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Use of genetic manipulation and gene editing in the Australian sugarcane industry: advances, relevance and barriers

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Abstract Several significant challenges threaten the future prosperity of the Australian sugarcane industry, and technologies such as genetic modification (GM) and, potentially, gene editing (GE) offer solutions to some of these problems. Adoption of these technologies, however, raises complex ethical, environmental and socioeconomic issues that would need to be carefully considered and addressed. We provide a summary of recent advances in GM and GE technologies (both in a broad sense and specifically in sugarcane), identify areas where strategic investment in GM and GE might be most relevant, and provide an assessment of current barriers to adoption for these technologies. The intent is to stimulate discussion and provide a foundation for informed decision-making and strategic planning in the industry.

Key words Genetic modification, gene editing, transgenic sugarcane, moth borers, pest resistance, ethical considerations

INTRODUCTION

There are several significant challenges that threaten the future prosperity of the industry, and recent advances in technologies such as genetic modification (GM) and gene editing (GE) offer potential solutions to some of these challenges. For definitions for these terms, and others relevant to this paper, see Appendix 1.

Here, we aim to:

- provide a summary of recent advances in GM and GE both in a broad sense and specifically in sugarcane;
- identify the areas where strategic investment in GM and GE research might be most relevant;
- provide an assessment of current barriers to adoption of these technologies, and potential implications for market access.

The intent is to stimulate discussion and provide a foundation for informed decision-making and strategic planning in the industry.

This is not the first time that these topics have been discussed withing the Australian sugarcane industry. In the late 2000s, the CRC for Sugar Industry Innovation through Biotechnology in partnership with the Sugarcane Gene Technology Group of the Australian Sugar Industry Alliance undertook a series of well-received industry workshops on the subject (Morris 2010). However, technology developments (particularly with respect to GE), the commercialisation of GM and GE sugarcane in Brazil, and the recent development of SRA's Ten-Year R&D Plan make it a timely opportunity to revisit the topic.

METHODOLOGIES ASSOCIATED WITH GM AND GE

Genetic modification

Transgenic crops can be produced either using *Agrobacterium* transformation, or by particle bombardment or "biolistics". Both methods can be used to generate transgenic sugarcane plants that stably express transgenes and are otherwise phenotypically normal in the field (Jackson *et al.* 2014; Joyce *et al*. 2014).

Gene (or genome) editing

Genome editing involves precisely mutating the genetic material in an organism to introduce targeted changes in observable traits (phenotype). Gene editing involves using site-specific nucleases such a CRISPR-Cas9 to cut the DNA at a specific location in a target gene, and then relies on the error-prone repair process to introduce mutations. The repair process can also be guided to produce a defined change by adding a DNA template (see Appendix 1).

APPLICATIONS OF GM AND GE

Genetic modification in medicine

The most publicly accepted application of GM has been for medical applications (so-called "red biotech"). Vaccines such as that for hepatitis B and some of the current quadrivalent flu vaccines approved in Australia are products that are synthesised by genetically modified cell cultures. Similarly, a range of pharmaceutical products are produced in GM cell lines. For example, injectable insulin for diabetics and tissue plasminogen activator (tPA) for treatment of heart attacks are produced in GM *Escherichia coli* bacteria and mammalian cells, respectively. The clear health benefits that result from these GM applications explain the high degree of public acceptance.

Genetic modification in environmental science

Genetically modified microorganisms can be employed in bioremediation to degrade pollutants and contaminants in the environment. For example, *Pseudomonas putida* has been genetically modified for enhanced degradation of toxic chemicals such as toluene and trichloroethylene (van den Wijngaard *et al*. 2006).

Genetic modification in agriculture

Genetic modification is extensively used in agriculture to enhance crop traits such as yield, resistance to pests and diseases, and tolerance to environmental stresses. Crops such as Bt cotton and Bt corn (genetically modified by the insertion of one or more genes from soil bacterium, *Bacillus thuringiensis*) have been genetically modified to produce proteins toxic to some insect pests, reducing the need for chemical pesticides and increasing yields (Tabashnik *et al*. 2013). Similarly, virus-resistant papaya has been developed through genetic modification, saving the papaya industry from devastation by papaya ringspot virus (Gonsalves 2006). Researchers have engineered drought-tolerant maize varieties by introducing genes responsible for stress response mechanisms (Setter *et al*. 2011).

