ROYAL SOCIETY TE APĀRANGI

# Ngā hangarau ā-ira i Aotearoa: Ōna whakamahinga

# Genetic technologies in Aotearoa New Zealand: How they're used

ROYAL SOCIETY TE APĀRANGI

# Ngā ihirangi
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This project is web-first.

The full content is available at https://www.royalsociety.org.nz/what-we-do/our-expert-advice/all-expert-advice-papers/genetic-technologies-in-aotearoa-new-zealand

# Ngā hangarau ā-ira i Aotearoa
# Genetic technologies in Aotearoa New Zealand

## He kupu whakataki
## Introduction

Here in Aotearoa New Zealand, scientists develop world-leading gene technology innovations in research labs every day. Many imported foods contain genetically modified ingredients and we already have gene-edited New Zealanders walking amongst us – the beneficiaries of life-saving gene therapies being trialled here. Today, the potential of new genetic technologies is exploding as techniques, including ones that use machine learning and artificial intelligence (AI), rapidly improve (1–3).

Aotearoa New Zealand has a complicated history with gene technologies, which goes back over 30 years. Our current regulations are among the strictest in the world (4,5). Researchers are allowed to alter genes of approved species inside the lab, but it is extremely difficult to get approval to apply this science outside the lab (for example, growing gene-edited crops outdoors).

In 2026, the way gene technologies are regulated may be changing with a new Gene Technology Bill being considered at Parliament.

As discussion increases about expanding the use of gene technologies in Aotearoa New Zealand, so does kōrero about what this means for our unique environment, economy, culture, and te ao Māori.

This paper is one of two:

- Genetic technologies in Aotearoa New Zealand – how they work
- Genetic technologies in Aotearoa New Zealand – how they're used.

With these publications, Royal Society Te Apārangi aims to help people better understand gene technologies – and the issues surrounding them – so more communities can join these important conversations.

## He aha ngā hangarau ā-ira?
## What are genetic technologies?

Genetic technologies are a collection of techniques applied to DNA.

In this report, we have divided genetic technologies into two broad categories:

1. 'Reading' DNA: DNA sequencing and genomics
2. Making changes to DNA: gene editing and genetic modification.

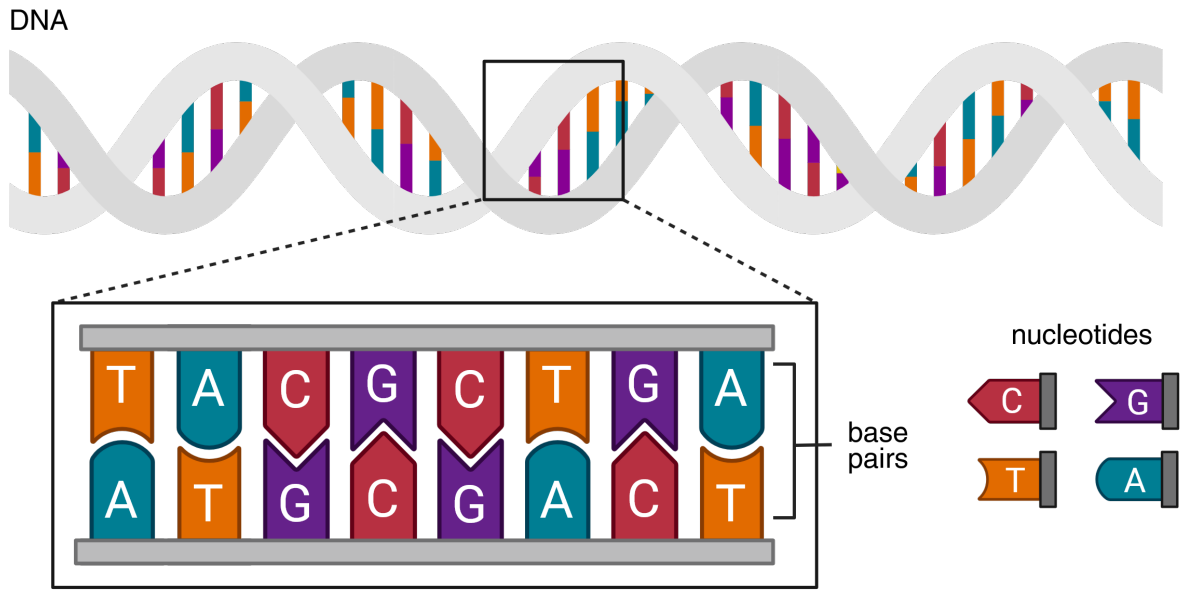
We use the term *genetic* technologies when referring to both reading and changing DNA. *Gene* technology refers to techniques for *changing* DNA, but we typically use either gene editing or genetic modification.

### He aha te pītau ira?
### What is DNA?

DNA is a molecule in almost all living things that carries genetic instructions used in development, general functioning, and reproduction.

DNA is collected and studied by researchers for wide-ranging reasons. These include informing the development of food varieties, gaining insights into the genetic causes of disease, and supporting conservation programmes.

FIGURE 1 | A DNA molecule consists of two strands that wind around one another to form a shape known as a double helix. The genetic instructions it carries are spelled out in nucleotides (A, T, C, G) that form base pairs that are the rungs of the DNA ladder.

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## Ngā hangarau ā-ira me ngā tikanga matatika
## Genetic technologies and ethics

Genetic technologies can be controversial worldwide, including in Aotearoa New Zealand. Concerns most often relate to the ethics of changing genes in food, people, and animals, and to issues of inequity, Indigenous rights, and privacy (both reading and changing genes).

Robust conversations about gene technology in this country have been taking place since the 1980s and are described in detail in these references (6–9).

## Ngā hangarau ā-ira me te ao Māori
## Genetic technologies and te ao Māori

In te ao Māori, the Māori worldview, DNA is linked with whakapapa, the genealogy of all human and non-human life, including animals and plants (10,11). Genetic material (DNA and the tissue it is extracted from) and associated data are tapu, sacred, and taonga, treasures (8,10,11).

Te Tiriti o Waitangi, this country's founding document, affords Māori tino rangatiratanga, absolute sovereignty, over taonga katoa, everything that is precious (12). In 2011, the Waitangi Tribunal report WAI262 identified data as a taonga (13,14). Māori therefore have an interest in protecting and governing genomic data related to Māori and taonga species, and benefitting from genomic research (9, 11). Changing DNA through gene technology modifies whakapapa. Genetic modification, which introduces foreign genes with different whakapapa, is often of greater concern to Māori than gene editing, which makes small changes to existing genes (8). However, it is important to assess the impacts of gene technology applications on a case-by-case basis (8). Perspectives vary between and within iwi, tribes – there is no single, universal Māori consensus on this issue (8,9,15).

### Tikanga and mātauranga Māori-guided gene technology research

Leading Māori researchers, in collaboration with iwi, strongly recommend that research in genetic technologies in Aotearoa New Zealand (genomics, gene editing, and genetic modification) be co-created with Māori (8,9). Māori and tangata Tiriti, Pākehā, researchers have developed multiple ethical frameworks to guide genetic research processes (7,11,13,16–23).

Co-created research projects involve engaging with Māori early and often throughout the research process (9). They are led by tikanga, protocols, and incorporate Mātauranga Māori and te ao Māori values to ensure genetic material is treated with respect (9). Māori data sovereignty and Māori data governance may require that genetic data is stored on local servers with access controlled by kaitiaki iwi (such as the Aotearoa Genomic Data Repository (24)), ensuring the information is used only for consented purposes (8).

Te ao Māori values are beginning to be applied more widely in genetic research in Aotearoa New Zealand (see examples below). Surveys have suggested that tikanga-led approaches to gene editing have strong support from both Māori and non-Māori (9).

### Collaborative and Māori-led projects

Examples in genomics (collecting, recording, studying genetic information):

- Kauri trees and myrtle rust – projects using DNA sequencing to track a disease that endangers kauri ngahere, forests (25–29)
- Ngā Iwi i Te Rohe o Te Waiariki – an aquaculture project supporting the development of yellowtail kingfish (30)
- Hector's and Māui dolphins – a project using genomics to aid conservation of these endangered taonga species (31)
- Explore more examples in these references (32–39).

An example of gene technology (*changing* DNA via gene editing or genetic modification) is Rākeia te Momo – a research project focused on turbocharging plant production (40).

## Ngā mōtika o ngā iwi taketake me ngā raraunga huinga ira
## Indigenous rights and genomic data

Māori and other Indigenous Peoples have a long history of experiencing inequity in, and harm from, genetic research (41–43) (discussed below in Genetic data collection and inequity). In response, several declarations have been developed. For example, the 2007 international United Nations Declaration on the Rights of Indigenous Peoples, Article 31 (44) states:

> **Indigenous Peoples have the right to maintain, control, protect and develop their** cultural heritage, traditional knowledge and traditional cultural expressions, as well as the manifestations of their sciences, technologies and cultures, including human and **genetic resources**, seeds, medicines, knowledge of the properties of fauna and flora, oral traditions, literatures, designs, sports and traditional games and visual and performing arts. They also have the right to maintain, control, protect and develop their intellectual property over such cultural heritage, traditional knowledge, and traditional cultural expressions.
>
> – 2007 United Nations Declaration on the Rights of Indigenous Peoples, Article 31 (44)

The 1997 Universal Declaration on the Human Genome and Human Rights (45) states:

- 'Everyone has a right to respect for their dignity and their rights regardless of their genetic characteristics'
- Genetics are 'expressed differently according to each individual's natural and social environment including the individual's state of health, living conditions, nutrition and education'
- Genomic research on people shall only occur if it is deemed safe and 'prior, free and informed consent of the person' is obtained
- 'The human genome in its natural state shall not give rise to financial gains' (45).

The 1992 Convention on Biological Diversity and the 2014 Nagoya Protocol recognise Indigenous rights to and interests in non-human genomic data (46). The Nagoya Protocol is an international treaty for the fair and equitable sharing of benefits arising from the use of genetic resources and associated traditional knowledge (46). The protocol requires users to exercise due diligence and follow the national access and benefit-sharing regulations of the country where the genetic resource was accessed, with consequences for non-compliance (46). The Protocol entered into force in 2014 with the required 50 ratifications (47). Aotearoa New Zealand has neither signed nor ratified the Nagoya Protocol (48,49).

Indigenous rights relating to genetic resources and data are further discussed in these references (33,41,50–53).

## Te whakaemi raraunga ā-ira me te tautika-kore
## Genetic data collection and inequity

All peoples should be able to benefit from information gained from DNA sequencing. Most genetic data, however, is currently collected from people in North America, Europe, and East Asia – wealthy, developed nations that can afford to collect, store, and investigate the information (52). Groups whose data is not recorded and studied can therefore be disadvantaged (52) – for example, when medicines are developed based on only a select group's genetic information and needs.

For us in Aotearoa New Zealand, this inequity means that Pākehā can benefit from genomic information from their ancestral homes in Europe, while Māori, Pacific peoples, and people from other minority groups have less ancestral data to draw on (54,55).

Māori and other non-European communities have good reason to be cautious of sharing genomic information with researchers. The field of genetics has been known to take from, but not give back to, Indigenous Peoples (42). A generalised example is using DNA from Indigenous Peoples to develop a product from which the Indigenous community does not receive any commercial benefits.

Genetic research in healthcare, in particular, has a history of inflicting harm upon Indigenous Peoples (42,56). For example, a variant of the gene MAO[1] was labelled the 'warrior gene' and used to perpetuate harmful stereotypes about violence and Māori men (58). This has been debunked and condemned as bad science (59–62), but events like this stoke distrust in genetics for many Māori.

Māori researchers are tackling these inequities and complicated histories through Māori-led hauora healthcare initiatives, including the development of the Aotearoa New Zealand genomic variome (54,63). A variome is a collection of all the different genomes that exist within a population (in this case Aotearoa New Zealand with an emphasis on Māori). It shows how each genome differs from a 'standard' human genome. An Aotearoa-specific variome or gene bank is a powerful resource when using Māori data in service of positive Māori outcomes (55,63,64).

Māori and other Indigenous Peoples' voices are essential to discussions about genetic records (41,54,55) and privacy (41,65), discussed next.

## Ngā hangarau ā-ira me te noho tūmataiti
## Genetic technology and privacy

Your DNA isn't yours alone. If you share your genetic data, you also share information about your parents, siblings, children, and even distant relatives – whether they have given consent or not.

Privacy of personal genetic data is a growing concern. Some people are worried, for example, that health and life insurance companies could withhold coverage for people who are shown to have a genetic predisposition to certain diseases, such as cancer or cardiovascular diseases. Genetic discrimination such as this is already happening in Aotearoa New Zealand (66). Concerns like this can lead to people not taking part in genetic studies (67), which may limit healthcare research and treatment options (68). As of 2025, Aotearoa New Zealand does not have legal protections over genetic health information (66,69) but several countries, including Australia and the United Kingdom, do (70).

Several online genealogical databases – to which you might send a saliva sample to learn about your genetic heritage – have been shown to be at risk from hacking (71) or have gone into bankruptcy without a plan for the extensive DNA data they store (72,73).

If collected and used ethically, however, large databases of genetic information could lead to benefits for society that could outweigh an individual's rights over their data (74). For instance, in healthcare, studies of genetic trends could lead to advances in public health, such as predicting risk factors for cardiovascular disease and identifying the best preventative medicines for people with particular genetic profiles. Large databases of genetic information could, on the other hand, be misused – for example, for profit, surveillance, or violating privacy.

Regulations about who can access genetic information do exist (74), although standards for data collection and privacy protection differ around the world (75). A lot of data is international (that is, stored in online databases whose servers are based overseas), so regulation on a single-country level is not enough (76). In te ao Māori, it may be important for genetic data from tangata whenua, Māori, and taonga species (see Genetic technologies and te ao Māori (pg 5)) to be kept in Aotearoa New Zealand and governed by iwi (11,14,16,17,24,41,51).

1 The MAO gene encodes monoamine oxidase, an enzyme involved in breaking down neurotransmitters such as serotonin and adrenaline (57). A genetic study related particular MAO gene variants with aggressive behaviour in Māori men (58).

# Te pūnaha hauora
# Healthcare

Genetic technologies (for either reading the sequences of or changing our DNA) have many important roles in healthcare.

Technologies for reading DNA, such as PCR (polymerase chain reaction) and sequencing technologies, have become integral to diagnosis, tracking infectious diseases, and learning about our genealogy.

Genomics and sequencing technologies are particularly useful in personalised medicine (also known as precision medicine). This is a developing field where healthcare is tailored to the needs of the individual rather than applying a one-size-fits-all approach (77,78).

Gene editing (to change DNA) is a common tool enabling the manufacture of many important medicines. It is also used in the developing field of gene therapy to treat diseases by changing a person's genes. Aotearoa New Zealand has hosted several clinical trials for gene therapies to treat rare disorders (79–84), so we already have gene-edited people in our communities.

## Te whakaraupapa ira me te huinga ira i te pūnaha hauora
## Gene sequencing and genomics in healthcare

Genetic technologies, such as PCR and sequencing, that allow us to read DNA can be used to:

- **Diagnose diseases, including:**
  - **Inherited genetic disorders**

    Genetic disorders that are caused by a single change in a single gene are the most straightforward to test (an example is cystic fibrosis). However, tests also exist for more complicated disorders that are caused by multiple genes.

    To develop a genetic test for a disorder, researchers must first study the disorder and identify which gene variants are causing it. This means tracing the genetics of affected families to isolate the cause. It is particularly important to do work in Aotearoa New Zealand because international researchers likely will not study the genes of Māori and Pacific peoples, who have different genetic histories and risks than Pākehā (55).

    Routine genetic tests in Aotearoa New Zealand include prenatal testing for disease-causing DNA changes and heel-prick tests in newborns for metabolic disorders that would benefit from immediate treatment.

  - **Infectious diseases**

    PCR tests and sequencing technologies are used to identify infectious diseases like COVID. They can also be used to identify the strain of virus or microbe behind the infection – knowledge which can be important for public health measures and vaccine development.

    *Case study:* A Wellington neonatal intensive care unit uses whole genome sequencing to identify infections in pre-term babies before illness can spread. In 2022, two babies had eye infections that turned out to be due to methicillin-resistant *Staphylococcus aureus* (MRSA) (85). All babies in the unit were rapidly tested and six babies without symptoms were quickly quarantined to halt the spread.

  - **Cancers**

    Sequencing technologies help health professionals and researchers detect and classify active tumours and identify which treatments would be most appropriate. Sequencing and PCR can also be used to identify gene variants that indicate a risk for developing cancers that can be inherited.

    *Case study:* Hereditary Diffuse Gastric Cancer is a deadly form of stomach cancer that is common in the McLeod whānau, family, in the Bay of Plenty. Whānau members teamed up with geneticists who paired DNA analyses with the whānau's deep knowledge of their whakapapa, genealogy, and found the genetic variant (version of a gene) that causes their cancer (86).

With this information, individuals can be screened for the gene variant and opt for preventative surgery before cancer develops. This research has saved over 400 lives in Aotearoa New Zealand and won Te Pūiaki Putaiao Matua a Te Pirimia, the Prime Minister's Science Prize in 2023 (87).

- **Choose appropriate treatments or preventions**

  Our genetics affect how our bodies respond to different drugs. The study of this is called pharmacogenomics and is an important part of personalised medicine (adapting healthcare to the individual). Sequencing technologies can be used to identify which treatments and dosages are appropriate for a patient.

  *Example:* certain types of chemotherapy for breast cancer are only appropriate if the tumour is HER2 positive (88) (meaning there is a lot of the HER2 protein, the target of the treatment). A genetic test can determine whether a tumour is HER2 positive.

  *Example:* drugs for pain relief like codeine are activated by a liver enzyme called CYP2D6 (88). Some people have an over-active enzyme, so codeine doesn't work well because it is processed too quickly. Other people have an under-active enzyme, so codeine is not activated and these people don't benefit from its analgesic properties. A genetic test would help doctors prescribe the safest, most effective pain relief and appropriate dose.

- **Track infectious diseases**

  Sequencing the DNA of diseases – human, animal, or plant – helps researchers, public health organisations, and government agencies keep tabs on where in the country disease-causing microbes are, whether numbers are rising, and whether they are evolving.

  Wastewater monitoring for COVID-19 is an important example in Aotearoa New Zealand. These measures allow public health to detect rises in cases without relying on people to test and report.

- **Unlock the past through DNA**

  - PCR is used to compare genetic variants within families for paternity testing and help adopted children find their biological families.

  - PCR and sequencing allow us to learn about whakapapa through ancestry testing: commercial genealogy companies can use regions of our DNA to find out which countries our ancestors were from.

    In-depth genetic studies have confirmed oral histories about Māori settlement of Aotearoa (89–92) and the journey of the first humans out of Africa 65,000 years ago.

  - We can also learn about our ancestors directly through ancient DNA. For example, DNA, extracted from the plaster casts of huddled people, was used to learn about relationships between victims at Pompeii and even (in some cases) their eye colour (93,94). Ancient DNA has also been recovered from moa bones (95–97) and the kiwi feathers in kākahu Māori cloaks (98), helping us tell our histories in Aotearoa.

