unaware of the synthetic biology solution, or were aware but held no, or only a little, knowledge. This was especially so for genetically engineering coral and pseudo-organisms. These results indicate that there is substantial room for improvement in raising public awareness of synthetic biology, which should correspond well with the synthetic biology technologies, particularly as there is a proliferation of research and commercial growth in the field. Science communicators may have a significant role to play here, developing communication materials and engaging with the people. Even though the application of synthetic biology

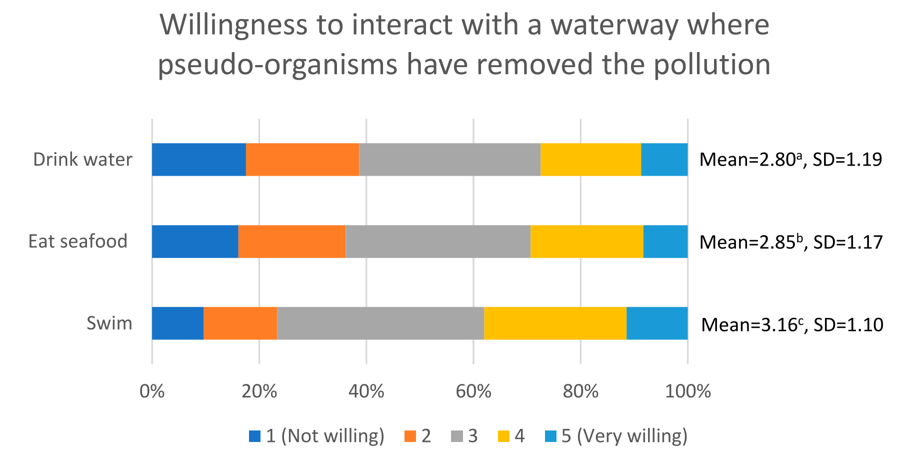

FIGURE 7 | Willingness to drink water, eat seafood or swim in a waterway where the technology has been used to remove the pollution. Notes: Different superscripts (a, b, and c) denote statistically significant differences between the means.

solutions may be many years away, being proactive in communicating may help to avoid, reduce and/or eliminate the spread of misinformation. With early and ongoing communication about synthetic biology, awareness across the general population should naturally grow.

When asked about a range of genetic modification methods, we found that people tended to be slightly less supportive of all the techniques presented. Participants were especially unsupportive of adding a gene from a different species (i.e., transgenic). While further research would be required to understand the reasons underlying less support for transgenics, this result provides early direction to synthetic biologists who have the option to choose different techniques. Additionally, it is worth noting that prior research has shown that publics do express concerns regarding transgenics and the cloning of animals (Einsiedel, 2005). It may be that the public consider inter-species gene transfer as especially invasive, risky, and unnatural (Carter et al., 2021). Yet even for the other gene modification techniques mentioned, overall support fell just below the mid-point of the scale, revealing that people were not very accepting of any of the gene modification techniques that are utilised by scientists in the field.

In contrast to the below-the-mid-point support for gene modification techniques, people were generally more supportive of developing the synthetic biology solution. This pattern of results suggest that people may be more supportive when there is context and a reason provided, for developing the technology—that is, a description of the problem it aims to solve, and how the technology compares with other available solutions. Thus, the somewhat depressed support observed for the genetic modification techniques could be partly explained by the fact that the techniques were presented sans any context. Yet, it is also noted that an explanation of the specific genetic modification technique did not accompany the context-rich problem-solution description—instead, it was only cursorily mentioned that genes would be "modified" or "edited". It may be hypothesised that support would have been different, and possibly tempered, if people were provided with the additional information on how the genes would be modified. Thus, future research may wish to explore this further by providing both the problem-solution description and an explanation of the specific genetic modification technique.