With respect to GM crops, the United States has led the way in adoption of the technology. According to the Food and Drug Administration (FDA), 94% of the US soybean crop was herbicide-tolerant GM varieties, 96% of the cotton crop was insect-resistant GM varieties, and 92% of the corn crop was insect-resistant GM varieties (https://www.fda.gov/food/consumers/agricultural-biotechnology). Other GM crops approved in the US include potato, papaya, summer squash, canola, alfalfa, apples, and pineapples. The adoption of GM technology has not been limited to crops, with the FDA also approving GM fish (AquAdvantage Salmon) and pigs (GalSafe pig) for consumption in the US.

More importantly from a sugar industry perspective, GM sugar beet expressing herbicide tolerance was deregulated in 1998, and by 2013 over 99% of the US sugar beet farmers had adopted GM sugar beet (Fernandez-Cornejo *et al.* 2016). At the time, sugar beet accounted for approximately half of the total sugar production in the US.

In Australia, GM varieties of both canola and cotton are grown commercially. Approximately 20% of the Australian canola crop consists of GM herbicide (glyphosate) tolerant varieties. This proportion has been limited by the moratoria on GM crop deployment currently in place in the Australian Capital Territory, Tasmania, and South Australia.

In contrast, more that 99% of the cotton grown in Australia is GM, expressing either insect resistance, herbicide tolerance, or (in most cases) both. In the early 1990s, the Australian cotton industry was in crisis due to failure to control the major caterpillar pest *Helicoverpa amigera* (cotton bollworm). GM cotton was developed in response to this crisis, and the current generation (Bollgard® 3) is based on a combination of three "stacked" toxins from the bacterium *Bacillus thuringiensis* (Bt). The specific insecticidal toxins employed are cry1Ac, cry2Ab and vip3A, and herbicide tolerance is based on the Roundup Ready© trait. The first insect-resistant GM cotton, which was developed by CSIRO in partnership with Monsanto, was planted commercially in 1996 following field testing over 6 years.

Bollgard® 3 cotton provides a platform for a highly successful integrated pest management (IPM) program for the Australian cotton industry, which has seen a 97% reduction in synthetic insecticide use since 1992. A strict Resistance Management Plan is in place for all farms growing Bollgard® 3 cotton (including, for instance, a requirement for refuge crops consisting of conventional (non-GM) cotton that encourages high populations of susceptible *H. amigera* to minimise the development of resistant pests). As indicated below, this system provides a potential model for integrated pest management (IPM) to control other pests such as fall armyworm or exotic moth borers.

GENETIC MODIFICATION AND GENE EDITING IN SUGARCANE

Genetic modification in sugarcane

The world's first GM sugarcane plants were produced at the University of Queensland in the early 1990s (Bower and Birch 1992). Following this, there were many studies that improved the transformation efficiency (using both particle bombardment and *Agrobacterium*) for a wide range of commercial varieties. Many foreign genes are prone to transgene silencing (e.g. Mudge *et al*. 2009), but this can be efficiently avoided by optimising transgene sequences (Jackson *et al*. 2014).

Research involving GM traits in sugarcane has focussed on four broad areas: resistance to biotic threats (pests and diseases); herbicide tolerance; resistance to abiotic threats; and metabolic engineering. These studies have been reviewed in detail by Budeguer *et al.* (2021), and just a summary of some key examples is included here.

Resistance to biotic threats

Amongst biotic threats, the earliest studies involved the relatively simple trait of engineering virus resistance through expression of viral proteins and later using RNA interference (RNAi) constructs. Target viruses included Sugarcane Mosaic Virus, Sorghum Mosaic Virus, Fiji Disease Virus and Sugarcane Yellow Leaf Virus (Budeguer *et al*. 2021 and references therein). Resistance to leaf scald disease (Zhang *et al*. 1999) and red rot (Nayyar *et al*. 2017) have also been engineered in transgenic sugarcane.