## Te rāwekeweke ira i te pūnaha hauora
## Gene editing in healthcare

Gene editing (rewriting short stretches of DNA) can be used to treat or cure genetic disorders and cancers.

### Gene technology to make medicines

Genetic modification (large changes to DNA, may include 'foreign' genes) and gene editing (small, precise changes to DNA) are essential tools for developing and producing many important medicines. Drug production of this kind often uses microorganisms in fermenters, much like in beer or yoghurt making.

These medicines include:

- Hormones – eg, insulin to treat diabetes or growth factors to treat growth disorders
- Antibodies – eg, monoclonal antibodies to treat COVID-19 or Herceptin to treat breast cancer

- RNA[2] drugs – eg, RNA drugs to attack RNA viruses such as CMV[3] or the function of disease-causing genes (eg, an RNA treatment for Spinal Muscular Atrophy (100))
- Vaccines – the active vaccine component can be either protein (eg, yearly flu vaccines and most childhood immunisations) or mRNA (such as some COVID-19 vaccines). Both require gene technology.

Gene technology is also an essential tool for the growing field of RNA-based medicine. Aside from gene therapy (discussed below), RNA can be used for rapid vaccine development and many other important applications (101,102).

## Te rāwekeweke ira i te haumanu ira
## Gene editing in gene therapy

### What is gene therapy?

Gene therapy is a medical approach that treats or prevents disease by using gene editing (among other technologies) to correct the underlying genetic problem (103–106).

Gene therapy can target DNA or RNA (102). CRISPR[4]-based systems allow precise gene editing with smaller changes than older genetic modification techniques. (Read more about gene editing and CRISPR in Genetic technologies – how they work.)

Gene therapy can:

- Introduce a new gene
- Tune an existing gene's activity
- Edit a gene directly.

Depending on the genetic disorder, gene therapy can treat it by supplementing the protein the gene should be making or getting rid of protein if there is too much or it is not behaving properly (107).

2 RNA, ribonucleic acid, is a single-stranded nucleic acid with multiple important functions in the cell.

3 CMV stands for cytomegalovirus. It is a common virus that is harmless to most people but can be dangerous to people who are pregnant or have compromised immune systems (99).

4 This stands for clustered regularly interspaced short palindromic repeats

Gene therapy can:

- Take place outside the body (*ex vivo*) (104) – eg, blood cells removed from the patient, modified, and then replaced like in CAR[5] T-cell therapy (when a patient's immune T-cells are genetically modified to recognise and attack cancer cells)

or

- Take place inside the body (*in vivo*) (104) – eg, genetic cures for hereditary angioedema (a swelling disorder) (82).

### Non-heritable gene editing

The type of cell that is edited determines whether changes to a person's genes are inherited by their potential future children:

- Reproductive cells (germline cells): any gene edits are inherited by future children
- Non-reproductive cells (somatic cells), which make up most of the body: gene edits are not inherited by future children.

As of 2026, all gene therapies available worldwide and currently under development affect only the people who receive treatment, not their children (discussed further on pg 16).

## Ka pēhea te whakamahia o te haumanu ira?
## How is gene therapy used?

### Gene therapy for cancer

Cancer is a genetic disease. It occurs when errors in DNA (either inherited or caused by carcinogens, such as UV radiation or cell misfunction) lead to uncontrolled cell growth, which forms tumours. Our immune system then struggles to distinguish tumour cells from healthy ones.

Traditional cancer treatments, such as radiation and chemotherapy, have well-documented significant side effects.

Gene editing as a cancer treatment is in its infancy, but it can potentially be used to:

- Treat cancer – by helping our existing immune defences fight tumours.

5 This stands for chimeric antigen receptor

*Example:* A new form of immunotherapy called CAR T-cell therapy uses our own T-cells – white blood cells that coordinate immune responses and directly kill infected cells in the body (108) – to target and attack cancer cells (108). Several treatments are available internationally, but the price is prohibitive (109) and side effects can be severe (110).

Clinical trials are underway in Aotearoa New Zealand to develop CAR T-cell therapy to treat blood cancers (79,80). Domestic manufacturing to keep costs of treatment down is also being explored. Overseas, CAR T-cell therapy is showing promise for the treatment of solid tumours (111–114) and even autoimmune disorders[6].

- Prevent cancer – by fixing heritable genetic variants that make cancer more likely. However, because this would require the use of germline gene editing, it is not currently being considered, but there are alternative approaches[7].

## Gene therapy for genetic disorders

Gene therapy is a treatment that addresses the genes (or gene products) that cause a disease, rather than a disease's symptoms.

Currently, gene therapy is only practical when a small change is required in just one location in the genome. Fortunately, many genetic disorders are due to a single DNA letter change (a single nucleotide variant or a SNV[8]) in a single gene.

Most single gene disorders are very rare but combined they occur at about 1% of the world population. An estimated 200,000 to 300,000 New Zealanders live with a genetic rare disorder (119,120) (defined as affecting fewer than or equal to 1 in 2,000 people (121)). Well-known examples are muscular dystrophy and cystic fibrosis, which affect around 1000 (122) and 600 (123) New Zealanders, respectively.

To date, gene therapy has not been designed for disorders caused by multiple genes (multifactorial disorders). For example, gout (a disorder that causes painful swelling in the joints) is a common example of a multifactorial genetic disorder (124) and affects people of Māori or Pacific descent at greater rates than Pākehā (125,126).

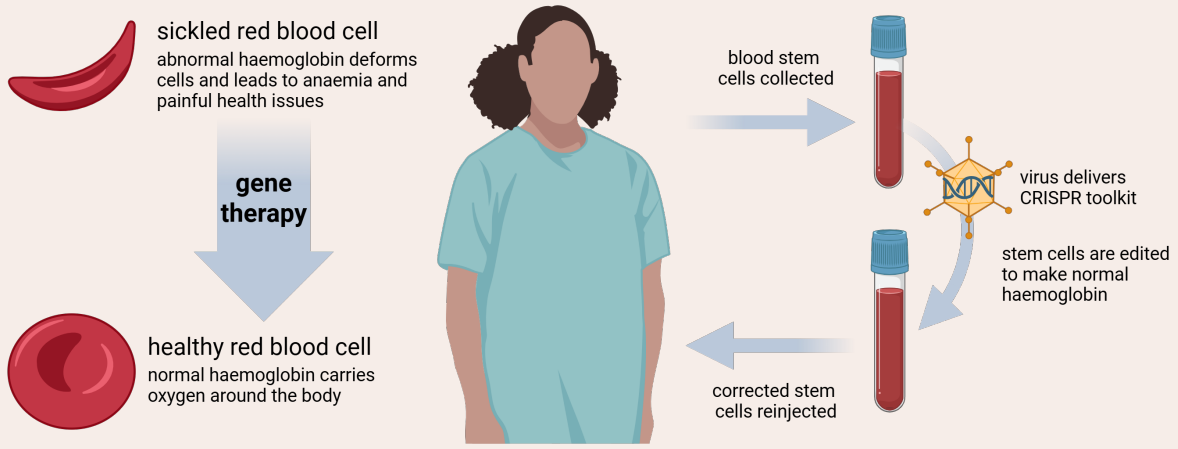
At the time of publication in 2025, 38 gene therapies have been approved for use in people by the FDA in the US (127) and about 500 more are in the pipeline. Two have been approved for use in Aotearoa New Zealand (128,129).

6 Clinical trials are underway for CAR-T cell therapies for rheumatoid arthritis, multiple sclerosis (115,116), lupus , and similar disorders . At time of writing, there have been about 40 clinical trials (115). Lab trials (pre-human testing) are testing CAR-T cell treatments for type I diabetes.

7 In some family situations, if a parent knows they are a carrier of a cancer-causing gene, IVF with genetic screening (117) could be sufficient to avoid inheritance.

8 SNVs are common (we each have 5–6 million SNVs in our genomes (118)) and usually do not cause disease. In fact, they are responsible for the genetic traits that make us unique.

FIGURE 2 | Sickle cell anaemia gene therapy

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## First CRISPR gene therapy cures sickle cell anaemia

One of the most prominent recent gene therapies – and the first to use CRISPR gene editing[9] – is a treatment for sickle cell anaemia and transfusion-dependent β-thalassemia (130–133). These are both blood disorders caused by SNVs in the gene that encodes haemoglobin, the protein that carries oxygen in our red blood cells. Both are serious disorders that can be deadly without treatment and affect about 8 million people globally[10] (134).

There has never been a cure for sickle cell anaemia (named for the crescent, or sickle, shape of the affected red blood cells), only treatment and pain management. Patients are likely to require blood transfusions and bone marrow transplants (135); sufferers are also at higher risk of infection and stroke (135).

The one-time gene therapy CASGEVY is an *ex vivo* (occurring outside the body) treatment that works by editing red blood stem cells to switch on the gene for foetal haemoglobin, which then produces a functional protein to compensate for the faulty adult protein (132,136,137). Twenty-nine of 30 eligible patients in the clinical trial went from multiple pain crises every year to zero in 12 months following treatment (138). There were no significant side effects from the treatment, but the FDA requires patients be closely monitored for 15 years for lasting impacts (138). The treatment was approved in the UK and US in 2023 (139–141) and the EU in 2024 (130).

CASGEVY, like all gene therapies, is prohibitively expensive: as of 2024 it cost 2.2 million USD per treatment (142). For more on this topic, see The costs and ethical considerations of gene editing in medicine (pg 14).

9 Other approved gene therapies mostly work by providing a missing gene without inserting it into the patient's own genome.

10 Incidence is low in Aotearoa New Zealand because the genes are most common in people of sub-Saharan African descent.

## Gene therapies under development

Clinical trials in humans are – as of 2025 – underway eg, (143) for gene-editing treatments to treat cardiovascular diseases (81,84,144–149), haemophilia (150), HIV AIDS (151–153), metabolic disorders (154,155) such as diabetes (156), muscle wasting disorders (157–159), dementia (148), chronic urinary tract infections[11] (161), congenital vision loss (162–164), congenital deafness (165), fragile skin disorders (166,167), hereditary angioedema (a swelling disorder) (82), and many more genetic disorders.

Gene therapies for many other conditions are at earlier testing stages in the lab. One example is a treatment that appears to reverse the premature aging disorder Hutchison-Gilford progeria[12] in mice (168), and another that edits lung cells to treat cystic fibrosis[13] (169–171). A long-term cure for diabetes (172) using gene therapy would improve the lives of millions around the world.

## Gene therapy in Aotearoa New Zealand

A number of these clinical trials are taking place in Aotearoa New Zealand (81,82,84,145–147,173), so we already have gene-edited people in our population.

Early trials included treatments for:

- Hereditary transthyretin amyloidosis, a rare disorder where buildup of faulty proteins[14] causes damage to the heart and nerves (81). The first clinical trials for a treatment using gene therapy were co-hosted by Aotearoa New Zealand (81). The *in vivo* therapy uses CRISPR to remove the disease-causing protein in the liver (and only the liver) (81). Early trials were successful; safe for patients and leading to lowered levels of the faulty protein (81). As of 2025, this drug is still in the clinical trial stage (174)
- Hereditary angioedema, a painful swelling disorder that can be deadly if it blocks airways. Aotearoa New Zealand co-hosted the first clinical trials of a gene therapy to treat the disorder (82,83), led by researchers in Auckland. The *in vivo* treatment delivers Cas9[15] and guideRNA to the liver, where it inactivates a gene that encodes a protein that is overactive in this disorder[16] (82). Early results were promising: the drug is safe and a single dose appears be sufficient for lifelong treatment (83). As of 2025, this drug is still in the clinical trial stage (175)
- High cholesterol and cardiovascular diseases due to familial hypercholesterolaemia and related disorders of cholesterol and lipid (fat) metabolism. New Zealanders have participated in clinical trials for two different gene therapies to combat treatment-resistant high cholesterol (84,146), one of which was developed by New Zealand and Australian researchers[17] (84).

  Cholesterol-lowering gene therapy could benefit millions of people with and at risk of cardiovascular diseases. Treatments

11 In this treatment, gene therapy targets the bacteria in the gut, rather than the person's own DNA (160).

12 Children with this disorder typically die at about age 14 (168).

13 Cystic fibrosis poses a huge challenge to gene therapy because immune defences in the lungs make it very difficult to deliver inhaled treatments into cells (169).

14 Mutations in the gene encoding transthyretin cause the protein to misfold (form the wrong three-dimensional shape) and aggregate into atypical fibres called amyloids in the nerves and the heart (81). These amyloids cause tissue damage and life-threatening disease (81).

15 This stands for CRISPR-associated protein 9.

16 The gene encodes a protein called Kallikrein, which, in people with the disorder, makes organs 'leaky' and causes swelling (82). Loss of the protein has no other detectable effects on health (82).

17 The therapy developed in Aotearoa New Zealand, CTX310, uses CRISPR *in vivo* to target and disable a liver gene that usually produces a protein in the liver, ANGPTL3 (84). ANGPTL3 acts to inhibit lipases, enzymes that break down lipids (fat), so when it is non-functional, lipases are more active and more fat is broken down (84). People with naturally low ANGPTL3 have low levels of cholesterol-rich fat particles called low-density lipoproteins (LDL) and reduced risk of atherosclerotic cardiovascular disease (176). Early results from the clinical trials show that the treatment is safe and successfully lowers ANGPTL3 levels.

The other gene therapy, VERVE-101, was developed overseas and phase 1 trials were conducted in Aotearoa New Zealand and the UK (177). It uses *in vivo* CRISPR to disable a gene that encodes the protein PCSK9, which regulates LDL-cholesterol processing (146). People with naturally low PCSK9 levels have low LDL-cholesterol and low rates of atherosclerotic cardiovascular disease (146). Early results from the gene therapy trials show that patients had significant reductions in PCSK9 and LDL-cholesterol (146,147). For more on PCSK9, see our publication Gene Editing Scenarios in Healthcare (178).

could be broadly applicable as gene edits do not have to treat the specific genetic cause, which can vary widely between people, just the resulting elevated cholesterol.

Researchers in Aotearoa New Zealand are also doing pre-clinical studies into gene therapies for epidermolysis bullosa (a fragile skin disorder) (179,180) and Batten disease (a degenerative, deadly childhood disease) (181–183). The gene therapy targeting Batten disease was developed in Aotearoa New Zealand through studies in sheep (181,182) and mice (183), and is currently undergoing clinical trials in humans in the US and UK (184).

### Regulating gene therapy

Cost is more of a stumbling block to the development of gene therapies than regulation. Under the proposed 2024 Gene Technology Bill, humans are not 'regulated organisms' (185). As with any medical procedure or product, gene therapies would be subject to rigorous efficacy and safety requirements under other legislation. At the time of publication in 2026, Aotearoa New Zealand has and is hosting several cutting-edge pre-clinical and clinical trials, but few have been approved[18] (128,129) and none are funded.

Read more about costs below.

### Delivering gene therapy: How to get CRISPR into human cells

The biggest challenge of gene therapy is getting the therapy to the right cells in the body. The first gene therapies have all involved blood cells because they are easy to access – getting treatment inside a solid organ is a lot harder.

Many *in vivo* gene therapies use hollowed-out viruses as vehicles called vectors to deliver genes and gene editing machinery (107,188). The viral packages cannot cause infectious disease[19, 20], but our immune systems learn to recognise them like they would a vaccine. This effectively makes these types of *in vivo* gene therapy a one-shot treatment – a second dose could cause a dangerous immune response (191).

At time of publication, one person has died as a result of a CRISPR gene therapy clinical trial (192). This was due to the delivery method, not the gene edit or the CRISPR machinery (192).

Research is underway to try to solve the delivery problem to increase treatment options (191); one alternative is to deliver treatments via nanoparticles (193,194), similar to the ones used for RNA vaccines. The clinical trials for gene therapies in Aotearoa New Zealand described above all used liponanoparticles (tiny fat capsules) for delivery (81,82,84,147).

## Ngā utu me ngā take matatika hei wānanga mō te rāwekeweke ira i ngā mahi rata

## The costs and ethical considerations of gene editing in medicine

Gene editing in healthcare holds huge promise for people living with (or pre-disposed to developing) a wide variety of disorders and illnesses. As described above, gene therapy and related treatments can save lives and greatly improve quality of life.

These benefits, however, must be weighed against the costs of gene editing in healthcare – financial, physical, and ethical – which can be substantial:

- **Financial costs**
  Internationally, the financial costs of gene editing in medicine are staggering. Many gene/cell therapies cost hundreds of

18 Treatments include gene therapy for Leber congenital amaurosis, a rare disease affecting vision in children (186), and spinal muscular atrophy, a childhood muscle wasting disorder (187). Both are gene therapies but neither involves gene edits to patients' genomes.

19 Only the viral coat (called a capsid or envelope) is used. Scientists use viruses because they are so good at infecting human cells – the proteins on the coat are specialised to recognise and bind proteins and sugars on the outside of human cells, and then get the virus and/or its genetic material inside. Viral coats are often specialised to only bind and infect specific cell types, like lung or liver, which is a helpful function for gene therapy. The viral coats used in gene therapy do not carry any of the original viral DNA so they cannot replicate (make more viruses) or infect more cells.

20 Some early gene therapy trials had high rates of cancer in participants because the viruses used as vectors disrupted cancer-causing genes (189,190). CRISPR's precision minimises this risk in today's gene therapies.

thousands, or even millions, of US dollars per treatment (142,195–197). Gene/cell therapies are very new, very labour intensive to develop, typically service small markets (ie, people with very rare disorders) with little competition, and are often personalised to the patient, all of which push the price up.

These prices mean that – unless covered by health insurance or government healthcare – the treatments are only truly accessible to self-funders (198). Some pharmaceutical companies have pledged to provide a certain number of treatments for rare conditions for free each year (199); others have withdrawn their treatments from places where the government is unwilling to pay (200,201) or abandoned projects (202).

Determined families affected by rare genetic disorders and cancers raise money (203) and advocate for research into lifesaving treatments to continue. Governments (204,204), hospitals (205), charities (204,206,207), and academics (205) sometimes try to bypass for-profit companies to provide treatment to people in need. Academics and policy-makers have proposed new ways to value and pay for therapies (208,209).

There is an argument that gene and cell therapies are actually cost *saving* when you take into account the lifelong costs associated with traditional treatments (210,211). By one 2023 estimate, the medical costs of supporting a person with sickle cell anaemia to the age of 64 was $USD 1.7 million (212). In this context, a one-time payment of $USD 2.2 million (213) for a cure via gene therapy is much more reasonable.

In contrast, future gene therapies for common conditions, such as high cholesterol (145) or diabetes (156), could hopefully become affordable over time, given the economy of scale.

- **Physical costs**
  Gene and cell therapies are not always straightforward. Treatments differ, but many for treating blood disorders require the patient to go through chemotherapy to kill off bone marrow containing faulty genes before they receive gene-edited cells with a functional version of the gene (214). Side effects of the various gene and cell therapy treatments can include higher risk for cancer (215).

  Many traditional treatments, on the other hand, are onerous, painful, and carry risks of significant side effects. For instance, people with hereditary angioedema experience unpredictable debilitating swelling, which can be life-threatening if it affects the airways (216). The disease can be managed with heavy-duty steroids (217,218), but this is often not enough to stop attacks from happening and steroids can cause damage to the liver (219).