Except for endangered species, where a little less than half were supportive, all other technologies were supported by around 60%–70% of the sample. While a much smaller proportion indicated less support (<20%), there was a considerable number—around 25%—who were moderately supportive. This indicates that many people may choose to be "on the fence." not holding particularly strong views one way or the other. Noting that uncertain attitudes—compared to certainly-held attitudes—are more malleable and transient (Petrocelli et al., 2007; Tormala, 2016), it is possible that some people with moderate support may be open to changing their opinion, being influenced by what their peers think or how they feel, for instance. For example, in a separate analysis of a larger dataset (of which the current study forms a part), we found that emotions and affect had a stronger influence than knowledge in explaining initial support for the development of synthetic biology across multiple domains (Mankad et al., 2021). This work suggests that how one views synthetic biology is largely influenced by how one feels about it, not by how much one knows about it. Thus, our earlier suggestion that there is a need to build awareness should not be interpreted as a straightforward, simplistic solution of educating people by providing facts, and a list of pros and cons. While providing balanced information is certainly important, perhaps the more critical factor to consider is how such communication impacts on people's emotions and affective evaluations of synthetic biology—because it is these factors that primarily explain people's support or otherwise for development of the technology. Thus, the provision of information is likely to be a much more complex process, where one must carefully consider such things as: what is being said and how, who is delivering the information, who is the audience, when the information is released and how real-time feedback is managed. Pre-testing communication material would help to fine-tune many of these variables, and to gain early insight into the likely emotional response among people.

While support was higher than the mid-point for all technologies, there was variation across the synthetic biology applications. Editing the genes of endangered species elicited less support whereas genetically engineering invasive pests, pseudo-organisms, and coral garnered greater support. This finding suggests that some people may feel it is less acceptable to modify animals that we are trying to save as compared to creating small synthetic organisms or modifying existing corals or animals that we are seeking to eradicate (i.e., pest species). Certainly, prior research on public perceptions of transgenic animals has revealed that not only do people consider the purpose, the process, and the nature of the benefits, but they also consider the type of organism being modified (Einsedel, 2005). Future research could explore this aspect, examining the reasons why support for genetically engineering endangered species may be less, though we can hypothesise that people may consider these animals as more interactive, wide-roaming, and reproducible creatures with the potential for greater impacts in ecological systems—thereby heightening peoples' perceptions of unintended consequences and risk potential. It may also relate to how people view the personal benefits derived from introducing the synthetic biology solution. In the case of managing invasive pest species, water pollution and coral reef degradation, people may perceive that they will directly benefit, as compared to helping endangered species, which has a broader conservation goal.

It also was apparent that there was greater variability and more reticence in the behavioural intention measures, as compared to the general support measure. That is, when asked about the technology being introduced locally, a higher proportion of participants (in the order of 20–30%) tended to report less favourable intentions (e.g., being bothered by its introduction). This contrasts with only 17% or less who did not support further development of these technologies when it was described in general. The slight increase in unsupportive responses to the local implementation of synthetic biology solutions highlights the importance of conducting research in a more realistic manner—posing questions that encourage people to think about what it would be like to live near the technology. These types of questions may stimulate more in-depth processing and evaluation, and is something that would be worthy of further exploration in qualitative investigations.

While our survey is one of the first to explore how the public in Australia may respond to different synthetic biology solutions, we note that the results should be considered as preliminary and requiring more in-depth investigation. The reason for our caution is because the technology was presented as a hypothetical solution that was being considered for use in the future, to manage a broad-scale environmental problem. Coupled with the fact that the participants were drawn from the population, it is likely that most participants did not perceive the technology as personally relevant or important. Future in-depth research could be undertaken by targeting place-based cohorts (i.e., groups of people who share a similar characteristic) with some sort of social or economic stake—such as residents who live near known polluted waterways or residents who rely on coral reefs for their livelihood. Questions could be asked to understand context-specific concerns among these groups, regarding implementation of the technology, their expectations regarding management of the technology, and how they would personally like to be involved in the process of decision-making. By taking this place-based approach, it would be possible to not only truly gauge support for local implementation, but to also explore tangible implementation measures that local communities might need.