Pest resistant sugarcane lines have been generated using both plant-derived insecticidal proteins and bacterial insecticidal proteins. In early proof-of-concept work undertaken at BSES, transgenic sugarcane expressing a potato *proteinase inhibitor II* gene showed resistance to the canegrub *Antitrogus consanguineus*, with canegrubs feeding on transgenic cane showing only 4.2% weight gain relative to controls feeding on non-transgenic cane (Nutt *et al*. 2001; SRDC Project BSS163 Final Report).

Most of the work on GM pest resistance, however, has focussed on using the insecticidal proteins from the bacterium *B. thuringiensis* (Bt) to develop resistance to lepidopteran moth borers (Budeguer *et al*. 2021). Early studies involving single Bt genes progressed to stacked Bt gene variants with differing modes of action (designed to reduce the likelihood of Bt resistance developing in the target pests), and field testing of transgenic lines with stacked Bt genes demonstrated strong efficacy against borers in transgenic lines with equivalent agronomic characters as the elite parent variety (Christofoletti *et al*. 2018). The success of these studies, along with the economic significance of lepidopteran stem borers (causing estimated losses of more than US$1 billion in Brazil) led to a Bt transgenic line becoming the first GM sugarcane to be grown commercially. This transgenic line (CTC20BT), which was produced by Centro de Tecnologia Canavieira, was approved for release in Brazil in 2017. As with the Australian cotton example described above, strict management requirements need to be

followed to minimise the risk of resistance developing in the target insects. Given that lepidopteran stem borers represent the highest biosecurity risk for the Australian sugarcane industry, the on-going effectiveness of this trait is of great interest to SRA.

As mentioned above, Bollgard® 3 cotton (containing stacked Bt genes) is the key underlying platform on which the successful IPM strategy for cotton is founded. This approach has the potential to play a similar role for the management of exotic moth borers in Australia should they arrive. While integrated pest management (IPM) options for moth borers have been partially successful in Indonesia and Papua New Guinea (Magarey *et al*. 2012; McGuire *et al*. 2012), the cotton example suggests that stacked Bt technology (or alternative GM traits) may be the best technology to underpin IPM for moth borers in Australia. A Bt-based approach would also most likely provide strong protection against other lepidopteran pests including fall armyworm (as demonstrated by Bollgard® 3 cotton).

Engineering herbicide tolerance

Herbicide tolerance (HT) in sugarcane is a trait that BSES and subsequently SRA invested heavily in through a partnership with DuPont between 2009 and 2015. Through this partnership, BSES assembled a team of researchers that were highly proficient at producing GM sugarcane, and tested thousands of independent transgenic lines in the field. While this did not progress to commercialisation, it demonstrated the feasibility of large-scale production of transgenic sugarcane when adequately funded.

Engineering resistance to abiotic threats

GM sugarcane studies related to abiotic threats have mostly focussed on drought tolerance (Budeguer *et al*. 2021 and references therein). For example, transgenic sugarcane producing the osmoprotectant glycine betaine were reported to produce 10-30% more sugar than conventional sugarcane under drought conditions (Sugiharto 2018). These plants, developed by PT Perkebunan Nusantara XI in Indonesia, are now being grown commercially, albeit only on land owned by the developer (USDA 2020).

Metabolic engineering

Metabolic engineering of sugarcane to produce higher value products *in planta* has also attracted the attention of sugarcane researchers. Production of the bioplastics polyhydroxybutyrate and polyhydroxyalkanoate in sugarcane leaves was achieved (albeit at low levels) by introducing multiple genes encoding novel bacterial enzymes in the biosynthetic pathways for these products (Petrosovits *et al*. 2007; Anderson *et al*. 2011).

More successfully, expression of isomaltulose synthase in the mature stems of transgenic sugarcane resulted in over 80% conversion of sucrose into the high value, low GI, acariogenic sugar isomaltulose in multiple generations in the field (Mudge *et al*. 2013), clearly demonstrating the feasibility of *in-planta* production of isomaltulose at a cost approaching that of sucrose.