- **Ethical considerations**
  The 1997 Universal Declaration on the Human Genome and Human Rights, Article 10 (45), states that:

> No research or research applications concerning the human genome, in particular in the fields of biology, genetics and medicine, should prevail over respect for the human rights, fundamental freedoms and human dignity of individuals or, where applicable, of groups of people.
>
> – 1997 Universal Declaration on the Human Genome and Human Rights, Article 10 (45)

Every country, culture, and community has differing perspectives on gene editing in healthcare. There are arguments regarding safety, consent, equity, disability rights, and eugenics. These complicated issues are discussed in depth in these reports in the references (221–229).

### Te Tiriti o Waitangi obligations

In Aotearoa New Zealand, we have obligations to te Tiriti o Waitangi and te ao Māori when considering gene technology for healthcare and wider applications. Our genes are inextricably linked with whakapapa and are considered taonga (8,10,11).

One example of culturally responsive healthcare research is a clinical trial for gene therapy that treats familial hypercholesterolemia, which involved Māori experts from the beginning of the process (230). Hui were held with affected whānau and healthcare workers to discuss the disease, its genetics, the clinical trial, and the access, affordability, and data protections surrounding resulting treatments (231). Whānau drove the design of protocols around healthcare, communications, and genetic data (collected and stored in Aotearoa New Zealand) (231).

## Te rāwekeweke i te ira tangata
## Gene editing in people

Gene editing in people is very new and very rare. The only instances in Aotearoa New Zealand have been in clinical trials. Currently, all gene therapies approved for use in humans are of somatic (non-reproductive) cells only. This means that the edits only affect the person receiving the treatment, not their future children. Gene edits that affect the germline (reproductive) cells are not allowed. Germline edits – performed at the embryo stage – are heritable, meaning the changes are passed on to future children.

There are multiple views on these topics. Some people think that any gene editing in humans is okay if it improves health but are less comfortable if it effects less-essential changes to, for example, sporting prowess[21] (178,220). The public and scientists alike have concerns about gene edits that can be inherited by future children (220,228,234–236), which would lead to a permanent change in the population gene pool.

21 See our publication Gene Editing Scenarios in Healthcare (178) for a hypothetical example involving gene edits to increase erythropoietin (a hormone that stimulates red blood cell production (232)) levels in the bloodstream. Erythropoietin has been used in sports doping (233).

### Gene-edited babies

In 2018, there was a global outcry after a researcher in China announced the birth of twin girls whose genes had been edited in an attempt make them resistant to HIV infection[22] (242–244). This led to leading scientists uniting to call for caution regarding germline editing and a hold on research until the technology was better understood (227,229,245–248). Researchers also called for the World Health Organization to develop and impose global standards for the use of these technologies (242,249–252). However, all countries still have their own policies and regulations regarding gene therapy and heritable genome editing (253,254). A survey in 2020 found that 75 countries, including Aotearoa New Zealand, ban or discourage germline editing (254) and none explicitly permit it (254). Regulations are evolving[23].

For further discussion on the ethical and legal considerations of gene editing in healthcare, see our previous publication: Gene editing scenarios in healthcare (178).

22 The researcher, He Jiankui, was imprisoned for three years for his actions (237) and admits that he acted in haste (238). The scientific community has debated whether the genome edits he made would help or harm the two girls (239–241); the unpublished study is full of scientific errors and ethical oversights (241).

23 In October 2024, South Africa updated their health guidelines in a way that appeared to allow germline genome editing in humans (255,256).

## Ngā hangarau ā-ira i te pūnaha hauora: Ngā mea e whakapaetia ana, hei ā hea hoki?

## Genetic technologies in healthcare: What to expect and when?

We hear about new medicines that are in the pipeline, but sometimes it's hard to know what's realistically happening soon. Here's a summary of what to expect:

### Already happening

- Genetic testing
- Disease tracking
- Medicines made using gene technologies (eg, insulin), though many of these are GM (genetically modified) rather than gene-edited.

### Newly available

- Some gene therapies for rare disorders, such as sickle cell anaemia
- Genetic treatments for cancer, such as CAR-T cell therapy
- Rapid development of diagnostics for new infectious diseases.

### 2–10 years away (being tested as of 2026)

- Personalised medicine (for the motivated and the self-funding (typically wealthy))
- More gene therapies, may include treatments for type II diabetes
- More cancer treatments
- 'Humanised' organ transplants from pigs to reduce deadly long waitlists
- Rapid vaccine development to new infectious diseases
- Medicine in our foods, eg, gene-edited cows that produce human insulin in their milk.

### Over 10 years away

- Personalised medicine more accessible
- Genetic treatment for complex conditions, such as Alzheimer's disease
- Personalised organ transplants – organs grown to be a genetic match for you
- MAYBE: germline editing to correct genes that could cause cancer and disorders
- MAYBE: stem cell technologies, when paired with IVF, to help same-sex couples have biological children.

# Te ahumahi mātāmua
# Primary industries

The primary industries – agriculture, horticulture, forestry, fisheries – are essential to Aotearoa New Zealand and important areas for innovation. Genetic technologies have an established and growing role in production and protection of primary industries worldwide. In fact globally, 13% of agricultural land is used to grow genetically modified crops (257).

Sequencing and genomics are used to:

- Track disease
- Aid breeding.

Gene editing and genetic modification can be used to alter plant or animal species to:

- Make foods tastier, appealing, safe, nutritious
- Resist disease, pests, and climate change
- Be more fit for purpose (eg, editing trees to make stronger wood).

While PCR and DNA sequencing are common tools in the primary industries in Aotearoa New Zealand, gene editing is rare due to regulatory constraints (258). Therefore, many gene-editing applications remain hypothetical in this country.

## Te whakaraupapa ira me te huinga ira i te ahumahi mātāmua
## DNA sequencing and genomics in primary industries

DNA sequencing technologies are important tools in primary industries, mainly used in disease management and breeding. These technologies can help growers and farmers innovate without needing to use gene editing, ie, accelerate conventional breeding.

### Disease testing in farm animals

An important application of DNA sequencing technologies in Aotearoa New Zealand is using PCR to screen cattle for *Mycoplasma bovis* (*M. bovis*) bacteria (259), which cause a range of serious health conditions in cows, including pneumonia and arthritis[24].

PCR tests can detect disease before symptoms show, preventing disease spreading between herds. They can be used to test the herd as a whole (by testing the milk from the farm) or individual cows to isolate infected animals (260). PCR is also used to screen imported semen to avoid bringing the disease into the country with breeding stock (261). An ambitious pest-management scheme aims to use tools that include PCR screening to eradicate *M. bovis* from Aotearoa New Zealand by 2028 (259,262).

*M. bovis* – a problem for cattle worldwide – was not detected in Aotearoa New Zealand until 2017 (263). DNA sequencing was used to determine how long the disease had been in the country, how it likely arrived, and where it came from – all important information for minimising harm from the disease (264). The sensitivity and efficiency of these technologies allow biosecurity to be nimble in protecting the cattle industry.

### Help with crop and stock breeding

PCR and DNA sequencing can be used to speed up traditional breeding in agricultural crops, such as fruit trees or pasture grass, and livestock. If breeders know the gene variant required for the desired trait, they can use these technologies to:

1. Identify the ideal parents to get the offspring breeders want, and
2. Identify the desired offspring genetically rather than waiting for the trait the gene encodes to show itself, which could take months or years.

This is called rapid genotyping. Because the growth of gene-edited crops and stock in Aotearoa New Zealand is strictly regulated (258,265), these technologies are a tool to accelerate conventional breeding as local innovators try to keep up with growers and farmers overseas who have access to cutting-edge gene-editing technologies.

In Aotearoa New Zealand, cows have been bred for the 'slick' gene, reducing the thickness of their coats, to keep them cool in changing climates (266,267). Breeders were able to sequence the DNA of calves at birth – rather than waiting to see how they grew up – to make breeding for the trait more efficient.

24 *M. bovis* does not infect humans.

## Te rāwekeweke ira i te ahumahi mātāmua
## Gene editing in primary industries

Gene editing and genetic modification are applied in the primary industries (agriculture, horticulture, and forestry) to foods and materials. Applications include protection from disease, pests, and the changing environment, as well as improving yields and quality to support our growing population.

Progress for gene technology in Aotearoa New Zealand's primary industries has stalled in recent years, compared with faster developments in human health. Our 2019 publication, Gene editing: scenarios in the primary industries (268), is still very relevant today.

Gene editing (making small, precise changes to DNA) has been slower to take the place of genetic modification (which involves making larger changes and introducing foreign DNA) in agriculture and horticulture than in animal and human genetics, partly because plants are harder to edit.

Here's a summary and update on recent developments in:

- Food
- Forestry
- Plant breeding
- Allergies.

### Gene editing and new foods

Gene editing is being used in the primary industries to keep up with the food supply and nutrition needs of changing populations, as well as environmental pressures.

Its applications include speeding up breeding for desirable traits, such as:

- Improved yield
- Shelf-life
- Taste and nutrition
- Hardiness against disease, pests, and climate change.

Gene-edited and genetically modified crops cannot be readily cultivated in Aotearoa New Zealand (258). However, we likely consume genetically modified ingredients – including rice, wheat, soy, and corn – via imported processed foods every day. In the US, 75–90% of soybean, cotton, and corn crops are genetically modified and over half of all crop land grows genetically modified plants (269).

Genetically modified crops use transgenes (genes from different organisms) to introduce a new function. Current research, however, is moving to modern gene-editing techniques utilising CRISPR, where researchers can fine-tune techniques so that edits are small, efficient, and accurate (270,271). Off-target edits are still a concern (272–274) but are rare (273). Further, specialised CRISPR systems and rigorous genetic testing ensure only the desired edits get into approved crops.

### Examples of gene editing in food

For a taste of recent progress in common foods, we can look to corn/maize. Recent gene edits using CRISPR techniques include resistance to the herbicide glyphosate; resistance to diseases such as leaf blight; and improved growth and reproduction under drought or salty conditions (275). Gene tweaks using CRISPR can influence the kernel number per corn cob to improve yield, and change protein levels, texture, and taste (276). Similar changes are being developed in rice and the other grains that provide most our dietary calories.

Recent genetically modified foods:

- Pink pineapples (277): modified to increase lycopene content, a coloured compound that occurs naturally in pineapples
- Impossible burger patties: contain proteins with a plant pigment called leghaemoglobin that looks like haemoglobin, the protein that makes muscle red. The proteins are originally from soy beans but produced by yeast (278).

Recent gene-edited foods:

- Sicilian Rouge tomato (279): edited to contain five times the typical levels of GABA. GABA is a neurotransmitter that aids in relaxation and helps lower blood pressure
- Self-pruning, fast-fruiting tomato (280): developed for urban farming
- Delayed ripening (eg, tomatoes) and non-browning fruits and vegetables: reducing

food waste (eg, potatoes, bananas, apples, eggplant, mushrooms)

- Climate-smart plants: improved heat tolerance (eg, bananas (281) and jasmine rice (282)
- Disease-resistant crop plants: protecting important food crops (eg, bananas (283) and cacao plants (284))
- Tasty greens (285): salad leaves edited to remove bitterness
- Healthy oils: edited to produce more omega-9 fatty acids (eg, soybeans (286), rapeseed (287), and rice (288))
- Low glycaemic index potatoes (289,290): edited to make modified starch molecules that are slow to digest and release energy when we eat them
- Big, high-protein fish (291): edited to grow faster and put on more muscle mass.

## Genetically modified and gene-edited foods – an ongoing discussion

People in Aotearoa New Zealand have been concerned about gene technology and food since the 1980s.

Opponents have voiced the opinion that the technology is unnatural and altering our foods may introduce allergens or give large corporations too much power over seed stocks. Some organic farmers are concerned about cross-pollination between modified crops and their own.

Supporters of the technology often argue that farmers have been reshaping the genetics of our food for millennia – through breeding for improved yield, taste, nutrition, and resilience – and gene editing is merely the latest tool in our toolbox to help feed the world as the population grows and arable land shrinks.

A 2025 survey suggests that New Zealanders feel cautiously optimistic about gene-edited crops (63% would eat), but are less sure about gene-edited meat, dairy, or fish (35-45% would eat) (292).

## Gene technologies and forests

The application of gene editing to forests has been slow. This is for three reasons:

1. Conifer trees – which dominate much of forestry in the western world – have large, complicated genomes and not many have been sequenced
2. Genetic technologies are difficult to use in trees
3. Controversies around gene technologies and strict regulations (293).

However, the technology holds great promise for disease resistance, adapting to climate change, and improving timber quality (294).

### Gene-edited forests in Aotearoa New Zealand

In 2025, Aotearoa New Zealand began the world's first field trial of gene-edited pine trees. Two separate edits are being tested to generate higher quality timber: one will straighten trees' growth so they are better suited to processing, and another will change synthesis of a high-value biopolymer, hemicellulose (295).

Under current regulations, the trees will have to be destroyed after five years – before they can flower – which will not be long enough to get a full picture of the gene edits' effects (296).

The Scion Group at the New Zealand Institute for Bioeconomy Science is also using gene editing to make Douglas fir trees that are sterile – but otherwise unchanged – to help Aotearoa New Zealand's problem with wilding pines (uncontrolled spread of introduced conifer trees) (295). However, under current legislation in 2025, researchers would not be able to test the fertility of these trees in the field (258).

See more about Douglas fir and wilding in our previous publication: Gene editing scenarios in the primary industries (268).

## Gene technologies and plant breeding

Developing new crop plants takes a long time. New fruit cultivars typically take 15–50 years to develop (297,298). Horticulturalists using traditional breeding must grow many generations of plants to get the perfect combination of genes, and generation time is the bottleneck in the process. Plants with desired traits are bred (one is used to pollinate another) and then the plants' offspring must

grow enough to:

1. Show whether they have inherited the desired traits (this can be sped up with DNA sequencing technologies), and
2. Be able to reproduce themselves to repeat the cycle.

### Fruit trees

Fruit tree breeding cycles are slow, usually taking at least ten years per generation (297). Trees (and crop plants), however, can be bred or gene-edited for rapid flowering. This involves engineering environments (299) and genetics (297) to shorten a tree's 'youth' and bypass the normal cellular checks that control timing around flowering. Rapid-flowering apple trees flower within a year (298). Speed breeding using rapid flowering and DNA sequencing technologies can allow 3–9 breeding generations per year (299) for staple crop plants.

For more on fast flowering in apples, see Gene editing scenarios in the primary industries (268).

## Null segregants

Plants that have been genetically modified to allow rapid flowering (gene editing is developing in this area) paired with traditional breeding gives horticulturalists the option to generate null segregants as their final crop. Null segregants are descendants of genetically modified parents but do not contain any edits themselves (in this case, the edits that confer rapid flowering). In 2024, the EPA reclassified null segregants as not genetically modified[25].

This is a win-win situation where breeders can use gene editing to speed up the development of a new product and a cautious public can avoid gene-edited produce. For instance, genetically modified rapid-flowering apple trees are used to develop a new type of apple faster than traditional breeding would allow. However, once the new apple tree has been produced, the genes encoding rapid flowering can be removed from any of its offspring. This means the apples grown for the public would have no traces of genetic modification or gene editing[26].

25 See EPA determination APP204173 (365).
26 https://www.youtube.com/watch?v=GLHatMyQCJs

## Gene editing and allergies

The issue of allergies is often raised in discussions about gene technologies and food.

### Concerns about creating allergens

There is a concern that inserting transgenes (genes from different organisms) – more common in earlier genetic modification techniques than recent ones – could introduce allergens (allergy-causing particles) into otherwise 'safe' foods. Due to these concerns, researchers are discouraged from using genes from known allergens (300).

Food regulators take this concern seriously. Genetically modified and gene-edited foods are subject to safety checks that are more stringent than for other foods.

In fact, there are very few recorded instances of an allergen being introduced. In the 1990s, researchers used a gene from Brazil nuts to alter the amino acid composition of soybeans. However, the beans were identified as a risk to people with Brazil nut allergies (301) and development was halted.

### Using gene editing to remove allergens

Gene editing has been used to remove allergens from our foods and environment. CRISPR has been used to remove common allergens from plant-based foods – including making allergy-safe wheat, soy, and peanuts – while maintaining taste and nutrition (302). Other projects include sterile trees to avoid release of pollen (303) and cows which make milk lacking a protein – β-lactoglobulin – that many people are allergic to[27] (304,305).

A cautious approach is taken in response to fears that gene editing in known allergens could change or introduce new epitopes (the part of the food that enflames the immune system), exacerbating the issue.

Researchers have also developed sensitive molecular tools for rapid detection of trace amounts of allergens in foods (306).

27 Some of this research was happening in Aotearoa New Zealand (see our previous publication, Gene editing scenarios in the primary industries (268)).

## Ngā hangarau ā-ira me te ahumahi mātāmua: Ngā mea e whakapaetia ana, hei ā hea hoki?

## Genetic technologies and primary industries: What to expect and when?

Gene technology has huge potential in the primary industries, but what are the realistic expectations? When could the world see gene-edited products in homes and on dinner plates?

Fresh GM and gene-edited foods are not available in Aotearoa New Zealand; examples are indicated below with (*).

### Already happening

- Herbicide and pesticide resistance (GM crops, not gene-edited)*
- Fruits and vegetables with improved traits, eg, pink pineapple (GM)* or produce with a longer shelf life*
- Vegetarian 'meats' (GM).

### Newly available

- Foods with new traits (eg, GABA-rich tomato, non-bitter salad greens, purple rice, waxy corn)*
- Foods with improved shelf life (eg, non-browning lettuce)*.

### 2 –10 years away (being tested now)

- Low-allergy foods (eg, low-gluten wheat) and forests
- More desirable foods (eg, seedless black raspberries, cassava without naturally occurring cyanide, protein-rich fish)
- Disease-resistant crops (eg, grapevines, apples, many others)
- Shelf-stable foods (eg, non-browning mushrooms)
- Some climate-resilient crops and stock animals (eg, heat-tolerant cows).

### Over 10 years away

- More climate-resilient crops (improved tolerance to drought and other adverse conditions, removing the requirement for chilling to flower)
- Disease-resistant plants
- Improved yield and crops that are easier to manage
- Crops that keep better, taste better, and have more nutrients
- Domestication of new crops.

# Te whāomoomo me te taiao
# Conservation and the environment

Genetic technologies are important tools in conservation's toolbox for the protection of native species and elimination of harmful invasive species (307). The wise use of genetic technologies can help protect taonga species and Aotearoa New Zealand's unique environment.

DNA sequencing and genomics are already being used to:

- Help breeding programmes
- Track the spread of invasive species and diseases
- Monitor water quality.

Gene editing is not systematically being used in practice yet, but could potentially be used in the future to:

- Stop invasive pest species from reproducing
- Make endangered species more resilient to challenges
- Engineer microbes for bioremediation (to clean up the environment)
- Bring extinct species back from the dead (the resulting species will not be true replicas).

In Aotearoa New Zealand, te Tiriti o Waitangi considerations are an important part of any work with taonga (treasured) species (17,51,308,309): read more in Genetic technologies and te ao Māori (pg 5).