The results herein are also confined to reporting on support for development of the technologies. More in-depth analysis of the larger set of survey data, including examining the qualitative responses regarding the reasons why people supported or did not support the technology (reported in part elsewhere in Hobman et al., 2022 and Carter et al., 2021) would reveal insights into the concerns that people hold. This information may then be used by scientists developing the solutions, by science communicators talking about the solutions, and by decision-makers deciding whether, when and how to implement such solutions. Ultimately, the more that synthetic biology work is informed by public opinion, the greater the chance that synthetic biology technologies will be designed and delivered in a socially responsible manner.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because as directed by the CSIRO's Social Sciences Human Research Ethics Committee (CSSHREC), there are ethical restrictions on sharing the data that was analysed in this study. The ethical restrictions pertain to the fact that participants did not consent to their data being shared. Data requests will be considered on an individual basis, but some data may not be able to be released to maintain confidentiality. Please contact the corresponding author and CSSHREC on csshrec@csiro.au quoting the number 013/18. Requests to access the datasets should be directed to please contact the corresponding author and CSSHREC on csshrec@csiro.au quoting the number 013/18.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by The CSIRO Social Sciences Human Research Ethics Committee. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

EH wrote the main manuscript text, analysed the data, and prepared all figures. All authors, EH, AM, and LC contributed to the conceptualisation of the study, developed the survey materials and methods, and reviewed the manuscript.

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REFERENCES

Akin, H., Rose, K. M., Scheufele, D. A., Simis-Wilkinson, M., Brossard, D., Xenos, M. A., et al. (2017). Mapping the Landscape of Public Attitudes on Synthetic Biology. *BioScience* 67 (3), biw171–300. doi:10.1093/biosci/biw171

Ancillotti, M., Rerimassie, V., Seitz, S. B., and Steurer, W. (2016). An Update of Public Perceptions of Synthetic Biology: Still Undecided? *Nanoethics* 10, 309–325. doi:10.1007/s11569-016-0256-3

Anthony, K. R. N., Helmstedt, K. J., Bay, L. K., Fidelman, P., Hussey, K. E., Lundgren, P., et al. (2020). Interventions to Help Coral Reefs under Global Change – A Complex Decision Challenge. *PLOS ONE* 15 (8), e0236399. doi:10.1371/journal.pone.0236399

Australian Academy of Science (2018). *Position Statement*. Gene Technology and Gene Modification. Available at: https://www.science.org.au/supporting-science/science-policy/position-statements/statement-gene-technology-gene-modification.

Bhattachary, D., Calitz, J. P., and Hunter, A. (2010). Synthetic Biology Dialogue. Available at: https://bbsrc.ukri.org/documents/1006-synthetic-biology-dialogue-pdf/. (Accessed June 10, 2019).

Carter, L., Mankad, A., Hobman, E. V., and Porter, N. B. (2021). Playing God and Tampering with Nature: Popular Labels for Real Concerns in Synthetic Biology. *Transgenic Res.* 30, 155–167. doi:10.1007/s11248-021-00233-2

Carter, L., and Mankad, A. (2021). The Promises and Realities of Integration in Synthetic Biology: A View from Social Science. *Front. Bioeng. Biotechnol.* 8, 622221. doi:10.3389/fbioe.2020.622221

Cormick, C., and Mercer, R. (2017). Community Attitudes to Gene Technology," in *Report Prepared for the Office of the Gene Technology Regulator*. Available at: http://www.instinctandreason.com.

Einsiedel, E. F. (2005). La opinión pública ante los animales transgénicos. *Rev. Sci. Tech. OIE* 24 (1), 149–157. doi:10.20506/rst.24.1.1562

Fraser, C., and Gray, P. (2020). Synthetic Biology in Australia, Office of the Chief Scientist – Occasional Paper. Available at: https://www.chiefscientist.gov.au/sites/default/files/2020-08/Synthetic%Biology%20paper.pdf. (Accessed May 10, 2022).

Gaskell, G., Stares, S., Allansdottir, A., Allum, N., Castro, P., Esmer, Y., et al. (2010). *Europeans and Biotechnology in 2010. Winds of Change? Report Prepared for the European Commission*. Brussels: Publications Office of the European Union.