Gene editing in sugarcane

The highly polyploid and heterozygous genome represents a potential challenge for the successful deployment of gene editing in sugarcane, because each gene can have 8-14 alleles with different expression levels (Mudge *et al*. 2009), and therefore multiple copies will need to be edited. The recent completion of the polyploid genome assembly for sugarcane variety R570 (Healy *et al.* 2024) will simplify this.

Despite these challenges, the CRISPR-Cas9 gene editing technology has been successfully used in sugarcane. A 2021 proof-of-concept study (Eid *et al*. 2021) was followed shortly after by a more agronomically relevant trait. The CRISPR-Cas 9 system was used to insert one or two targeted mutations into the *acetolactate synthase* gene to engineer herbicide tolerance (Oz *et al.* 2021). These herbicide tolerant (HT) lines have not progressed to commercialisation due to the demanding requirements to sequence the full genome of transgenic lines to prove that no foreign DNA is present in the genome (a current requirement in the US).

The first GE sugarcane varieties to be recognised as non-GM and approved for commercial planting were Cana Flex I and Cana Flex II (Embrapa Agroenergia, Brazil) in late 2021. These varieties contain a gene knockout that leads to modified lignin composition in Cana Flex I, and a gene knockout which inactivates an *acyltransferase*

leading to a claimed 15% increase in sugar accumulation in the culm (https://www.futurefarming.com/crop-solutions/brazil-develops-non-transgenic-crispr-edited-sugarcane/; accessed 27 November 2024).

While this represents a breakthrough in terms of the technology, the commercial relevance of these varieties is uncertain. While Cana Flex I has improved digestibility for bioethanol production, improved enzyme cocktails that are becoming available to aid digestion of conventional cell walls, and although Cana Flex II provides an increase in culm sucrose, the background variety SP80-3280 has relatively low CCS (J Eglinton, pers. comm. 2022).

FUTURE OPPORTUNITIES FOR GM IN THE SUGARCANE INDUSTRY

Based on the examples described above, we conclude that the two highest priority traits for GM sugarcane are (a) resistance to pests; and (b) enabling diversification opportunities. These are explored further below.

Engineering enhanced resistance to exotic and endemic pests

Engineering resistance to insect pests is arguably the highest priority target trait for deployment in GM sugarcane in Australia. This could be done either using the established Bt technology, or through alternative transgenes.

The stacked Bt gene approach would have lower risk because it is proven technology. While there are existing transgenic lines that are already commercially available in Brazil, the preferred approach would probably be to generate transgenic versions of the leading varieties that are currently used in the Australian industry. Although lower risk, the Bt approach utilises third party IP, and growers would need to pay a fee to access the technology. It is currently unclear what this fee might be, but for Bollgard® 3 cotton growers pay $315 per hectare each year plus an additional $42 per hectare in resistance management costs. (This fee is set to be below the typical cost of insecticide sprays that are required for conventional cotton, and a different model might be required for sugarcane.) Another advantage of the Bt technology is that it is active against both lepidopteran pests (such as exotic moth borers and fall armyworm) and coleopteran pests (such as canegrubs, which represent the major endemic pest for the Australian industry), and it will therefore provide resistance to the major endemic and exotic threats currently facing the industry.

For the alternative approaches to engineering pest resistance (such as expression of lectins, proteinase inhibitors or RNA interference constructs) the preferred approach would probably be to first assess the gene products in lab-based bioassays to identify the most promising candidates before embarking on transgenic plant studies. Improvements in our ability to minimise transgene silencing (Jackson *et al.* 2014) should result in greater efficacy than that seen in earlier studies. An advantage of this approach is the opportunity to obtain a greater share of IP ownership during the development phase, although a detailed assessment of the IP landscape around the selected transgene would need to be explored to clarify this.