## Te whakaraupapa me te huinga ira i te ao whāomoomo me te taiao
## Sequencing and genomics in conservation and the environment

### DNA sequencing in breeding

Genetic information about endangered species can be used by conservationists to increase the success of breeding programmes. For example, it can help pair individuals that are most likely to have healthy offspring, strengthening the gene pool of the whole population.

Kākāpō conservationists, led by the Department of Conservation and Ngāi Tahu, have been early adopters of sequencing technologies to help breeding.

As of 2025, there are 242 kākāpō in Aotearoa New Zealand (310), all descended from 51 'founder' birds (311). Genetic diversity is essential for a species' survival and conservationists guiding a population back from a small surviving group must be careful to avoid the downsides of inbreeding. This is where the genomics come in: by 2023, almost all individuals had had their entire genomes sequenced (38,312). Scientists and conservationists have identified genes important for disease susceptibility, egg number, and fertility (38), and they use this information to matchmake the kākāpō (38,310).

In the plant world, the culturally important and critically threatened native swamp maire is being protected by a collaborative effort between iwi Rangitāne o Manawatū, Te Herenga Waka – Victoria University of Wellington, and the Bioeconomy Science Institute.

Samples of maire DNA from the Palmerston North region have been sequenced (35) to better understand how to protect this taonga species. The resulting genome sequence was named 'Ngā Hua o te Ia Whenua', 'the fruits of the land', and is believed to be the first genome to be given a te reo Māori name (35,313).

### DNA sequencing and tracking disease in native species

Kauri dieback is a deadly disease that has been leaving gaps in our ancient ngāhere, forests, over the past decade. The disease, caused and spread by invasive soil microbes called *Phytophthora agathidicida*, threatens to push kauri to extinction (25).

Iwi kaitiaki and research partners (26,27) use PCR to identify infected trees and track the spread of the disease. A rapid lab turnaround means sick trees can be quickly quarantined to avoid the disease spreading further.

### DNA sequencing and tracing the spread of invasive species

Researchers can sequence the genomes of harmful invasive microbes, insects, or bigger pests (314,315) to find out clues about where the pest came from and how it might have travelled to or within Aotearoa New Zealand.

### Monitoring biodiversity and water contamination with eDNA

Environmental DNA (eDNA) is genetic material from environmental samples, such as soil, water, and even air (316).

Researchers, in partnership with iwi and communities, study eDNA to identify which organisms have been in different environments. Rivers are common sites for eDNA sampling in Aotearoa New Zealand and abroad. eDNA was used, for example, in the early detection of invasive New Zealand mudsnails in an American river (317). eDNA is also used to monitor the health of waterways (308,309,318–320), including by counting taonga native species (308), measuring levels of bacteria, such as *E. coli*, and detecting the impacts of farming (308) and forestry (318) on the ecosystem.

## Ngā hangarau ira i te ao whāomoomo me te taiao

Gene technology in conservation and the environment

### Gene technology (gene editing and genetic modification) to make endangered species more resilient to threats

Gene editing can be used to help struggling species cope better with a changing world. Interventions could include using CRISPR to introduce or alter genes to improve disease resistance, climate resilience, or fertility.

In the US, for example, researchers are preparing to gene edit the American chestnut to remove genes that make the trees susceptible to a deadly blight (321). A promising genetic modification approach may provide disease resistance via a transgene from wheat (322).

### Gene editing to restore genetic diversity in endangered species

Genetic diversity, meaning a large degree of genetic differences between individuals in a population or gene pool, is crucial for a healthy species – be it plants, animals, or fungi. If individuals are very genetically similar (or inbred) then they share the same weaknesses, putting them at risk of all being wiped out by a single illness or event.

Species brought back from the brink of extinction using traditional conservation have low genetic diversity, because they are all descendants of a small number of breeding ancestors. Kākāpō have very low genetic diversity because of this (323).

Gene editing could be used to introduce genetic diversity (324,325) to at-risk species by:

- Fixing harmful mutations (eg, disease-causing gene variants)
- Reintroducing lost traits, using stored DNA from preserved tissue
- Introducing variation to genes that encode essential parts of the immune system, such as antibodies.

### Gene editing endangered species for easier tracking

Researchers have floated the idea of genetically 'barcoding' endangered species to make it easier to monitor population numbers (326). The barcodes are short stretches of DNA from non-coding regions (ie, not in genes or any instruction-carrying DNA sequence), with a unique sequence for each individual. Like reading a tag on a bird's ankle, researchers can use PCR to 'read' the identity of an individual. A key benefit of this system is that you can detect an individual from eDNA without having to capture the bird.

### Gene-editing microbes to help clean up the environment

Our tiniest conservationists might be the most impactful: microbes can evolve to tidy up the mess humans leave behind (bioremediation). In nature, innovations often evolve naturally when new substances are introduced to an environment – such as bacteria that eat pesticides (327,328), clear oil spills (329), and devour plastic (330) – and scientists who know where to look can harness and improve new abilities found in nature.

Specialist microbes for bioremediation can also be engineered in the lab (via synthetic biology), in some cases introducing traits that do not already exist in nature. Aotearoa-founded company Lanzatech developed a system that funnels byproduct gases (eg, hydrogen, carbon monoxide, or carbon dioxide) from manufacturing into a vat with bacteria that repurpose them into useful chemicals and fuels – keeping the waste gases out of the atmosphere (331). Researchers overseas have developed living systems to detect and signal environmental contamination – eg, a version of bacterium *E. coli* that glows red in the presence of arsenic (291).

## Cloning endangered species

Gene technology can be used to clone endangered animals if we have tissue that contains DNA (and an appropriate surrogate). In this case, cloning refers to taking a cell from an adult animal and converting it into a gamete (egg or sperm cell) or embryo (332). In contrast, plants can be cloned just by taking cuttings and propagating them.

Although cloning is different to the 'de-extinction' of long-gone species (described below), there are still many practical and ethical issues to consider before scientists choose to use cloning in conservation (discussed in (332)).

The Northern white rhino is a prime candidate for conservation through cloning. As of 2025, the known population is just two females (333). Scientists have tried to do rhino IVF (without cloning) using a Southern white rhino surrogate (334) but have not had success yet.

## Bringing extinct species back from the dead?

'De-extinction' is different to cloning, because scientists do not have access to cells from living or preserved animals. Instead, they edit the genes of living animals so they are more similar to those of extinct animals.

In 2025, scientists used gene-editing techniques to 'resurrect dire wolves' from their 10,000-year extinction (335,336).

The wolves are not exactly dire wolves (337) – they are grey wolves that have gene edits to make them look and sound more like dire wolves. Scientists used traces of ancient dire wolf DNA to identify critical differences between it and the DNA of modern grey wolves. Grey wolf embryos were gene-edited in the lab in 20 sites over 14 genes to switch to the dire wolf DNA sequence (336). The embryos were then carried to full term by surrogate mothers (large hounds, not wolves) (336).

News of the wolves' births in 2025 incited debate (337,338) about the authenticity and ethics of de-extinction technologies.

People in favour say:

- 'De-extinction' of dire wolves returns a special part of our ecological history, undoing an extinction that humanity likely contributed to (336)
- Research into 'de-extinction' will help develop technologies that could help today's endangered species (336).

Opponents say:

- These are just gene-edited grey wolves[28] (337,338)
- This is cruelty to animals because:
  - We do not know how these altered genetics will affect the wolves' wellbeing
  - If this were true de-extinction, then the dire wolves are returning to a changed environment they are not adapted to.
- 'De-extinction' is taking resources and awareness away from protection of today's endangered species.

Our own moa nunui, South Island giant moa, has been proposed for de-extinction (340). The team behind the dire wolf are working with Ngāi Tahu Research Centre, Canterbury Museum, and sponsor Sir Peter Jackson to 'resurrect' the moa in the next five to ten years (340). Early reactions from Aotearoa New Zealand experts have generally been negative (341).

## Gene editing to reduce invasive species without using chemical or physical pest controls

- The sterile insect technique: Engineer members of a pest species (typically male) to be infertile and release a large number into the wild. There, they will mate with wild insects but produce no young, shrinking the population over time (342).

28 For official distinctions between hybrids and 'de-extinct' species, see (339).

Examples include mosquitoes carrying dengue fever in Brazil (343) and moths that damage cabbage crops in the US (344). The sterile technique is also used with invasive plants – for example, a research group in the US has been working on a sterile eucalyptus to stop these introduced trees spreading (345,346).

- The toxic male technique: Engineer a male insect to produce toxic proteins that kill the female when they mate (347). Unlike the sterile insect technique, you don't have to wait a generation to see a change in population numbers. This research is new – being piloted in the lab with fruit flies (347) – but could be used against disease-carrying mosquitoes or other invasive insect species in the future.
- Gene drive: A genetic defence that controls populations by infiltrating wild pest species with gene-edited individuals. The altered pests are intended to mate with wild individuals, with a goal to either change the pest's characteristics (ie, a mosquito that cannot carry malaria (348) or a mouse that cannot catch tick-borne disease (349)) or limit reproduction.

  Conservationists have proposed using gene drives to rid Aotearoa New Zealand of invasive species that put our native fauna and flora at risk (350).

For more information on potential applications for gene drives in Aotearoa New Zealand – and associated technical challenges and ethical risks – see our previous publication: Gene editing scenarios in pest control (351).

## Ngā hangarau ira i te ao whāomoomo: Ngā tūraru

### Gene technology in conservation: Risks

Researchers and conservationists take risks seriously and a cautious approach is why most of the interventions described above are still at the development stage. Here, we list the risks with hypothetical examples.

- **Gene-edited pests spreading beyond the target area**

  A trait designed to disable pests (eg, a gene drive for infertility) is a risk if it spreads into the area the pest is originally from (352–356). However, scientists can design genetic contingencies to limit the spread of gene drives (356–358). Island nations like Aotearoa New Zealand are ideal testing grounds, due to the inbuilt isolation (358).

  *Scenario:* A gene drive released to limit populations of brushtail possums in Aotearoa New Zealand could spread to Australia, where the possums are endemic and protected.

- **Unintended gene-editing consequences**

  - **Trait trade-offs**

    A gene-edited trait chosen for a desired effect in a certain circumstance may have a negative impact in a different circumstance (356). Animal wellbeing needs to be considered when weighing trade-offs.

    *Scenario:* An endangered bear is gene-edited to put on weight faster to store energy reserves for winter after lean summers. However, in bountiful summers the bear could be at risk of getting so chubby it loses mobility.

  - **Low-information edits**

    Editing a poorly understood gene could have unintended consequences. Just because we know the sequence of a genome does not mean we know what all the genes do – this takes years of careful research.

    *Scenario:* Conversationists edit a gene known to control egg numbers in an endangered bird, with hopes to increase clutch size. However, the same gene may have an important role in development and the gene edit could lead to birth defects.

  - **Off-target edits**

    Gene editing can cause unintended changes to DNA away from the target gene (359). These changes can cause unexpected traits in the edited species that could be harmful to it or its ecosystem (356,360). However, careful quality control, including resequencing the entire genome, makes sure only individuals carrying correct edits make it into the field.

*Scenario:* Researchers gene edit an at-risk fruit tree to make it more drought hardy. However, if an edit also occurred off target, in a completely different gene, and it could result in trees with fewer flowers, so it yields less fruit.

- **Evolved resistance**

  Pests can evolve to be resistant to almost anything. Even if resistance rates are fractions of a percent, the offspring of the survivors will reproduce and grow a population of resistant individuals (356).

  Gene editing interventions in conservation can however be designed to anticipate and minimise resistance (361). Conservationists can use genetic surveillance to keep an eye out for resistant strains.

  *Scenario:* Gene-edited toxic male mosquitos might evolve so that the toxic protein in their sperm loses its function. When these males mate, the female might survive to carry offspring who also make the non-functional protein.

- **Disruption of ecosystems**
  No species lives in isolation. Conservation plans around a species (356,360,362) must consider the whole ecosystem, as effects can be far-reaching.

  *Scenario:* Conservationists use gene editing to eliminate a disease that affects an endangered bat. Bat numbers rise and they gorge themselves on their favourite fruit. If a native bird eats from the same tree, it might now have to compete to get enough food. The birds would lay fewer eggs and, because the tree relies on the birds to distribute its seeds, impacts would ripple through the forest.

- **Complacency in conservation**

  If we know that we can use gene editing as a 'last resort' to save at-risk species, then we might not bother to use traditional conservation to prevent situations becoming dire (363,364).

- **Societal impacts**

  The conservation value of an intervention must be weighed against societal concerns. An invasive species may be damaging to our native ecosystems while also carrying cultural importance. Examples include introduced plants we like to eat or enjoy in our surroundings and introduced animals that are important as pets or for hunting.

- **Changing a taonga species**

  There is a concern that gene-editing a species to protect it will alter whakapapa. This concern could be addressed on a case-by-case basis by kaitiaki guardians of the taonga (8). Careful kōrero is crucial in deciding which interventions are appropriate for each species and situation.

## Ngā hangarau ira i te ao whāomoomo me te taiao: Ngā mea e whakapaetia ana, hei ā hea hoki?

## Genetic technologies in conservation and the environment: What to expect and when?

Genetic technologies have the potential to make big changes in conservation and environmental protections, but the ethics and implications are complex. Most applications described above are still under development. Here's a rough timeline of things we can realistically expect to see soon.

### Already happening

- Using genomics to improve breeding of endangered species.

### Newly available

- Disease tracking
- Identifying genetic variations responsible for positive or negative traits
- Environmental monitoring
- Gene drives to control or suppress pest species (trial scale).

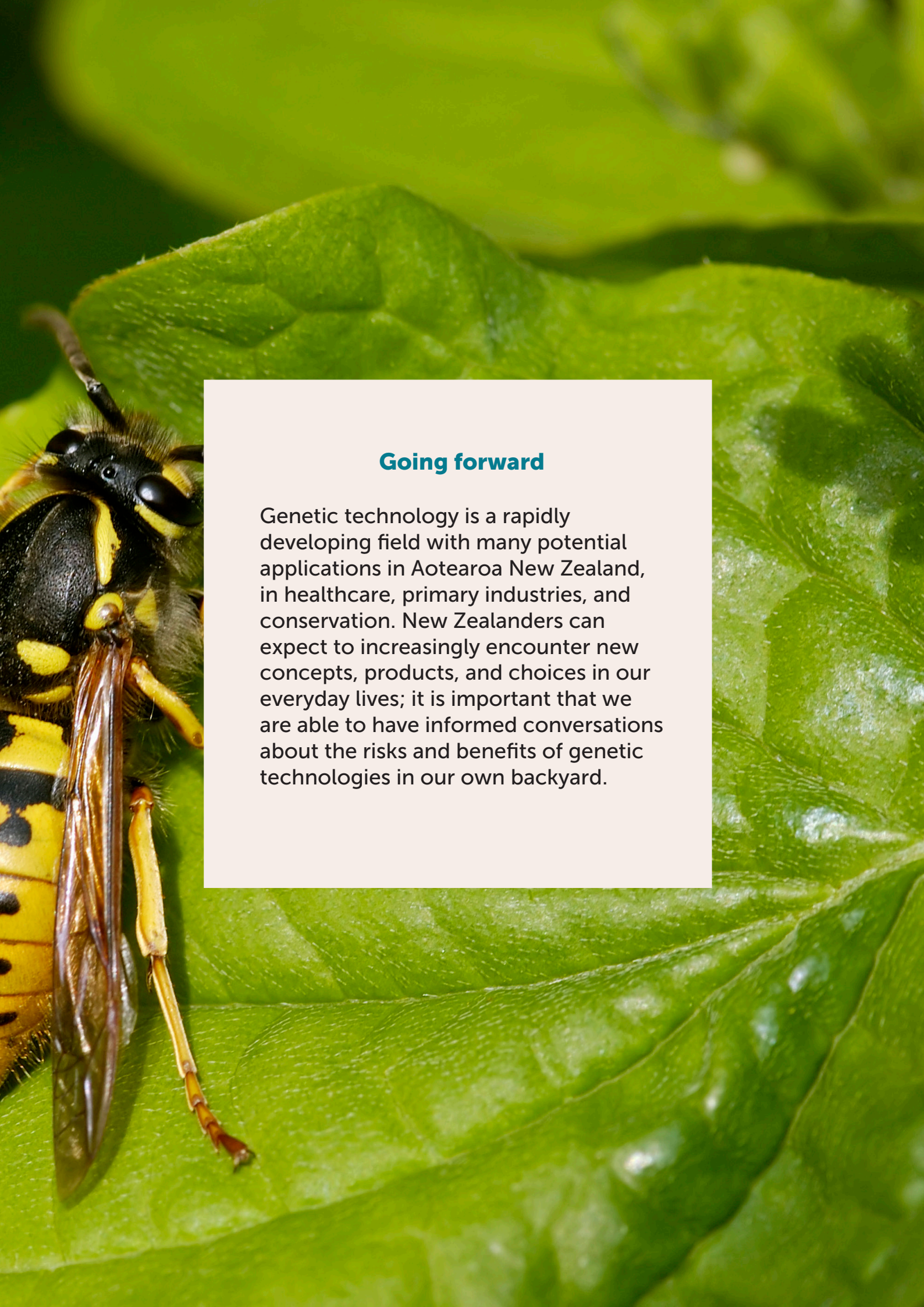
### 2–10 years away (being tested now)

- Widespread environmental monitoring using DNA
- Cloning of endangered species from stored tissues
- Vaccination of wildlife with bespoke vaccines for specific diseases
- Gene editing to provide conservation species with resistance to environmental factors
- Gene drives to control or suppress pest species.

### Over 10 years away

- Gene editing to build resilience against climate change
- Real-time environmental monitoring with DNA
- Stem-cell technologies for wildlife species.

We go into detailed scenarios of gene editing and conservation in our previous publication: Gene editing scenarios in pest control (351).



## Going forward

Genetic technology is a rapidly developing field with many potential applications in Aotearoa New Zealand, in healthcare, primary industries, and conservation. New Zealanders can expect to increasingly encounter new concepts, products, and choices in our everyday lives; it is important that we are able to have informed conversations about the risks and benefits of genetic technologies in our own backyard.

## Ngā mihi
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Conflicts of interest:

Professor Black is a member of the Māori Focus Group, which supports Ministry of Business, Innovation and Employment (MBIE) to identify and understand Māori rights and interests for inclusion in policy advice to Government regarding gene technology. Professor Black is also participating in a research programme with MBIE, weaving cultural authority into developing gene drives for pest wasps.

Dr Gladding is the founder of Theranostics Lab, a company which offers molecular diagnostics, pharmacogenomic testing.

Professor Wilcox co-chairs Te Ira Tātai Whakaheke Charitable Trust whose mission is to ensure culturally safe use of genomics in Māori healthcare. Professor Wilcox also co-leads the He Kākano and Rakeiora projects, is Deputy Director of Maurice Wilkins Centre, and is co-chair (Māori) of Rare Diseases of New Zealand (RDNZ) research network leadership group.

Professors Allan and Robertson are members of the Technical Advisory Group which provides technical advice to MBIE on up-to-date gene technology regulation.