Gray, P., Meek, S., Griffiths, P., Trapani, J., Small, I., Vickers, C., et al. (2018). *Synthetic Biology in Australia: An Outlook to 2030*. Report for the Australian Council of Learned Academies Available at: http://www.acola.org.au.

Hart Research Associates (2013). Awareness and Impressions of Synthetic Biology: A Report of Findings Based on a National Survey Among Adults," in *Synthetic Biology Project*. Washington: The Woodrow Wilson International Center For Scholars.

Hobman, E. V., Mankad, A., Carter, L., and Ruttley, C. (2022). Genetically Engineered Heat-Resistant Coral: An Initial Analysis of Public Opinion. *PLOS ONE* 17 (1), e0252739. doi:10.1371/journal.pone.0252739

Mankad, A., Hobman, E. V., and Carter, L. (2021). Effects of Knowledge and Emotion on Support for Novel Synthetic Biology Applications. *Conserv. Biol.* 35 (2), 623–633. doi:10.1111/cobi.13637

Owen, R., and Pansera, M. (2019). "Responsible Innovation and Responsible Research and Innovation," in *Handbook on Science and Public Policy*. Editors D. Simon, S. Kuhlmann, J. Stamm, and W. Canzler (Cheltenham: Edward Elgar Publishing Limited), 26–48. doi:10.4337/9781784715946.00010

Owen, R., Stilgoe, J., Macnaghten, P., Gorman, M., Fisher, E., and Guston, D. (2013). "A Framework for Responsible Innovation," in *Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society*. Editors R. Owen, J. Bessant, and M. Heintz (New York: John Wiley & Sons), 27–50. doi:10.1002/9781118551424.ch2

Pauwels, E. (2013). Public Understanding of Synthetic Biology. *BioScience* 63, 79–89. doi:10.1525/bio.2013.63.2.4

Petrocelli, J. V., Tormala, Z. L., and Rucker, D. D. (2007). Unpacking Attitude Certainty: Attitude Clarity and Attitude Correctness. *J. Personality Soc. Psychol.* 92 (1), 30–41. doi:10.1037/0022-3514.92.1.30

Pew Research Center August (2018). *Most Americans Accept Genetic Engineering of Animals that Benefits Human Health. but many oppose other uses*. Washington, DC: Pew Research Center.

Rylott, E. L., and Bruce, N. C. (2020). How Synthetic Biology Can Help Bioremediation. *Curr. Opin. Chem. Biol.* 58, 86–95. doi:10.1016/j.cbpa.2020.07.004

Segelbacher, G., Bosse, M., Burger, P., Galbusera, P., Godoy, J. A., Helsen, P., et al. (2021). New Developments in the Field of Genomic Technologies and Their Relevance to Conservation Management. *Conserv. Genet.* 23, 217–242. doi:10.1007/s10592-021-01415-5

StataCorp (2021). *Stata Statistical Software: Release 17*. TX, United States: StataCorp LLC.

Stilgoe, J., Owen, R., and Macnaghten, P. (2013). Developing a Framework for Responsible Innovation. *Res. Policy* 42 (9), 1568–1580. doi:10.1016/j.respol.2013.05.008

Scott, D., Abdelhakim, D., Miranda, M., Hoft, R., and Cooper, H. D. (2015). "Potential Positive and Negative Impacts of Components, Organisms and Products Resulting from Synthetic Biology Techniques On The Conservation and Sustainable use of Biodiversity, and Associated Social, Economic and Cultural Considerations," in *Part I of: Synthetic Biology. Secretariat of the Convention on Biological Diversity*. Technical Series No. 82. Montreal, 60.

The Third Review of the National Gene Technology Scheme (2018). *The Third Review of the National Gene Technology Scheme*. Canberra: Department of Health Available at: https://www.genetechnology.gov.au/sites/default/files/2022-02/2017-review-final-report.pdf.

Tormala, Z. L. (2016). The Role of Certainty (And Uncertainty) in Attitudes and Persuasion. *Curr. Opin. Psychol.* 10, 6–11. doi:10.1016/j.copsyc.2015.10.017

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