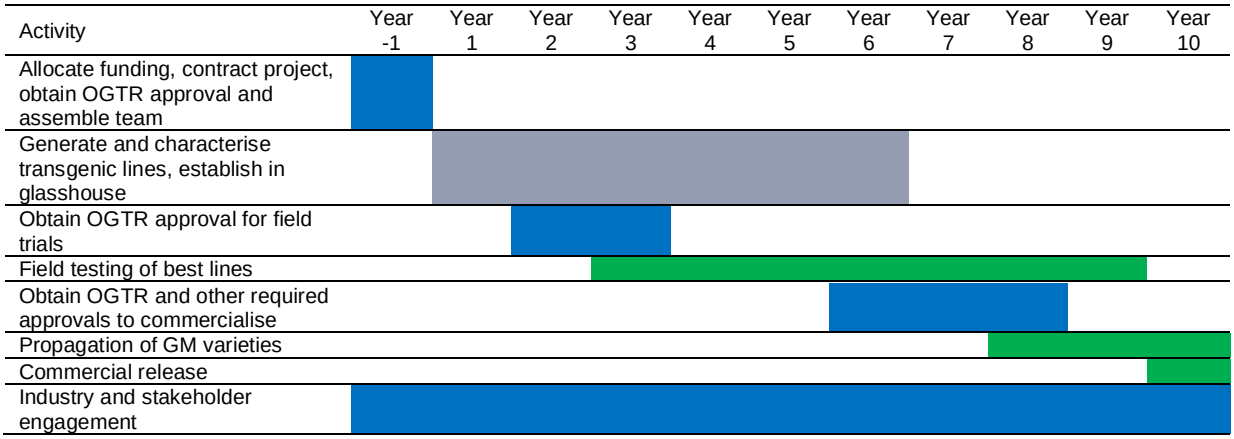
Bioenergy and diversification

Although not as high a priority as pest resistance, future deployment of GM/GE technologies to aid the development of bioenergy and diversification opportunities may be justified if the industry embraces the bioeconomy opportunities outlined in the Industry Roadmap released in 2022. Preliminary exploration of GE is being undertaken within the ARC Research Hub for Engineering Plants to Replace Fossil Carbon, and any future work will be informed by the direction that the industry sets in the future.

Feasibility, costs and timelines for development of GM sugarcane

The previous CSR/Sucrogen-funded SugarBooster program at UQ (isomaltulose production) and the BSES/SRA-funded HT cane program clearly demonstrate the feasibility of producing and field testing thousands of independent transgenic sugarcane lines. However, the development and regulatory approval of GM sugarcane would require a significant investment in both time and money. Based on both the cotton industry's experience and the above-mentioned large-scale GM sugarcane programs, the in-house development through to commercial release of high-quality GM lines would likely take approximately 10 years (Table 1). The investment required is difficult to predict without understanding the intended scale of the project, but in 2010 the BSES CEO Eoin Wallis signalled the intention to invest $40 million into the development of herbicide-tolerant cane (https://www.couriermail.com.au/news/queensland/bundaberg/super-crops/news-story/22cc3afbf74ed8324c7bf8c3f1136a6f).

Table 1. Indicative timeline for the development of GM sugarcane lines, based on previous experience with GM cotton and sugarcane. Colours indicate administrative tasks (blue), laboratory-based activities (grey) and field-based activities (green).



Social and ethical considerations

Public perception and acceptance of GM/GE crops

A survey of consumers' perceptions of and attitudes towards genetically modified foods conducted by Food Standards Australia New Zealand (2022) revealed that nearly half of respondents (46.7%) expressed concerns primarily about human safety, trust in GM producers/scientists, environmental impact, and animal welfare. Consumer support for GM foods varied, with approximately 30% supportive, 30% neutral, and 40% opposed. Indirect evidence from supermarket shelves suggests a different response for processed foods, which appear to be more readily accepted by consumers despite the presence of GM ingredients, and it would be expected that processed sugar derived from GM sugarcane might fit in this category. Building and maintaining consumer trust will require effective communication, and GM products with benefits beyond industry (including the environment and/or animal welfare) will likely be preferred. Government agencies remain a key source of unbiased information to help consumers learn more about genetic modification and the range of techniques that are emerging. A survey in Australia in 2007 found that canegrowers were more supportive of GM than the general public, with 68% approval for GM applications where genetic material is not present in the final product (as is the case for sugar) compared to 41% support amongst the general public (Romanach *et al.* 2007).