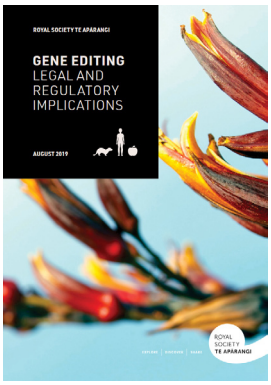
## Read more

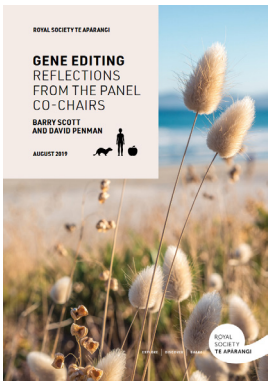
Read about the latest innovations in genetic technologies:

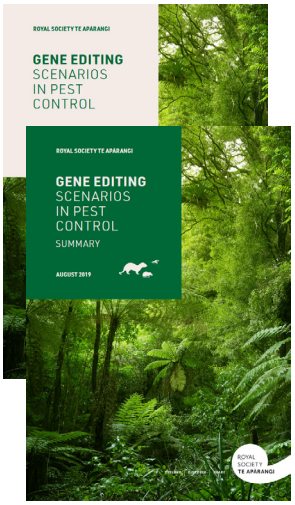
- Genetic technologies in Aotearoa New Zealand – how they're used
- Full content is available on the Society's webpage

Our previous publications on genetic technologies include:

- Gene editing: Legal and regulatory implications
- Gene editing: Scenarios in healthcare
- Gene editing: Scenarios in primary industries
- Gene editing: Scenarios in pest control
- Gene editing: Reflections from the panel co-chairs.

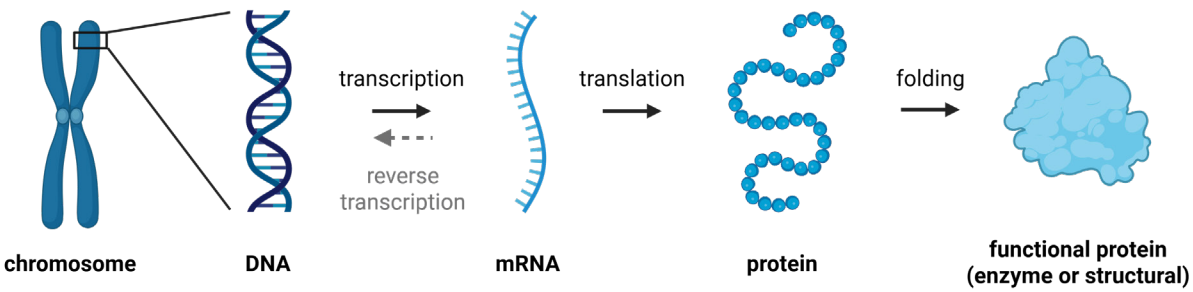





## Kuputaka
# Glossary

| | |
|---|---|
| "-ase" | Words that end in -ase are usually enzymes. Examples are lactase (digests lactose), nuclease (cuts DNA or RNA), and reverse transcriptase (builds DNA from an RNA template). |
| allele | An allele is one of two or more versions of a gene. An individual inherits two alleles for most genes, one from each parent. Exceptions include sex-linked genes on the X and Y chromosomes in men, where a single X chromosome is inherited from the mother and a single Y chromosome from the father. Women generally have two X chromosomes (and no Y) and men one X and one Y. |
| amino acid \| waikawa amino | A molecule that serves as the building block of proteins. Twenty different amino acids are found in proteins, each with different chemical properties. |
| artificial selection | See conventional breeding. |
| base | The basic unit of our genetic instructions: DNA instructions are encoded in the sequence of its chemical 'letters' or bases. There are four bases: adenine (A), cytosine (C), guanine (G) and thymine (T). Another base, uracil (U) replaces T in RNA. |
| base editor | In a version of CRISPR, a base editor is an engineered cas9 that edits DNA by changing one base (A,T,G,C) into another. |
| base pair | A base pair is two chemical bases bonded, via a hydrogen-bond, to one another forming a "rung" of the DNA ladder. |
| biotechnology | Biotechnology is the use of biology to develop new products, methods and organisms intended to improve human health, the environment and society. |
| Cas nickase | A version of Cas9 that only cuts one strand of DNA, not both. |

FIGURE 3 | Central dogma

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| | |
|---|---|
| Cas9 | In CRISPR, Cas9 is an enzyme that cuts DNA as directed by guideRNA. Cas9 is a nuclease. |
| cell \| pūtau | A cell is the basic building block of living things. |
| chromosome \| pūira | A chromosome is an organized package of DNA (each comprising a single molecule), often found in the nucleus of the cell. Different organisms have different numbers of chromosomes. Humans have 23 pairs of chromosomes. Each parent contributes one chromosome to each pair so that offspring get half of their chromosomes from their mother and half from their father. |
| conventional breeding \| whakatupu | Choosing parent organisms with desirable traits and breeding these to produce offspring with the same desirable traits. Results can be variable, and the trait is not always passed from parent to offspring. Tools and techniques in this category do not fall under genetic modification regulations. |
| CRISPR (Clustered Randomly Interspaced Short Palindromic Repeats) | CRISPR-Cas9 is a genome editing tool that is creating a buzz in the science world. It can be faster, cheaper and more accurate than previous techniques for editing DNA and has a wide range of potential applications. CRISPR is a molecular system that guides a protein called Cas9 towards a chosen sequence of DNA. Cas9 cuts the DNA at that chosen sequence. |
| data sovereignty | The concept that if data is stored in a country, then the rules of that country apply to it. More broadly, data sovereignty relates to individuals, particular groups, and nations having ownership over and the ability to control their own data as they see fit.<br>Indigenous data sovereignty states that data is subject to the laws of the nation from which it is collected. It recognises that Indigenous Peoples have inherent rights and responsibilities to Indigenous data. Māori data sovereignty refers to the rights Māori have to data that relates to Māori. |
| DNA (deoxyribonucleic acid) \| pītau ira | The DNA molecule consists of two strands that wind around one another to form a shape known as a double helix. It carries genetic instructions used in development, general functioning and reproduction in almost all living things. |
| DNA sequencing | DNA sequencing is a laboratory technique used to determine the exact sequence of bases (A, C, G, and T) in a DNA molecule. |
| dominant \| ira tāpua | The stronger version of a pair of alleles. Dominant alleles show their effect even if there is only one copy in the genome, for example the allele for brown eyes. |
| double helix | The structure formed by double-stranded molecules of DNA. It has the shape of a twisted ladder. |
| eDNA | The diverse genetic material that can be found in environmental samples such as soil, water, and even air. |

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|---|---|
| enzyme \| pūmua whākōkī | A biological catalyst that is almost always a protein. It speeds up the rate of a specific chemical reaction. |
| epigenomics | Epigenomics, the study of chemical changes that regulate the expression, or use, of the entire collection of DNA molecules in an organism's cells. An epigenome refers to the total changes for an individual. |
| eukaryote | Organism composed of one or more cells with a nucleus – a special compartment to store DNA. Member of one of the three main divisions of the living world, the other two being bacteria and archaea. |
| evolution/evolve \| kukuwhatanga | Adaptation based on the process of natural selection. Successful organisms survive and reproduce while unsuccessful ones die off. |
| ex vivo | Taking place outside the body – eg, gene therapy on human cells in a Petri dish. |
| exon | Segment of a eukaryotic gene that consists of a sequence of nucleotides that will be represented in messenger RNA. In protein-coding genes, exons encode amino acids in the protein. An exon is usually adjacent to a noncoding DNA segment called an intron. |
| gene \| ira | The gene is the basic physical unit of inheritance. Genes are made up of DNA and are passed from parents to offspring and contain the information needed to specify traits. Genes are arranged, one after another, on structures called chromosomes. |
| gene bank | A store of genetic material and/or the information it encodes. |
| gene drive | Gene drives use gene technology to ensure that a gene is copied across from one DNA strand to its paired DNA strand. This means that the gene and its associated trait are passed on to all subsequent generations, even if the gene confers a disadvantage on the species. |
| gene editing | Technologies that change the genome of a living organism without (permanently) introducing foreign DNA. Gene editing is typically more precise than genetic modification and leaves less trace in the genome. |
| gene pool \| mātāira | A gene pool refers to the combination of all the genes (including alleles) present in a reproducing population or species. A large gene pool has extensive genomic diversity and is better able to withstand environmental challenges. Inbreeding contributes to a smaller gene pool, making populations or species less able to adapt and survive when faced with environmental challenges. |
| gene therapy | A procedure aimed at replacing, manipulating or supplementing non-functioning genes. |
| gene variant \| rerenga | A gene variant is a permanent change (mutation) in the DNA sequence that makes up a gene. Can be inherited or acquired during the lifetime. |

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| genetic discrimination | The unequal treatment of individuals based on an aspect of their genetic code or genome, such as the risk for genetic disorder. Genetic discrimination can involve such genomic information being used against individuals in a variety of circumstances, such as employment, health or disability, insurance status, or education, or health care. |
| genetic material | Genetic material can be a gene, a part of a gene, a group of genes, a DNA molecule, a fragment of DNA, a group of DNA molecules, or the entire genome of an organism. |
| genetic modification \| raweke ira | Technologies that change the genome of a living organism with the addition of foreign DNA (from another species). What technology and resultant organisms are encompassed under this definition varies by country. |
| genetic technology | Any modern technique used for modifying genes. Products of gene technologies can be used in areas such as human and animal health, medicines, and food production. |
| genetic testing | A tool for identifying changes in DNA that could increase the risk of developing a disease. It can describe any number of different techniques. |
| genetic variant | A variation between individuals in a population due to a difference in a specific nucleotide at a defined point in the DNA sequence. |
| genome \| huinga ira | The complete set of genes or genetic material present in a cell or organism. |
| genotype (noun) | A genotype is a scoring of the type of variant present at a given location (i.e., a locus) in the genome. It can be represented by symbols. For example, BB, Bb, bb could be used to represent a given variant in a gene. Genotypes can also be represented by the actual DNA sequence at a specific location, such as CC, CT, TT. DNA sequencing and other methods can be used to determine the genotypes at millions of locations in a genome in a single experiment. Some genotypes contribute to an individual's observable traits, called the phenotype. |
| genotype (verb) | To determine the genotype of an organism. This can be accomplished by PCR- or sequencing-based tests and also through family histories. |
| germline | The germline is the cells that produce eggs and sperm as well as the eggs and sperm themselves that are used by sexually reproducing organisms to pass on genes from generation to generation. Egg and sperm cells are called germ cells. |
| guideRNA | A component of CRISPR. The guide RNA (gRNA) dictates the region of DNA where Cas9 will bind and cut. Cas9 first binds the gRNA and then only binds DNA that is an exact complement to the gRNA sequence. Researchers design gRNA to target Cas9 to the desired site for editing. |

| | |
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| heritable | A gene or trait passed on to future children. It can lead to a permanent change in the population gene pool. Heritable traits can be heterozygous - meaning having one copy of an alteration, or homozygous - meaning both copies have the alteration. |
| immunotherapy | Immunotherapy is treatment that uses your body's own immune system, eg, to help fight cancer. |
| in vitro | Term used by biochemists to describe a process taking place in an isolated cell-free extract. Also used by cell biologists to refer to cells growing in culture (in vitro), as opposed to in an organism (in vivo). (Latin for "in glass.") |
| in vivo | In an intact cell or organism. (Latin for "in life.") |
| Intron | Noncoding region of a eukaryotic gene that is transcribed into mRNA but is then excised before the mRNA is used. |
| knockout | A gene modified to lose its function. Also used to refer to the organism with the gene knockout or as a verb - "to knock out a gene." |
| molecule \| rāpoi ngota | Group of atoms joined together by covalent bonds. |
| mutagen | An agent that generates mutations in DNA. Examples include x-rays, UV light, and various chemicals. |
| mutagenesis \| iranoi | Process by which DNA of an organism is changed due to a mutation. Can occur spontaneously in nature or via exposure to mutagens such as chemicals or radiation. Can also be used in a targeted way via gene editing. |
| mutation \| iranoi | A change that occurs in a DNA sequence. Mutations are relatively common in our DNA, but most have no detectable effect. |
| nuclease | An enzyme that cuts nucleic acids (DNA or RNA). There are two main types: ones that cut randomly and ones that only cut when they recognise a given DNA/RNA sequence. |
| nucleic acid | DNA or RNA or related information-carrying molecules. |
| null segregant | The offspring of a gene-edited or gene-modified parent that no longer contains any altered DNA. |
| off-target effects | An edit to the genome where the genome editing system cuts at a different place in the DNA to the one that was intended to be edited. |
| PAM site (protospacer adjacent motif) | In CRISPR, a PAM (protospacer adjacent motif) site is a 2–6 base pair sequence near a guide RNA binding site. It must be present for Cas9 to bind. It is a safety check to confirm the DNA is an invader and part of the bacterium. Researchers can alter the PAM requirements of engineered cas proteins to make them more or less strict. |

| | |
|---|---|
| PCR (polymerase chain reaction) | A technique used to make many copies of a given DNA sequence. |
| pegRNA (prime editing guide RNA) | In prime editing, pegRNA contains both the guide RNA sequence and the template for DNA changes required in the gene edit. |
| point mutation | Change of a single nucleotide in DNA, especially in a region of DNA coding for protein. |
| prime editing | A version of CRISPR that allows researchers to add short sequences of DNA to the target site. |
| protein \| pūmua | Proteins are an important class of molecules found in all living cells. A protein is composed of one or more long chains of amino acids, the sequence of which corresponds to the DNA sequence of the gene that encodes it. |
| recessive \| iramoe | When the allele of a gene shows its effect only if both copies in the genome are the same. |
| recombinant DNA | Any DNA molecule formed by joining DNA segments from different sources. Recombinant DNAs are widely used in the cloning of genes, in the genetic modification of organisms, and in molecular biology generally. |
| recombination | Process in which DNA molecules are broken and the fragments are rejoined in new combinations. Can occur in the living cell – for example, through crossing-over during meiosis – or in vitro using purified DNA and enzymes that break and ligate DNA strands. |
| retrovirus | RNA-containing virus that replicates in a cell by first making an RNA–DNA intermediate and then a double-strand DNA molecule that becomes integrated into the cell's DNA. |
| reverse transcriptase | Enzyme first discovered in retroviruses that makes a double-stranded DNA copy from a single-stranded RNA template molecule. |
| reverse transcription | Using RNA as a template to make a complementary DNA strand (the reverse direction to transcription). |
| RNA (ribonucleic acid) | Ribonucleic acid. A single-stranded nucleic acid. Can have multiple functions within an organism, including being the intermediate product between a gene (encoded by DNA) and a protein – this form of RNA is called mRNA, messenger RNA. |
| selective breeding | See conventional breeding. |
| somatic cell | Any cell of the body except sperm and egg cells. |
| stem cell | Undifferentiated cell that can continue dividing indefinitely, producing daughter cells that can either commit to differentiation or remain a stem cell (in the process of self-renewal). |

| | |
|---|---|
| synthetic biology | A subset of biotechnology which includes the design and construction of biological systems and devices, as well as the redesign of existing biological systems for useful purposes. |
| synthetic nucleic acid | Nucleic acid molecules (DNA or RNA) that are chemically synthesized or amplified but can base pair with naturally occurring nucleic acid molecules. |
| trait \| huaira | A trait is a specific characteristic of an organism. Traits can be determined by genes or the environment, or more commonly by interactions between them. |
| transcription | Copying of one strand of DNA into a complementary RNA sequence by the enzyme RNA polymerase. |
| transgene | The foreign or modified gene that has been added to create a transgenic organism. |
| transgenic | Introducing specific genetic material from one donor organism to another host organism to produce a desired trait, where the two organisms are not sexually compatible species. |
| transposon | Segment of DNA that can move from one position in a genome to another. |
| variome | A collection of all the variations to the 'typical genome' present in a population. |
| vector | A small nucleic acid molecule, usually derived from a bacteriophage or plasmid, which is used to carry the fragment of DNA to be cloned into the recipient cell, and which enables the DNA fragment to be replicated. |
| wild-type | Normal, non-mutant form of an organism; the form found in nature (in the wild). |

# Ngā tohutoro
## References


1. Lin J, Ngiam KY. How data science and AI-based technologies impact genomics. *Singapore Medical Journal.* 2023;64(1): 59. https://doi.org/10.4103/singaporemedj.SMJ-2021-438.

2. Vilhekar RS, Rawekar A. Artificial intelligence in genetics. *Cureus.* 2024;16(1): e52035. https://doi.org/10.7759/cureus.52035.

3. Dixit S, Kumar A, Srinivasan K, Vincent PMDR, Ramu Krishnan N. Advancing genome editing with artificial intelligence: opportunities, challenges, and future directions. *Frontiers in Bioengineering and Biotechnology.* 2024;11. https://doi.org/10.3389/fbioe.2023.1335901.

4. Everett-Hincks J, Henaghan M. Gene editing in Aotearoa – legal considerations for policy makers. *Victoria University of Wellington Law Review.* 2019;50(3): 515–550. https://doi.org/10.26686/vuwlr.v50i3.5990.

5. Dinica V. Transitioning to what? The role of genetic-engineering in New Zealand's (circular) bioeconomy debates. *Journal of Environmental Policy & Planning.* 2021;23(2): 194–212. https://doi.org/10.1080/1523908X.2021.1893161.

6. *Gene editing.* Office of the Former Prime Minister's Chief Science Advisor. https://www.pmcsa.ac.nz/topics/gene-editing/ [Accessed 3rd December 2025].

7. Te Momo OHF. Biotechnology: The language of multiple views in Māori communities. *Biotechnology Journal.* 2007;2(9): 1179–1183. https://doi.org/10.1002/biot.200700123.

8. Hudson M, Mead ATP, Chagné D, Roskruge N, Morrison S, Wilcox PL, et al. Indigenous perspectives and gene editing in Aotearoa New Zealand. *Frontiers in Bioengineering and Biotechnology.* 2019;7. https://www.frontiersin.org/articles/10.3389/fbioe.2019.00070

9. Clark A, Wilcox P, Morrison S, Munshi D, Kurian P, Mika J, et al. Identifying Māori perspectives on gene editing in Aotearoa New Zealand. *Communications Biology.* 2024;7(1): 1–7. https://doi.org/10.1038/s42003-024-05896-1.

10. Mead ATP, Hudson M, Chagné D. *Maori perspectives and gene editing: A discussion paper.* 2017.

11. Hudson M, Beaton A, Milne M, Port W, Russell K, Smith B, et al. T*e mata ira: Guidelines for genomic research with Māori.* University of Waikato. 2016. https://www.waikato.ac.nz/assets/Uploads/Research/Research-institutes-centres-and-groups/Centres/MIGC/Te-Mata-Ira-Genome-Research-Guidelines.pdf [Accessed 31st October 2024].

12. *Te Tiriti o Waitangi, The Treaty of Waitangi.* Te Rua Mahara o te Kāwanatanga Archives New Zealand. https://archives.govt.nz/discover-our-stories/the-treaty-of-waitangi [Accessed 13th May 2020].