With respect to safety of sugar derived from GM sugarcane, it is worth noting that approximately half of the sugar sold in US supermarkets over the last two decades has been derived from GM sugar beet, with no adverse effects. This is not surprising given the fact that sugar is a highly refined product. Similarly, the raw sugar from the commercially grown Brazilian GM sugarcane varieties has no traces of DNA or protein and is therefore equivalent to conventional sugar (Lajolo *et al*. 2021).

Ethical issues (ownership/biodiversity impacts)

Though GM crops have the potential to improve food security by increasing yields, reducing post-harvest losses, and enhancing nutritional content (Qaim and Kouser 2013), genetic modification (GM) technology presents various ethical considerations and raises questions about our social contract regarding food production, safety, and environmental stewardship. Key ethical principles and considerations include safety (Caswell 2015; Nuffield Council on Bioethics 1999), autonomy (Hudson *et al*. 2005; Davison 2010), justice (Thompson 2010; Kaplinsky and Hall 2016), and environmental sustainability (Mallapaty 2020; Pardo and Alibhai 2008). GM foods have faced resistance from some consumers and environmental groups who express concerns about potential risks to human health, environmental impacts, and corporate control of the food supply (MacKenzie *et al*. 2014). Another major concern of the advocate against GM is the economic inequality that may arise due to the concentration of GM seed ownership among a few large corporations has raised concerns about economic equity and the resultant dependence of farmers on expensive patented seeds (Howard and Howard 2010).

Regulatory landscape: Comparison of global GM regulatory frameworks

Regulations on GM crop cultivation and trade are highly varied across the globe, with some more mature in their experiences and thus flexible enough to accommodate the entry of gene edited products for authorization. Many European countries, such as France and Germany, have banned growing GM crops. The United States and Brazil have more favourable regulations for GM crops and are among the world's largest producers of such crops. In the United States, for instance, the regulations are more supportive of GMOs (128 GM plant varieties have been granted non-regulated status), whereas the European Union has much stricter guidelines and requires all GM-derived foods (including processed foods) to be labelled.

A robust regulatory framework is essential to address the social contract and ethical considerations of genetic modification. Regulatory bodies must ensure that GM technologies are developed, tested, and deployed in a manner that upholds safety, autonomy, justice, and environmental stewardship principles. In Australia, GMOs are regulated through a nationally consistent legal scheme, including the Australian *Gene Technology Act 2000*, the *Gene Technology Regulations 2001*, and the corresponding state laws. The Office of the Gene Technology Regulator (OGTR) administers the gene technology regulatory system.

Although GM sugarcane lines have not been commercialised in Australia, the OGTR have approved multiple dealings involving intentional release (DIRs) relating to field testing of GM sugarcane varieties, and therefore the relevant aspects of sugarcane biology are well understood by the regulator. Similarly, approvals have been granted for Bt and HT cotton, and the background data relating to these transgenes and traits is well known to the regulator. One would anticipate, therefore, that future DIR requests would be relatively simple unless a novel trait and transgene are involved.

A key consideration for the Australian sugarcane industry are the impacts on raw sugar export primarily to South Korea, Indonesia and Japan, so the current regulatory landscape and levels of consumer acceptance in these markets is of critical importance. The most readily available information in this area relates to Japan.

Despite on-going public concern relating to GM foods, Japan has increased imports of GM foods. Interestingly, Japan featured second, after the US, in the number of approvals of GM events for food, feed and cultivation (ISAAA 2018), yet no GM crop planting occurs (except the ornamental blue rose). Nine major agricultural products, including sugar beet, require mandatory labelling, but only if the GM DNA or protein encoded by this DNA is detectable (https://www.foodnavigator-asia.com/Article/2023/07/26/japan-2022-gm-government-data-highlights-continued-stability-of-genetically-modified-crops-locally/)). Given that DNA and protein are undetectable in raw sugar produced from the Bt-expressing GM sugarcane varieties that are commercialised in Brazil (Lajolo *et al.* 2021), it seems reasonable to conclude that raw sugar derived from GM sugarcane would not require labelling in Japan. However, this assumption requires testing.

Unlike Japan, Korea currently grows GM crops (including maize and soybean) commercially (Sul *et al.* 2021), but the debate about GM crops remains a social issue, and the government authorities therefore take a very conservative view when undertaking safety reviews prior to approving commercial production of GM crops. Like Japan, labelling as GM is only required where DNA or the encoded protein is present, and therefore raw sugar would likely not require labelling as GM.

Indonesia also has commercial production of GM crops, including the recent addition of drought-resistant GM sugarcane (https://www.isaaa.org/gmapprovaldatabase/event/default.asp?EventID=340&Event=NXI-1T). Given that GM sugarcane is now being produced commercially in Indonesia, there may be less of a regulatory barrier to import in this jurisdiction. Again, labelling requirements follow the Japanese approach, and so raw sugar should be excluded from mandatory labelling requirements (Wahidin and Purnhagen 2020).

In summary, raw sugar derived from GM sugarcane might not require mandatory labelling by our major trading partners (although this superficial analysis will need confirming). However, in all three jurisdictions the social acceptance of GM food remains a potential trade barrier, and the significance of this requires a more thorough evaluation.

China remains a potential trading partner for raw sugar, even though Australia does not currently export raw sugar there. In this respect, it is worth noting that China have recently approved the import of the commercially-grown Brazilian sugarcane lines engineered for resistance to stem borers (https://www.reuters.com/article/markets/currencies/brazils-ctc-expects-more-genetically-modified-sugarcane-use-after-china-approva-idUSKBN2TW1P2/). This demonstrates in principle support for GM sugarcane, although this will be assessed on a case-by-case basis.

In 2020, the Japanese Ministry of Health, Labor and Welfare approved the production and sale of the world first CRISPR edited fruit, a tomato developed by the University of Tsukuba and Sanatech (Hiroshi 2022). The fruit features five times the normal amount of γ-aminobutyric acid (GABA), an amino acid linked to lower blood pressure, by editing genes that normally limit GABA production. The tomato was not regulated as a genetically modified product (ISAAA 2021).

Both Japan and Australia have taken steps in the last several years to clarify their regulation of gene edited crops and products. Importantly, organisms with an introduced mutation but no inserted DNA (i.e. SDN-1, see Appendix 1) are not considered GMOs within the meaning of the Australian *Gene Technology Act 2000*, or by the Japanese Government.

It is clear from the data gathered above that there is a diverse range of legislation and frameworks on how best to regulate GM crop cultivation. Even within continents or larger geographic regions, the local approaches can vary widely. Almost, all view products created by SDN-1 as not being a GMO and the resultant product will follow the regulatory path of the conventionally bred plant varieties (Schmidt *et al*. 2020). However, divergence emerges again regarding SDN-2 techniques: Australia and Japan have opted for a conservative threshold by finding that organisms edited using the SDN-2 technique will be regulated as a GMO (Thygesen 2019; Tsuda *et al*. 2019).

RECOMMENDATIONS

Strategic directions for research and development in GM sugarcane

Despite the many opportunities outlined above, consumer acceptance and development/regulatory costs remain significant barriers to widespread adoption of GM and GE technologies. However, experience with cotton in Australia and sugarcane in Brazil demonstrates that these barriers can be overcome with sufficient investment.

GE represents a potential “non-GM” approach, but its utilisation for sugarcane improvement is currently limited by a lack of clear target genes for traits of interest. Capacity development in this technology may be justified if corresponding investment is made in target gene identification.

At this point in time, GM approaches to engineer resistance to both exotic and endemic pests represent the most promising application of GM in the Australian sugarcane industry, and recent developments in Brazil make this a timely opportunity to assess the views of the Australian industry. As a next step, engagement with key industry stakeholders is recommended to stimulate discussion and establish the Australian industry’s level of interest in pursuing a GM approach for pest resistance.