13. Waitangi Tribunal Te Rōpū Whakamana i te Tiriti o Waitangi. K*o Aotearoa tēnei: A report into claims concerning New Zealand law and policy affecting Māori culture and identity, te taumata tuatahi.* Wai 262, Waitangi Tribunal Report; 2011. https://forms.justice.govt.nz/search/Documents/WT/wt_DOC_68356054/KoAotearoaTeneiTT1W.pdf

14. Royal Society Te Apārangi. *Mana raraunga data sovereignty.* 2023. https://www.royalsociety.org.nz/assets/Mana-Raraunga-Data-Sovereignty-web-V1.pdf [Accessed 13th February 2025].

15. Kathlene L, Munshi D, Kurian P, Morrison SL. Cultures in the laboratory: Mapping similarities and differences between Māori and non-Māori in engaging with gene-editing technologies in Aotearoa, New Zealand. *Humanities and Social Sciences Communications.* 2022;9(1): 100. https://doi.org/10.1057/s41599-022-01104-9.

16. Rye CE, Puketapu-Watson H, Wihongi H, Te Aika B, Macartney-Coxson D, de Ligt J, et al. Rakeiora Genomics Platform: A pathfinder for genomic medicine research in Aotearoa New Zealand. *Journal of the Royal Society of New Zealand.* 2025;0(0): 1–25. https://doi.org/10.1080/03036758.2025.2469626.

17. Hudson M, Thompson A, Wilcox P, Mika J, Battershill C, Stott M, et al. *Te nohonga kaitiaki guidelines for genomic research on taonga species (with background).* Genomics Aotearoa. 2021. https://www.genomics-aotearoa.org.nz/sites/default/files/2022-02/Te%20Nohonga%20Kaitiaki%20Guidelines%20for%20genomic%20research%20on%20taonga%20species%20%28with%20background%29.pdf [Accessed 31st October 2024].

18. Mead SM, Mead HM. Tikanga Māori: Living by Māori values. Wellington: Huia Publishers; 2003.

19. Roberts RM. Walking backwards into the future: Māori views on genetically modified organisms. WINHEC: *International Journal of Indigenous Education Scholarship.* 2005;(1): 49–60.

20. Tipene-Matua B, Wakefield B. Establishing a Māori ethical framework for genetic research with Māori. In: *Genes, Society and the Future.* Dunedin: Human Genome Research Project; 2007. https://ourarchive.otago.ac.nz/esploro/outputs/bookChapter/Establishing-a-Maori-Ethical-Framework-for/9926480374001891 [Accessed 21st October 2025].

21. Wilcox PL, Charity JA, Roberts MR, Tauwhare S, Tipene-Matua B, Kereama-Royal I, et al. A values-based process for cross-cultural dialogue between scientists and Māori. *Journal of the Royal Society of New Zealand.* 2008;38(3): 215–227. https://doi.org/10.1080/03014220809510555.

22. Environmental Protection Agency. *Incorporating Māori perspectives into decision-making.* 2016. https://www.epa.govt.nz/assets/Uploads/Documents/Te-Hautu/293bdc5edc/EPA-Maori-

Perspectives.pdf [Accessed 21st October 2025].

23. NZCER, Bright N, Boyd S. *Hei whakaarotanga: Engaging with models of health and wellbeing that draw on mātauranga Māori.* 2024. https://doi.org/10.18296/rep.0039. [Accessed 21st October 2025].

24. Te Aika B, Liggins L, Rye C, Perkins EO, Huh J, Brauning R, et al. Aotearoa genomic data repository: An āhuru mōwai for taonga species sequencing data. *Molecular Ecology Resources.* 2025;25(2): e13866. https://doi.org/10.1111/1755-0998.13866.

25. Lambert S, Waipara N, Black A, Mark-Shadbolt M, Wood W. Indigenous biosecurity: Māori responses to kauri dieback and myrtle rust in Aotearoa New Zealand. In: *The Human Dimensions of Forest and Tree Health.* Palgrave Macmillan, Cham; 2018. p. 109–137. https://doi.org/10.1007/978-3-319-76956-1_5. [Accessed 3rd July 2025].

26. Bradshaw RE, Bellgard SE, Black A, Burns BR, Gerth ML, McDougal RL, et al. Phytophthora agathidicida: Research progress, cultural perspectives and knowledge gaps in the control and management of kauri dieback in New Zealand. *Plant Pathology*. 2020;69(1): 3–16. https://doi.org/10.1111/ppa.13104.

27. Gibson J, Franca B, Black A, MacDonald LTAoT, Brower AL. Co-management of kauri dieback in the Waitākere ranges, Aotearoa New Zealand. *Case Studies in the Environment.* 2023;7(1). https://doi.org/10.1525/cse.2023.1830829.

28. Byers AK, Condron L, O'Callaghan M, Waipara N, Black A. Whole genome sequencing of Penicillium and Burkholderia strains antagonistic to the causal agent of kauri dieback disease (Phytophthora agathidicida) reveals biosynthetic gene clusters related to antimicrobial secondary metabolites. *Molecular Ecology Resources.* 2025;25(2): e13810. https://doi.org/10.1111/1755-0998.13810.

29. Cox MP, Guo Y, Winter DJ, Sen D, Cauldron NC, Shiller J, et al. Chromosome-level assembly of the Phytophthora agathidicida genome reveals adaptation in effector gene families. *Frontiers in Microbiology.* 2022;13. https://doi.org/10.3389/fmicb.2022.1038444.

30. *Genomic resources for selective breeding of kingfish/haku.* Genomics Aotearoa. https://www.genomics-aotearoa.org.nz/our-work/te-ao-maori-projects/genomic-resources-selective-breeding-kingfish/haku [Accessed 10th October 2025].

31. Bennington SM, Bourke SD, Wilkinson SP, Englebert N, Bond DM, Jeunen GJ, et al. New insights into the population structure of Hector's dolphin (Cephalorhynchus hectori) revealed using environmental DNA. *Environmental DNA.* 2024;6(5): e70024. https://doi.org/10.1002/edn3.70024.

32. *Detection of species and hybrids in Ngā Roimata ō Tōhe, Pimelea eremitica.* Genomics Aotearoa. https://www.genomics-aotearoa.org.nz/our-work/te-ao-maori-projects/detection-species-and-hybrids-nga-roimata-o-tohe-pimelea-eremitica [Accessed 10th October 2025].

33. Henare KL, Parker KE, Wihongi H, Blenkiron C, Jansen R, Reid P, et al. Mapping a route to Indigenous engagement in cancer genomic research. *The Lancet Oncology.* 2019;20(6): e327–e335. https://doi.org/10.1016/S1470-2045(19)30307-9.

34. Legget ME, Cameron VA, Poppe KK, Aish S, Earle N, Choi Y, et al. The multi-ethnic New Zealand study of acute coronary syndromes (MENZACS): Design and methodology. *Cardiogenetics.* 2021;11(2): 84–97. https://doi.org/10.3390/cardiogenetics11020010.

35. Balkwill CG, Deslippe JR, Horton P, David C, Wu C, Koot E, et al. De-novo assembly of a reference genome for a critically threatened Aotearoa New Zealand tree species, Syzygium maire (Myrtaceae). *Tree Genetics & Genomes.* 2024;20(5): 1–20. https://doi.org/10.1007/s11295-024-01659-5.

36. Balkwill CG, Koot E, Ritchie P, Chagné D, Deslippe JR. Adaptive potential of Syzygium maire, a critically threatened habitat specialist tree species in Aotearoa New Zealand. *Evolutionary Applications.* 2025;18(10): e70161. https://doi.org/10.1111/eva.70161.

37. Dussex N, Valk T van der, Morales HE, Wheat CW, Díez-del-Molino D, Seth J von, et al. Population genomics of the critically endangered kākāpō. *Cell Genomics.* 2021;1(1). https://doi.org/10.1016/j.xgen.2021.100002.

38. Guhlin J, Le Lec MF, Wold J, Koot E, Winter D, Biggs PJ, et al. Species-wide genomics of kākāpō provides tools to accelerate recovery. *Nature Ecology & Evolution.* 2023;7(10): 1693–1705. https://doi.org/10.1038/s41559-023-02165-y.

39. *Saving the kākāpō.* Te Rūranga o Ngā Tahu. https://ngaitahu.iwi.nz/opportunities-and-resources/publications/te-karaka/saving-the-kakapo/ [Accessed 30th October 2025]

40. Gillies DA, Chapman N. *A report on turbo breeding research: Interviews with key informants.* Whitimaia Ltd. 2020. https://sites.massey.ac.nz/teaurangahau/wp-content/uploads/sites/53/2020/08/Turbo-breeding-report-FINAL.pdf [Accessed 22nd October 2025].

41. Hudson M, Garrison NA, Sterling R, Caron NR, Fox K, Yracheta J, et al. Rights, interests and expectations: Indigenous perspectives on unrestricted access to genomic data. *Nature Reviews Genetics.* 2020;21(6): 377–384. https://doi.org/10.1038/s41576-020-0228-x.

42. Sherman CA, Nataneli S, Claw KG, Mooney JA. Echoes of eugenics: Confronting its effects in indigenous genomics. *Genetics.* 2025; iyaf127. https://doi.org/10.1093/genetics/iyaf127.

43. Ross-Hellauer T, Reichmann S, Cole NL, Fessl A, Klebel T, Pontika N. Dynamics of cumulative advantage and threats to equity in open science: A scoping review. *Royal Society Open Science.* 2022;9(1): 211032. https://doi.org/10.1098/rsos.211032.

44. UN General Assembly. *United Nations declaration on the rights of indigenous peoples.* Report number: A/RES/61/295, 2007. https://www.ohchr.

org/en/indigenous-peoples/un-declaration-rights-indigenous-peoples [Accessed 2nd July 2025].

45. *Universal Declaration on the Human Genome and Human Rights.* Office of the United Nations High Commissioner for Human Rights. https://www.ohchr.org/en/instruments-mechanisms/instruments/universal-declaration-human-genome-and-human-rights [Accessed 28th May 2025].

46. *Nagoya Protocol on access to genetic resources and the fair and equitable sharing of benefits arising from their utilization to the convention on biological diversity: text and annex.* United Nations. 2011.

47. *History.* Convention on Biological Diversity. https://www.cbd.int/abs/background [Accessed 30th October 2025].

48. *Parties to the Nagoya Protocol.* Convention on Biological Diversity. https://www.cbd.int/abs/nagoya-protocol/signatories [Accessed 30th October 2025].

49. Ministry of Foreign Affairs & Trade. *Convention on Biological Diversity – Nagoya Protocol on access to genetic resources and the fair and equitable sharing of the benefits arising from their utilization.* New Zealand Treaties Online. https://www.treaties.mfat.govt.nz/search/details/p/41/1230 [Accessed 30th October 2025].

50. Kukutai T. Indigenous data sovereignty—A new take on an old theme. *Science.* 2023;382(6674): eadl4664. https://doi.org/10.1126/science.adl4664.

51. Kukutai T, Black A. CARE-ing for Indigenous nonhuman genomic data — rethinking our approach. *Science.* 2024;385(6708): eadr2493. https://doi.org/10.1126/science.adr2493.

52. Carroll SR, Herczog E, Hudson M, Russell K, Stall S. Operationalizing the CARE and FAIR Principles for Indigenous data futures. *Scientific Data.* 2021;8(1): 108. https://doi.org/10.1038/s41597-021-00892-0.

53. Hutchins L, Mc Cartney A, Graham N, Gillespie R, Guzman A. Arthropods are kin: Operationalizing Indigenous data sovereignty to respectfully utilize genomic data from Indigenous lands. *Molecular Ecology Resources.* 2025;25(2): e13822. https://doi.org/10.1111/1755-0998.13822.

54. Robertson SP, Hindmarsh JH, Berry S, Cameron VA, Cox MP, Dewes O, et al. Genomic medicine must reduce, not compound, health inequities: The case for hauora-enhancing genomic resources for New Zealand. *New Zealand Medical Journal.* 2018;131(1480): 81–89.

55. Baynam G, Julkowska D, Bowdin S, Hermes A, McMaster CR, Prichep E, et al. Advancing diagnosis and research for rare genetic diseases in Indigenous peoples. *Nature Genetics.* 2024;56(2): 189–193. https://doi.org/10.1038/s41588-023-01642-1.

56. Dodson M, Williamson R. Indigenous peoples and the morality of the Human Genome Diversity Project. *Journal of Medical Ethics.* 1999;25(2): 204–208. https://doi.org/10.1136/jme.25.2.204.

57. Lea R, Chambers G. Monoamine oxidase, addiction, and the "warrior" gene hypothesis. *New Zealand Medical Journal.* 2007;120(1250). http://www.nzma.org.nz/journal/120-1250/2441/

58. Hall D, Green M, Chambers G, Lea R. Tracking the evolutionary history of the warrior gene in the South Pacific. In: *11th International Human Genetics Meeting, Brisbane, Australia*; August 6–10; 2006.

59. Merriman T, Cameron V. Risk-taking: Behind the warrior gene story. *New Zealand Medical Journal.* 2007;120: U2440.

60. Hook GR. "Warrior genes" and the disease of being Māori. *MAI Review.* 2009;2.

61. Perbal L. The 'warrior gene' and the Māori people: The responsibility of the geneticists. *Bioethics*. 2013;27(7): 382–387. https://doi.org/10.1111/j.1467-8519.2012.01970.x.

62. Wensley D, King M. Scientific responsibility for the dissemination and interpretation of genetic research: Lessons from the 'warrior gene' controversy. *Journal of Medical Ethics.* 2008;34(6): 507–509.

63. Caron NR, Chongo M, Hudson M, Arbour L, Wasserman WW, Robertson S, et al. Indigenous genomic databases: Pragmatic considerations and cultural contexts. *Frontiers in Public Health.* 2020;8: 111. https://doi.org/10.3389/fpubh.2020.00111.

64. Beaton A, Hudson M, Milne M, Port RV, Russell K, Smith B, et al. Engaging Māori in biobanking and genomic research: A model for biobanks to guide culturally informed governance, operational, and community engagement activities. *Genetics in Medicine.* 2017;19(3): 345–351. https://doi.org/10.1038/gim.2016.111.

65. Kukutai T. Protecting pieces of us: The need for Indigenous perspectives in the fuzzy world of biometric data regulation. *Science.* 2025;388(6743): eadw9973. https://doi.org/10.1126/science.adw9973.

66. Fraser H, Gamet K, Jackson S, Shelling A, Lacaze P, Tiller J. Genetic discrimination by insurance companies in Aotearoa New Zealand: experiences and views of health professionals. *New Zealand Medical Journal.* 2023;136(1574): 32–52. https://doi.org/10.26635/6965.6116.

67. Robinson JO, Carroll TM, Feuerman LZ, Perry DL, Hoffman-Andrews L, Walsh RC, et al. Participants and study decliners' perspectives about the risks of participating in a clinical trial of whole genome sequencing. *Journal of Empirical Research on Human Research Ethics.* 2016;11(1): 21–30. https://doi.org/10.1177/1556264615624078.

68. Shelling AN, Bicknell LS, Bohlander SS, Cox MP, Filoche SK, Fraser HG, et al. Genomic discrimination in New Zealand health and life insurance. AGenDA: Against Genomic Discrimination in Aotearoa. *New Zealand Medical Journal.* 2022;135(1551): 7–12.

69. Webster M. *The privacy risks of insurers misusing your genetic testing.* Privacy Commissioner. https://www.privacy.org.nz/blog/the-privacy-risks-of-insurers-misusing-your-genetic-testing/ [Accessed 25th November 2025].

70. Tiller J, Lacaze P, Otlowski M. The Australian moratorium on genetics and life insurance: evaluating policy compared to Parliamentary recommendations regarding genetic discrimination. *Public Health Research & Practice.* 2022;32(4): e3242235. https://doi.org/10.17061/phrp3242235.

71. Edge MD, Coop G. Attacks on genetic privacy via uploads to genealogical databases. *eLife.* 2020;9: e51810. https://doi.org/10.7554/eLife.51810.

72. Jamali L. 23andMe files for bankruptcy protection. *BBC [Internet]*. 2025 Mar 24. https://www.bbc.com/news/articles/c9q4r9xy9wro [Accessed 27th May 2025].

73. *Attorney General Bonta urgently issues consumer alert for 23andMe customers. State of California* - Department of Justice - Office of the Attorney General. https://oag.ca.gov/news/press-releases/attorney-general-bonta-urgently-issues-consumer-alert-23andme-customers [Accessed 27th May 2025].

74. Clayton EW, Evans BJ, Hazel JW, Rothstein MA. The law of genetic privacy: Applications, implications, and limitations. *Journal of Law and the Biosciences.* 2019;6(1): 1–36. https://doi.org/10.1093/jlb/lsz007.

75. Liu H, Liu Y, Zhao Y, Ma Y, Chen Q, Xu H, et al. A scoping review of human genetic resources management policies and databases in high- and middle-low-income countries. *BMC Medical Ethics.* 2025;26(1): 37. https://doi.org/10.1186/s12910-025-01192-7.

76. Joly Y, Dalpé G, Dupras C, Bévière-Boyer B, De Paor A, Dove ES, et al. Establishing the International Genetic Discrimination Observatory. *Nature Genetics.* 2020;52(5): 466–468. https://doi.org/10.1038/s41588-020-0606-5.

77. *What is precision medicine?* Genomics Aotearoa. https://www.genomics-aotearoa.org.nz/education-events/precision-medicine [Accessed 23rd September 2025].

78. Kosorok MR, Laber EB. Precision medicine. *Annual review of statistics and its application.* 2019;6: 263–286. https://doi.org/10.1146/annurev-statistics-030718-105251.

79. Weinkove R, George P, Fyfe R, Dasyam N, Nouri Y, Ostapowicz T, et al. A phase 1 dose escalation trial of third-generation CD19-directed CAR T-cells incorporating CD28 and toll-like receptor 2 (TLR2) intracellular domains for relapsed or refractory B-cell non-Hodgkin lymphomas (ENABLE). In: *ASH Annual Meeting & Exposition*; December 11; 2023. https://ash.confex.com/ash/2023/webprogram/Paper178872.html [Accessed 9th July 2024].

80. Fyfe R, Anstis O, Kapadia K, Jordan M, Sword DO, Weinkove R. Experiences and perspectives on chimeric antigen receptor (CAR) T-cell therapy among recipients, carers and referrers (RE-TELL): A qualitative study to inform CAR T-cell service design. *BMJ open*. 2024;14(1): e071112. https://doi.org/10.1136/bmjopen-2022-071112.

81. Gillmore JD, Gane E, Taubel J, Kao J, Fontana M, Maitland ML, et al. CRISPR-cas9 in vivo gene editing for transthyretin amyloidosis. *New England Journal of Medicine.* 2021;385(6): 493–502. https://doi.org/10.1056/NEJMoa2107454.

82. Longhurst HJ, Lindsay K, Petersen RS, Fijen LM, Gurugama P, Maag D, et al. CRISPR-Cas9 in vivo gene editing of KLKB1 for hereditary angioedema. *New England Journal of Medicine.* 2024;390(5): 432–441. https://doi.org/10.1056/NEJMoa2309149.

83. Cohn DM, Gurugama P, Magerl M, Katelaris CH, Launay D, Bouillet L, et al. CRISPR-based therapy for hereditary angioedema. *New England Journal of Medicine.* 2025;392(5): 458–467. https://doi.org/10.1056/NEJMoa2405734.

84. Laffin LJ, Nicholls SJ, Scott RS, Clifton PM, Baker J, Sarraju A, et al. Phase 1 trial of CRISPR-Cas9 gene editing targeting ANGPTL3. *New England Journal of Medicine.* 2025; NEJMoa2511778. https://doi.org/10.1056/NEJMoa2511778.

85. White RT, Bakker S, Burton M, Castro ML, Couldrey C, Dyet K, et al. Rapid identification and subsequent contextualization of an outbreak of methicillin-resistant Staphylococcus aureus in a neonatal intensive care unit using nanopore sequencing. *Microbial Genomics.* 2024;10(7): 001273. https://doi.org/10.1099/mgen.0.001273.

86. Guilford P, Hopkins J, Harraway J, McLeod M, McLeod N, Harawira P, et al. E-cadherin germline mutations in familial gastric cancer. *Nature.* 1998;392(6674): 402–405. https://doi.org/10.1038/32918.

87. *Winner of te Puiaki Pūtaiao Matua a te Pirimia the Science Prize.* Prime Minister's Science Prizes Aotearoa New Zealand. https://pmscienceprizes.org.nz/2023-winner-of-te-puiaki-putaiao-matua-a-te-pirimia-the-science-prize/ [Accessed 22nd October 2025].

88. Oates J, Lopez D. Pharmacogenetics: An important part of drug development with a focus on its application. *International Journal of Biomedical Investigation.* 2018;1(2): 111. https://doi.org/10.31531/2581-4745.1000111.

89. Murray-McIntosh RP, Scrimshaw BJ, Hatfield PJ, Penny D. Testing migration patterns and estimating founding population size in Polynesia by using human mtDNA sequences. *Proceedings of the National Academy of Sciences.* 1998;95(15): 9047–9052. https://doi.org/10.1073/pnas.95.15.9047.

90. Knapp M, Horsburgh KA, Prost S, Stanton JA, Buckley HR, Walter RK, et al. Complete mitochondrial DNA genome sequences from the first New Zealanders. *Proceedings of the National Academy of Sciences.* 2012;109(45): 18350–18354. https://doi.org/10.1073/pnas.1209896109.

91. Walter R, Buckley H, Jacomb C, Matisoo-Smith E. Mass migration and the Polynesian settlement

of New Zealand. *Journal of World Prehistory.* 2017;30(4): 351–376. https://doi.org/10.1007/s10963-017-9110-y.

92. Bunbury MME, Petchey F, Bickler SH. A new chronology for the Māori settlement of Aotearoa (NZ) and the potential role of climate change in demographic developments. *Proceedings of the National Academy of Sciences.* 2022;119(46). https://doi.org/10.1073/pnas.2207609119.

93. Curry A. Surprising identities of Pompeii victims rewrite stories from the cataclysm. *Science.* 2024; https://doi.org/10.1126/science.zc3fbc5.

94. Pilli E, Vai S, Moses VC, Morelli S, Lari M, Modi A, et al. Ancient DNA challenges prevailing interpretations of the Pompeii plaster casts. *Current Biology.* 2024;34(22): 5307-5318.e7. https://doi.org/10.1016/j.cub.2024.10.007.

95. Verry AJF, Mitchell KJ, Rawlence NJ. Genetic evidence for post-glacial expansion from a southern refugium in the eastern moa (Emeus crassus). *Biology Letters.* 2022;18(5): 20220013. https://doi.org/10.1098/rsbl.2022.0013.

96. Edwards SV, Cloutier A, Cockburn G, Driver R, Grayson P, Katoh K, et al. A nuclear genome assembly of an extinct flightless bird, the little bush moa. *Science Advances.* 2024;10(21): eadj6823. https://doi.org/10.1126/sciadv.adj6823.

97. Allentoft ME, Rawlence NJ. Moa's Ark or volant ghosts of Gondwana? Insights from nineteen years of ancient DNA research on the extinct moa (Aves: Dinornithiformes) of New Zealand. *Annals of Anatomy - Anatomischer Anzeiger.* 2012;194(1): 36–51. https://doi.org/10.1016/j.aanat.2011.04.002.

98. Hartnup K, Huynen L, Te Kanawa R, Shepherd LD, Millar CD, Lambert DM. Ancient DNA recovers the origins of Māori feather cloaks. *Molecular Biology and Evolution.* 2011;28(10): 2741–2750. https://doi.org/10.1093/molbev/msr107.

99. *Cytomegalovirus (CMV)*. Healthify. https://healthify.nz/health-a-z/c/cytomegalovirus-cmv [Accessed 2nd February 2026].

100. Haque US, Yokota T. Recent progress in gene-targeting therapies for Spinal Muscular Atrophy: Promises and challenges. Genes. 2024;15(8): 999. https://doi.org/10.3390/genes15080999.

101. Kim YK. RNA therapy: Rich history, various applications and unlimited future prospects. *Experimental & Molecular Medicine.* 2022;54(4): 455–465. https://doi.org/10.1038/s12276-022-00757-5.

102. Sparmann A, Vogel J. RNA-based medicine: From molecular mechanisms to therapy. *The EMBO Journal.* 2023;42(21): e114760. https://doi.org/10.15252/embj.2023114760.

103. *Gene therapy basics.* American Society of Gene & Cell Therapy. https://patienteducation.asgct.org/gene-therapy-101/gene-therapy-basics [Accessed 18th November 2024].

104. Landhuis E. The definition of gene therapy has changed. *Nature.* 2021; d41586-021-02736–02738. https://doi.org/10.1038/d41586-021-02736-8.

105. Solomon B. *Gene therapy*. genome.gov. https://www.genome.gov/genetics-glossary/Gene-Therapy [Accessed 18th November 2024].

106. *What is gene therapy?* FDA; https://www.fda.gov/vaccines-blood-biologics/cellular-gene-therapy-products/what-gene-therapy [Accessed 18th November 2024].

107. Lundstrom K. Viral vectors in gene therapy: Where do we stand in 2023? *Viruses.* 2023;15(3): 698. https://doi.org/10.3390/v15030698.

108. *CAR T cells: Engineering immune cells to treat cancer.* National Cancer Institute. https://www.cancer.gov/about-cancer/treatment/research/car-t-cells [Accessed 31st October 2024].

109. Cliff ERS, Kelkar AH, Russler-Germain DA, Tessema FA, Raymakers AJN, Feldman WB, et al. High cost of chimeric antigen receptor T-Cells: Challenges and solutions. *American Society of Clinical Oncology Educational Book.* 2023;(43): e397912. https://doi.org/10.1200/EDBK_397912.

110. Choi G, Shin G, Bae S. Price and prejudice? The value of chimeric antigen receptor (CAR) T-cell therapy. *International Journal of Environmental Research and Public Health.* 2022;19(19): 12366. https://doi.org/10.3390/ijerph191912366.

111. O'Hanlon Cohrt K. *Clinical trial roundup: Gene-editing therapies for gastrointestinal cancers.* CRISPR Medicine News. https://crisprmedicinenews.com/news/clinical-trial-roundup-gene-editing-therapies-for-gastrointestinal-cancers/ [Accessed 12th November 2024].

112. CRISPR Therapeutics. *CRISPR Therapeutics presents data at the Society for Immunotherapy of Cancer (SITC) 37th annual meeting.* CRISPR Therapeutics. https://crisprtx.com/about-us/press-releases-and-presentations/crispr-therapeutics-presents-data-at-the-society-for-immunotherapy-of-cancer-sitc-37th-annual-meeting [Accessed 12th November 2024].

113. Wu S. *Safety and activity of Programmed Cell Death-1 knockout engineered T cells in patients with previously treated advanced esophageal squamous cell carcinoma: An open-label, single-arm phase 1 study.* NCT03081715, 2019. https://clinicaltrials.gov/study/NCT03081715 [Accessed 13th November 2024].

114. Foy SP, Jacoby K, Bota DA, Hunter T, Pan Z, Stawiski E, et al. Non-viral precision T cell receptor replacement for personalized cell therapy. *Nature.* 2023;615(7953): 687–696. https://doi.org/10.1038/s41586-022-05531-1.

115. Mullard A. CAR-T therapy for multiple sclerosis enters US trials for first time. *Nature.* 2024; https://doi.org/10.1038/d41586-024-00470-5.

116. UCSF. *UCSF multiple sclerosis trial: KYV-101, a CD19 CAR T cell therapy, in participants with treatment refractory progressive multiple sclerosis.* https://clinicaltrials.ucsf.edu/trial/NCT06451159 [Accessed 12th November 2024].

117. Vriesen N, Carmany EP, Natoli JL. Clinical outcomes of preimplantation genetic testing for hereditary cancer syndromes: A systematic review. *Prenatal Diagnosis.* 2022;42(2): 201–211. https://doi.org/10.1002/pd.6084.

118. *Human Genomic Variation.* genome.gov. https://www.genome.gov/about-genomics/educational-resources/fact-sheets/human-genomic-variation [Accessed 3rd October 2025].

119. Ministry of Health – Manatū Hauora. *Te Rautaki o Aotearoa e Pā ana ki ngā Mate Mokorea: Te horopaki me ngā taunakitanga - Aotearoa New Zealand Rare Disorders Strategy: Context and evidence.* 2024.

120. *Rare disorders in New Zealand*. Rare Disorders New Zealand. https://raredisorders.org.nz/about-rare-disorders/rare-disorders-in-nz/ [Accessed 14th May 2025].

121. *What is a rare disorder?* Rare Disorders New Zealand. https://raredisorders.org.nz/about-rare-disorders/what-is-a-rare-disorder/ [Accessed 14th May 2025].

122. Theadom A, Rodrigues M, Poke G, O'Grady G, Love D, Hammond-Tooke G, et al. A nationwide, population-based prevalence study of genetic muscle disorders. *Neuroepidemiology.* 2019;52(3–4): 128–135. https://doi.org/10.1159/000494115.

123. *Cystic fibrosis.* Healthify. https://healthify.nz/health-a-z/c/cystic-fibrosis [Accessed 16th October 2025].

124. Dalbeth N, Choi HK, Joosten LAB, Khanna PP, Matsuo H, Perez-Ruiz F, et al. Gout. *Nature Reviews Disease Primers*. 2019;5(1): 69. https://doi.org/10.1038/s41572-019-0115-y.

125. Dalbeth N, House ME, Horne A, Te Karu L, Petrie KJ, McQueen FM, et al. The experience and impact of gout in Māori and Pacific people: a prospective observational study. *Clinical Rheumatology.* 2013;32(2): 247–251. https://doi.org/10.1007/s10067-012-2110-5.

126. Robinson PC, Merriman TR, Herbison P, Highton J. Hospital admissions associated with gout and their comorbidities in New Zealand and England 1999–2009. *Rheumatology.* 2013;52(1): 118–126. https://doi.org/10.1093/rheumatology/kes253.

127. *Approved cellular and gene therapy products.* FDA. https://www.fda.gov/vaccines-blood-biologics/cellular-gene-therapy-products/approved-cellular-and-gene-therapy-products [Accessed 31st October 2024].

128. *Recent approvals: New active ingredients or new indications.* Medsafe. https://www.medsafe.govt.nz/profs/PUArticles/March2023/Recent-approvals-new-active-ingredients-new-indications.html [Accessed 2nd December 2025].

129. *Recent approvals: New active ingredients or new indications*. Medsafe. https://www.medsafe.govt.nz/profs/PUArticles/June2024/Recent-approvals-new-active-ingredients-new-indications.html [Accessed 2nd December 2025].

130. *Casgevy.* European Medicines Agency. https://www.ema.europa.eu/en/medicines/human/EPAR/casgevy [Accessed 3rd November 2025].

131. *Casgevy and Lyfgenia: Two gene therapies approved for sickle cell disease.* Yale Medicine. https://www.yalemedicine.org/news/gene-therapies-sickle-cell-disease [Accessed 7th November 2024].

132. Philippidis A. CASGEVY makes history as FDA approves first CRISPR/cas9 genome edited therapy. *Human Gene Therapy.* 2024;35(1–2): 1–4. https://doi.org/10.1089/hum.2023.29263.bfs.

133. Leonard A, Tisdale JF. A new frontier: FDA approvals for gene therapy in sickle cell disease. *Molecular Therapy.* 2024;32(2): 264–267. https://doi.org/10.1016/j.ymthe.2024.01.015.

134. Thomson AM, McHugh TA, Oron AP, Teply C, Lonberg N, Vilchis Tella V, et al. Global, regional, and national prevalence and mortality burden of sickle cell disease, 2000–2021: a systematic analysis from the Global Burden of Disease Study 2021. *The Lancet Haematology.* 2023;10(8): e585–e599. https://doi.org/10.1016/S2352-3026(23)00118-7.

135. Mayo Clinic Staff. *Sickle cell anemia.* Mayo Clinic. https://www.mayoclinic.org/diseases-conditions/sickle-cell-anemia/diagnosis-treatment/drc-20355882 [Accessed 18th November 2024].

136. Brown H. *Casgevy – how it works.* Genomics Education Programme. 2023. https://www.genomicseducation.hee.nhs.uk/blog/casgevy-how-it-works/ [Accessed 7th November 2024].

137. Adashi EY, Gruppuso PA, Cohen IG. CRISPR therapy of sickle cell disease: The dawning of the gene editing era. *The American Journal of Medicine.* 2024;137(5): 390–392. https://doi.org/10.1016/j.amjmed.2023.12.018.

138. Cellular, Tissue, and Gene Therapies Advisory Committee Meeting. *FDA briefing document - Drug name: exagamglogene autotemcel - Applicant: Vertex Pharmaceuticals Inc*. Office of Therapeutic Products, Federal Drug Advisory. 2023. https://www.fda.gov/media/173414/download

139. Office of the Commissioner. *FDA approves first gene therapies to treat patients with sickle cell disease.* FDA. https://www.fda.gov/news-events/press-announcements/fda-approves-first-gene-therapies-treat-patients-sickle-cell-disease [Accessed 29th October 2024].

140. Medicines and Healthcare products Regulatory Agency. *MHRA authorises world-first gene therapy that aims to cure sickle-cell disease and transfusion-dependent β-thalassemia.* GOV.UK. https://www.gov.uk/government/news/mhra-authorises-world-first-gene-therapy-that-aims-to-cure-sickle-cell-disease-and-transfusion-dependent-thalassemia [Accessed 29th October 2024].

141. Wong C. UK first to approve CRISPR treatment for diseases: What you need to know. *Nature.* 2023;623(7988): 676–677. https://doi.org/10.1038/d41586-023-03590-6.

142. Watt A. Casgevy: Launch sequence and price analysis of the first marketed CRISPR therapy. *Pharmaceutical Technology.* 2024. https://www.pharmaceutical-technology.com/analyst-comment/casgevy-launch-crispr-therapy/ [Accessed 18th November 2024].

143. Healey N. Next-generation CRISPR-based gene-editing therapies tested in clinical trials. *Nature Medicine.* 2024;30(9): 2380–2381. https://doi.org/10.1038/d41591-024-00056-8.

144. Sethi Y, Mahtani AU, Khehra N, Padda I, Patel N, Sebastian SA, et al. Gene editing as the future of cardiac amyloidosis therapeutics. *Current Problems in Cardiology.* 2023;48(8): 101741. https://doi.org/10.1016/j.cpcardiol.2023.101741.

145. Naddaf M. First trial of 'base editing' in humans lowers cholesterol — but raises safety concerns. *Nature.* 2023;623(7988): 671–672. https://doi.org/10.1038/d41586-023-03543-z.

146. Hooper AJ, Tang XL, Burnett JR. VERVE-101, a CRISPR base-editing therapy designed to permanently inactivate hepatic PCSK9 and reduce LDL-cholesterol. *Expert Opinion on Investigational Drugs.* 2024;33(8): 753–756. https://doi.org/10.1080/13543784.2024.2369747.

147. Horie T, Ono K. VERVE-101: A promising CRISPR-based gene editing therapy that reduces LDL-C and PCSK9 levels in HeFH patients. *European Heart Journal - Cardiovascular Pharmacotherapy.* 2024;10(2): 89–90. https://doi.org/10.1093/ehjcvp/pvad103.

148. Aimo A, Castiglione V, Rapezzi C, Franzini M, Panichella G, Vergaro G, et al. RNA-targeting and gene editing therapies for transthyretin amyloidosis. *Nature Reviews Cardiology.* 2022;19(10): 655–667. https://doi.org/10.1038/s41569-022-00683-z.

149. Henry TD, Chung ES, Alvisi M, Sethna F, Murray DR, Traverse JH, et al. Cardiotropic AAV gene therapy for heart failure: a phase 1 trial. *Nature Medicine.* 2025;31(11): 3845–3852. https://doi.org/10.1038/s41591-025-04011-z.

150. Chowdary P, Shapiro S, Makris M, Evans G, Boyce S, Talks K, et al. Phase 1–2 trial of AAVS3 gene therapy in patients with hemophilia B. *New England Journal of Medicine.* 2022;387(3): 237–247. https://doi.org/10.1056/NEJMoa2119913.

151. Excision BioTherapeutics. *A phase 1/2a, sequential cohort, single ascending dose study of the safety, tolerability, biodistribution, and pharmacodynamics of EBT 101 in aviremic HIV-1 infected adults on stable antiretroviral therapy.* NCT05144386, 2024. https://clinicaltrials.gov/study/NCT05144386 [Accessed 13th November 2024].

152. Excision BioTherapeutics. *Long-term follow-up study of HIV-1 infected adults exiting a parent study where EBT-101 was administered.* NCT05143307, 2024. https://clinicaltrials.gov/study/NCT05143307 [Accessed 13th November 2024].

153. Hussein M, Molina MA, Berkhout B, Herrera-Carrillo E. A CRISPR-cas cure for HIV/AIDS. *International Journal of Molecular Sciences.* 2023;24(2): 1563. https://doi.org/10.3390/ijms24021563.

154. Yilmaz BS, Gissen P. Genetic therapy approaches for ornithine transcarbamylase deficiency. *Biomedicines.* 2023;11(8): 2227. https://doi.org/10.3390/biomedicines11082227.

155. Martinez M, Harding CO, Schwank G, Thöny B. State-of-the-art 2023 on gene therapy for phenylketonuria. *Journal of Inherited Metabolic Disease.* 2024;47(1): 80–92. https://doi.org/10.1002/jimd.12651.

156. Cheng Y, Wang H, Li M. The promise of CRISPR/Cas9 technology in diabetes mellitus therapy: How gene editing is revolutionizing diabetes research and treatment. *Journal of Diabetes and its Complications.* 2023;37(8): 108524. https://doi.org/10.1016/j.jdiacomp.2023.108524.

157. Mendell JR, Al-Zaidy S, Shell R, Arnold WD, Rodino-Klapac LR, Prior TW, et al. Single-dose gene-replacement therapy for Spinal Muscular Atrophy. *New England Journal of Medicine.* 2017;377(18): 1713–1722. https://doi.org/10.1056/NEJMoa1706198.

158. Strauss KA, Farrar MA, Muntoni F, Saito K, Mendell JR, Servais L, et al. Onasemnogene abeparvovec for presymptomatic infants with two copies of SMN2 at risk for spinal muscular atrophy type 1: the Phase III SPR1NT trial. *Nature Medicine.* 2022;28(7): 1381–1389. https://doi.org/10.1038/s41591-022-01866-4.