Policy recommendations for safe and beneficial use of GM technology

Developing policy recommendations for the safe and beneficial use of genetically modified (GM) technology involves addressing regulatory, safety, ethical, and socioeconomic aspects. Traits such as Bt-driven insect resistance will require strict management policies to minimise the risk of resistance developing. These issues should become a focus for discussion if the industry is supportive of a GM future for the Australian sugarcane industry.

Education and outreach strategies to improve understanding and acceptance of GM sugarcane

To improve understanding and acceptance of genetically modified (GM) sugarcane among growers and sugar millers in Australia, a comprehensive and targeted approach is necessary. While this remains a challenge, the success on GM cotton demonstrates that it is possible. Specific education and outreach strategies (Morris 2010) could include:

- Stakeholder Meetings and Workshops to discuss the benefits, safety, and management practices of GM sugarcane with experts and industry.
- Integrated communication and information dissemination to industry and general public: Develop easy-to-understand brochures, fact sheets, and guides that explain the science behind GM sugarcane, its benefits, and safety protocols

- Economic Impact Studies: Provide data and case studies showing the economic and environmental benefits of successful GM sugarcane and other crops in Australia and overseas.
- Offer technical support and consultation services to sugar mills to address any specific concerns they may have about GM sugarcane.
- Provide access to experts who can answer questions and provide guidance on handling GM crops.
- Use multiple channels, including print media, social media, radio, and local agricultural publications, to reach a broad audience.
- Collaborate on initiatives that provide funding, resources, and support for adopting GM sugarcane.
- Engage with policymakers to ensure supportive regulatory frameworks for GM sugarcane.
- Advocate for policies that provide incentives for adopting GM crops, such as grants, subsidies, or tax benefits.
- Maintain transparency about the research, development, and approval processes of GM sugarcane.
- Regularly communicate updates and findings from scientific studies, field trials, and economic analyses.

CONCLUSIONS

GM and GE technology offers innovative solutions for some of the major challenges that the Australian sugarcane industry is currently facing, especially in the areas of pest resistance and the bioeconomy. However, the adoption of these technologies raises complex ethical and socioeconomic issues that must be carefully considered and addressed. Effective regulation, transparent communication, and inclusive decision-making processes will be essential if the industry decides to take this path.

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APPENDIX 1: KEY DEFINITIONS

CRISPR/Cas9 system: A tool scientists use to precisely edit parts of an organism's DNA. The name stands for Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) and CRISPR-associated protein 9 (Cas9). CRISPR is a part of a bacterium's immune system that helps it remember and fight off viruses.

Genetic modification (also called genetic engineering): Is a process that uses laboratory-based technologies to alter the DNA makeup of an organism.

Gene editing (also called genome editing): Is the alteration of the genetic material of a living organism by inserting, replacing, or deleting a DNA sequence, typically with the aim of improving some characteristic. Gene editing is carried out using Site-Directed Nucleases, and there are three broad categories of outcomes: SDN-1. SDN-2 and SDN-3:

- SDN-1 events (and the resulting organisms) involve the creation of a double-stranded break in the DNA, and then the insertion of a mutation during the error-prone DNA repair mechanisms. These organisms are not considered to be GMOs in many jurisdictions (including Australia).
- SDN-2 events (and resulting organisms) have targeted mutations that are guided by the addition of a short DNA template with the altered DNA sequence. Because the foreign DNA is integrated into the genome, these organisms are commonly considered to be GMOs.
- SDN-3 events (and the resulting organisms) are similar to SDN-2, but the inserted DNA is a larger sequence such as a foreign gene, and the resulting organisms are generally considered to be GMOs.

Genetically modified organism (GMO): Is an organism that has been modified by gene technology, or an organism that has inherited particular traits from an organism (the initial organism), being traits that occurred in the initial organism because of gene technology.

Organism: Is defined in the *Gene Technology Act 2000* as a biological entity that is viable, capable of reproduction or capable of transferring genetic material.

Gene technology: Is defined in the *Gene Technology Act 2000* as any technique for the modification of genes or other genetic material, but does not include sexual reproduction, homologous recombination or any other technique specified in Schedule 1A of the *Gene Technology Regulations 2001*.

Transgenic: Genetically modified to contain foreign DNA.