159. Mercuri E, Muntoni F, Baranello G, Masson R, Boespflug-Tanguy O, Bruno C, et al. Onasemnogene abeparvovec gene therapy for symptomatic infantile-onset spinal muscular atrophy type 1 (STR1VE-EU): An open-label, single-arm, multicentre, phase 3 trial. *The Lancet Neurology.* 2021;20(10): 832–841. https://doi.org/10.1016/S1474-4422(21)00251-9.

160. *Locus Biosciences announces first patient treated in the ELIMINATE registrational phase 2/3 trial of LBP-EC01 for urinary tract infections.* Locus Bioscience. http://www.locus-bio.com/locus-biosciences-announces-first-patient-treated-in-the-eliminate-registrational-phase-2-3-trial-of-lbp-ec01-for-urinary-tract-infections/ [Accessed 12th November 2024].

161. Kim P, Sanchez AM, Penke TJR, Tuson HH, Kime JC, McKee RW, et al. Safety, pharmacokinetics, and pharmacodynamics of LBP-EC01, a CRISPR-Cas3-enhanced bacteriophage cocktail, in uncomplicated urinary tract infections due to Escherichia coli (ELIMINATE): the randomised, open-label, first part of a two-part phase 2 trial. *The Lancet Infectious Diseases.* 2024;0(0). https://doi.org/10.1016/S1473-3099(24)00424-9.

162. O'Leary K. In vivo gene editing for inherited vision loss. *Nature Medicine.* 2024; https://doi.org/10.1038/d41591-024-00035-z.

163. Pierce EA, Aleman TS, Jayasundera KT, Ashimatey BS, Kim K, Rashid A, et al. Gene editing for CEP290-associated retinal degeneration. *New England Journal of Medicine.* 2024;390(21): 1972–1984. https://doi.org/10.1056/NEJMoa2309915.

164. Maeder ML, Stefanidakis M, Wilson CJ, Baral R, Barrera LA, Bounoutas GS, et al. Development of a gene-editing approach to restore vision loss in Leber congenital amaurosis type 10. *Nature Medicine*. 2019;25(2): 229–233. https://doi.org/10.1038/s41591-018-0327-9.

165. Xue Y, Tao Y, Wang X, Wang X, Shu Y, Liu Y, et al. RNA base editing therapy cures hearing loss induced by OTOF gene mutation. *Molecular Therapy.* 2023;31(12): 3520–3530. https://doi.org/10.1016/j.ymthe.2023.10.019.

166. Gurevich I, Agarwal P, Zhang P, Dolorito JA, Oliver S, Liu H, et al. In vivo topical gene therapy for recessive dystrophic epidermolysis bullosa: a phase 1 and 2 trial. *Nature Medicine.* 2022;28(4): 780–788. https://doi.org/10.1038/s41591-022-01737-y.

167. Tang JY, Marinkovich MP, Wiss K, McCarthy D, Truesdale A, Chiou AS, et al. Prademagene zamikeracel for recessive dystrophic epidermolysis bullosa wounds (VIITAL): a two-centre, randomised, open-label, intrapatient-controlled phase 3 trial. *The Lancet.* 2025;406(10499): 163–173. https://doi.org/10.1016/S0140-6736(25)00778-0.

168. Koblan LW, Erdos MR, Wilson C, Cabral WA, Levy JM, Xiong ZM, et al. In vivo base editing rescues Hutchinson–Gilford progeria syndrome in mice. *Nature.* 2021;589(7843): 608–614. https://doi.org/10.1038/s41586-020-03086-7.

169. Bulcaen M, Carlon MS. Gene editing flows to the lungs. *Science*. 2024;384(6701): 1175–1176. https://doi.org/10.1126/science.adq0059.

170. Lesté-Lasserre C. Lung-targeted CRISPR therapy offers hope for cystic fibrosis. *New Scientist.* 2024; https://www.newscientist.com/article/2435568-lung-targeted-crispr-therapy-offers-hope-for-cystic-fibrosis/ [Accessed 12th November 2024].

171. Sun Y, Chatterjee S, Lian X, Traylor Z, Sattiraju SR, Xiao Y, et al. In vivo editing of lung stem cells for durable gene correction in mice. *Science.* 2024;384(6701): 1196–1202. https://doi.org/10.1126/science.adk9428.

172. Bornstein SR, Wright JF, Steenblock C. The promising potential of gene therapy for diabetes mellitus. *Nature Reviews Endocrinology.* 2024;20(11): 627–628. https://doi.org/10.1038/s41574-024-01030-7.

173. Gillmore JD, Gane E, Täubel J, Pilebro B, Echaniz-Laguna A, Kao J, et al. Nexiguran ziclumeran gene editing in hereditary ATTR with polyneuropathy. *New England Journal of Medicine.* 2025;393(14): 1375–1386. https://doi.org/10.1056/NEJMoa2510209.

174. Intellia Therapeutics. *Study to evaluate safety, tolerability, pharmacokinetics, and pharmacodynamics of NTLA-2001 in patients with hereditary transthyretin amyloidosis with polyneuropathy (ATTRv-PN) and patients with transthyretin amyloidosis-related cardiomyopathy (ATTR-CM).* clinicaltrials.gov. https://clinicaltrials.gov/study/NCT04601051 [Accessed 19th November 2025].

175. Intellia Therapeutics. *NTLA-2002 in adults with hereditary angioedema (HAE) (NTLA-2002).* clinicaltrials.gov. https://clinicaltrials.gov/study/NCT05120830 [Accessed 19th November 2025].

176. Kersten S. ANGPTL3 as therapeutic target. *Current Opinion in Lipidology.* 2021;32(6): 335–341. https://doi.org/10.1097/MOL.0000000000000789.

177. *VERVE-101: CRISPR-based gene editing therapy shows promise in reducing LDL-C and PCSK9 levels in patients with HeFH.* American College of Cardiology. https://www.acc.org/Latest-in-Cardiology/Articles/2023/11/08/20/14/http%3a%2f%2fwww.acc.org%2fLatest-in-Cardiology%2fArticles%2f2023%2f11%2f08%2f20%2f14%2fsun-445pm-heart1-aha-2023 [Accessed 31st October 2024].

178. Royal Society Te Apārangi. *Gene editing: Scenarios in healthcare.* 2019 Aug. https://www.royalsociety.org.nz/assets/Uploads/Gene-Editing-Summary-Healthcare-DIGITAL.pdf [Accessed 20th November 2024].

179. du Rand A, Hunt J, Verdon D, Buttle B, Dunbar PR, Purvis D, et al. Efficient dual Cas9 nickase correction of a prevalent pathogenic LAMB3 variant for junctional epidermolysis bullosa. *JID Innovations.* 2025;5(3): 100343. https://doi.org/10.1016/j.xjidi.2024.100343.

180. du Rand A, Hunt J, Samson C, Loef E, Malhi C, Meidinger S, et al. Highly efficient CRISPR/Cas9-mediated exon skipping for recessive dystrophic epidermolysis bullosa. *Bioengineering & Translational Medicine.* 2024;9(4): e10640. https://doi.org/10.1002/btm2.10640.

181. Linterman KS, Palmer DN, Kay GW, Barry LA, Mitchell NL, McFarlane RG, et al. Lentiviral-mediated gene transfer to the sheep brain: Implications for gene therapy in Batten disease. *Human Gene Therapy.* 2011;22(8): 1011–1020. https://doi.org/10.1089/hum.2011.026.

182. Mitchell NL, Russell KN, Wellby MP, Wicky HE, Schoderboeck L, Barrell GK, et al. Longitudinal in vivo monitoring of the CNS demonstrates the efficacy of gene therapy in a sheep model of CLN5 batten disease. *Molecular Therapy.* 2018;26(10): 2366–2378. https://doi.org/10.1016/j.ymthe.2018.07.015.

183. Cain JT, Likhite S, White KA, Timm DJ, Davis SS, Johnson TB, et al. Gene therapy corrects brain and behavioral pathologies in CLN6-Batten disease. *Molecular Therapy.* 2019;27(10): 1836–1847. https://doi.org/10.1016/j.ymthe.2019.06.015.

184. Neurogene Inc. *Gene therapy study for children with CLN5 Batten disease (CLN5-200).* NCT05228145, 2024. https://clinicaltrials.gov/study/NCT05228145 [Accessed 19th November 2025].

185. Collins J. *Gene technology bill* 2024. Dec 17, 2024. https://www.legislation.govt.nz/bill/government/2024/0110/7.0/LMS1009752.html

186. Darrow JJ. Luxturna: FDA documents reveal the value of a costly gene therapy. *Drug Discovery Today.* 2019;24(4): 949–954. https://doi.

org/10.1016/j.drudis.2019.01.019.

187. Hoy SM. Onasemnogene abeparvovec: First global approval. *Drugs.* 2019;79(11): 1255–1262. https://doi.org/10.1007/s40265-019-01162-5.

188. Saey TH. Most of today's gene therapies rely on viruses — and that's a problem. *Science News [Internet].* 2023 Oct 20. https://www.sciencenews.org/article/gene-therapy-virus-crispr-editing-disease [Accessed 13th November 2024].

189. Scudellari M. How repairing DNA through gene therapy overcame high-profile failures. *Science News [Internet].* 2022 Mar 22. https://www.sciencenews.org/article/gene-therapy-history-high-profile-failures [Accessed 18th November 2024].

190. Hacein-Bey-Abina S, Garrigue A, Wang GP, Soulier J, Lim A, Morillon E, et al. Insertional oncogenesis in 4 patients after retrovirus-mediated gene therapy of SCID-X1. *The Journal of Clinical Investigation.* 2008;118(9): 3132–3142. https://doi.org/10.1172/JCI35700.

191. Ledford H. The immune system can sabotage gene therapies — can scientists rein it in? *Nature.* 2024;630: 13–14. https://doi.org/https://doi.org/10.1038/d41586-024-01483-w.

192. Lek A, Wong B, Keeler A, Blackwood M, Ma K, Huang S, et al. Death after high-dose rAAV9 gene therapy in a patient with Duchenne's muscular dystrophy. *New England Journal of Medicine.* 2023;389(13): 1203–1210. https://doi.org/10.1056/NEJMoa2307798.

193. Duan L, Ouyang K, Xu X, Xu L, Wen C, Zhou X, et al. Nanoparticle delivery of CRISPR/Cas9 for genome gditing. *Frontiers in Genetics.* 2021;12: 673286. https://doi.org/10.3389/fgene.2021.673286.

194. Mirón-Barroso S, Domènech EB, Trigueros S. Nanotechnology-based strategies to overcome current barriers in gene delivery. *International Journal of Molecular Sciences.* 2021;22(16): 8537. https://doi.org/10.3390/ijms22168537.

195. Devlin H. 'It's a real-life Hunger Games': A lifesaving drug costs $2m, but not every child can get it. *The Guardian [Internet].* 2022 Mar 5. https://www.theguardian.com/business/2022/mar/05/real-life-hunger-games-lifesaving-drug-costs-2m-dollars [Accessed 30th October 2024].

196. Regalado A. There is a new most expensive drug in the world. Price tag: $4.25 million. *MIT Technology Review [Internet].* 2024 Mar 20; https://www.technologyreview.com/2024/03/20/1089996/there-is-a-new-most-expensive-drug-in-the-world-price-tag-4-25-million/ [Accessed 30th October 2024].

197. *The top 5 most expensive FDA-approved gene therapies.* Pharma Life Sciences. https://www.techtarget.com/pharmalifesciences/feature/The-Top-5-Most-Expensive-FDA-Approved-Gene-Therapies [Accessed 20th November 2024].

198. Antrobus K. *How we can make gene therapies available to all.* World Economic Forum. https://www.weforum.org/stories/2021/10/how-we-can-make-gene-therapies-available-to-all/ [Accessed 20th November 2024].

199. Miller A. *Ethical Implications of the Novartis Lottery.* America Society of Human Genetics. https://www.ashg.org/publications-news/trainee-newsletter/ethical-implications-of-the-novartis-lottery/ [Accessed 20th November 2024].

200. Pagliarulo N. *Bluebird, winding down in Europe, withdraws another rare disease gene therapy.* BioPharma Dive. https://www.biopharmadive.com/news/bluebird-withdraw-gene-therapy-europe-skysona/608666/ [Accessed 20th November 2024].

201. Alvarado D. *Novartis stops work on gene therapy acquired in Gyroscope deal*. BioPharma Dive. https://www.biopharmadive.com/news/novartis-gyroscope-gene-therapy-discontinue-geographic-atrophy/693233/ [Accessed 20th November 2024].

202. Jensen K. *Orchard abandons promising gene therapy for rare immune disorder.* BioPharma Dive. https://www.biopharmadive.com/news/orchard-abandon-gene-therapy-ada-scid/601232/ [Accessed 20th November 2024].

203. Yasir S, Bhagat SV, Hylton S. With a $2.1 million cure their only hope, parents plead for help online. *The New York Times [Internet].* 2022 Apr 6. https://www.nytimes.com/2022/04/06/business/india-spinal-muscular-atrophy.html [Accessed 20th November 2024].

204. *NIH launches new collaboration to develop gene-based cures for sickle cell disease and HIV on global scale.* National Institutes of Health. https://www.nih.gov/news-events/news-releases/nih-launches-new-collaboration-develop-gene-based-cures-sickle-cell-disease-hiv-global-scale [Accessed 20th November 2024].

205. Booth C. *When there's no commercial incentive to develop gene therapy – hospitals will try to fill the gap.* The Conversation. http://theconversation.com/when-theres-no-commercial-incentive-to-develop-gene-therapy-hospitals-will-try-to-fill-the-gap-230699 [Accessed 20th November 2024].

206. Cohen J, Kaiser J. *NIH and Gates Foundation lay out ambitious plan to bring gene-based treatments for HIV and sickle cell disease to Africa.* ScienceInsider. https://www.science.org/content/article/nih-and-gates-foundation-lay-out-ambitious-plan-bring-gene-based-treatments-hiv-and [Accessed 20th November 2024].

207. Valsecchi MC. Rescue of an orphan drug points to a new model for therapies for rare diseases. *Nature.* 2023; https://doi.org/10.1038/d43978-023-00145-1.

208. Jørgensen J, Kefalas P. The use of innovative payment mechanisms for gene therapies in Europe and the USA. *Regenerative Medicine.* 2021;16(4): 405–422. https://doi.org/10.2217/rme-2020-0169.

209. Zhang JX, Shugarman LR. Value-based payment and financing for cell and gene therapies: challenges and potential solutions. *Journal of*

*Medical Economics.* 2024;27(1): 678–681. https://doi.org/10.1080/13696998.2024.2346406.

210. Garrison LP, Jiao B, Dabbous O. Gene therapy may not be as expensive as people think: challenges in assessing the value of single and short-term therapies. *Journal of Managed Care & Specialty Pharmacy.* 2021;27(5). https://doi.org/10.18553/jmcp.2021.27.5.674.

211. Salzman R, Cook F, Hunt T, Malech HL, Reilly P, Foss-Campbell B, et al. Addressing the value of gene therapy and enhancing patient access to transformative treatments. *Molecular Therapy.* 2018;26(12): 2717–2726. https://doi.org/10.1016/j.ymthe.2018.10.017.

212. Johnson KM, Jiao B, Ramsey SD, Bender MA, Devine B, Basu A. Lifetime m edical costs attributable to sickle cell disease among nonelderly individuals with commercial insurance. *Blood Advances.* 2023;7(3): 365–374. https://doi.org/10.1182/bloodadvances.2021006281.

213. Pagliarulo N. *Pricey new gene therapies for sickle cell pose access test. BioPharma Dive.* https://www.biopharmadive.com/news/crispr-sickle-cell-price-millions-gene-therapy-vertex-bluebird/702066/ [Accessed 20th November 2024].

214. Ginn SL, Mandwie M, Alexander IE, Edelstein M, Abedi MR. Gene therapy clinical trials worldwide to 2023—an update. *The Journal of Gene Medicine.* 2024;26(8): e3721. https://doi.org/10.1002/jgm.3721.

215. Klapwijk JC, Del Rio Espinola A, Libertini S, Collin P, Fellows MD, Jobling S, et al. Improving the assessment of risk factors relevant to potential carcinogenicity of gene therapies: A consensus article. *Human Gene Therapy.* 2024;35(15–16): 527–542. https://doi.org/10.1089/hum.2024.033.

216. Busse PJ, Christiansen SC. Hereditary angioedema. *New England Journal of Medicine.* 2020;382(12): 1136–1148. https://doi.org/10.1056/NEJMra1808012.

217. Gelfand JA, Sherins RJ, Alling DW, Frank MM. Treatment of hereditary angioedema with danazol. *New England Journal of Medicine.* 1976;295(26): 1444–1448. https://doi.org/10.1056/NEJM197612232952602.

218. Xu Y, Zhi Y. Long-term prophylaxis of hereditary angioedema with danazol. *Chinese Medical Journal.* 2022;135(21): 2642–2643. https://doi.org/10.1097/CM9.0000000000002144.

219. World-first gene editing treatment to eliminate angioedema life changing, patient says. *RNZ [Internet].* 2024 Feb 1. https://www.rnz.co.nz/news/national/508176/world-first-gene-editing-treatment-to-eliminate-angioedema-life-changing-patient-says [Accessed 30th October 2024].

220. *Americans are closely divided over editing a baby's genes to reduce serious health risk.* Pew Research Center. 2022. https://www.pewresearch.org/internet/2022/03/17/americans-are-closely-divided-over-editing-a-babys-genes-to-reduce-serious-health-risk/ [Accessed 21st November 2024].

221. *Editing our genes: Promises and pitfalls on RNZ.* Royal Society Te Apārangi. https://www.royalsociety.org.nz/news/editing-our-genes-promises-and-pitfalls-on-rnz/ [Accessed 20th November 2024].

222. Sufian S, Garland-Thompson R. *The dark side of CRISPR.* Scientific American. 2021; https://www.scientificamerican.com/article/the-dark-side-of-crispr/ [Accessed 21st November 2024].

223. Zhang S. The last children of Down syndrome. *The Atlantic [Internet].* 2020 Dec. https://www.theatlantic.com/magazine/archive/2020/12/the-last-children-of-down-syndrome/616928/ [Accessed 23rd October 2024].

224. Sway. (2020) *Should you choose your baby's eye color?* [Podcast] Oct 22. https://www.nytimes.com/2020/10/22/opinion/sway-kara-swisher-jennifer-doudna.html [Accessed 21st November 2024].

225. Baer N. *The promise and peril of CRISPR.* Johns Hopkins University Press. 2024. https://doi.org/10.56021/9781421449302. [Accessed 21st November 2024].

226. Joseph AM, Karas M, Ramadan Y, Joubran E, Jacobs RJ. Ethical perspectives of therapeutic human genome editing from multiple and diverse viewpoints: A scoping review. *Cureus.* 2022; https://doi.org/10.7759/cureus.31927.

227. Hudson AO, Skuse G. *Human genome editing offers tantalizing possibilities – but without clear guidelines, many ethical questions still remain.* The Conversation. http://theconversation.com/human-genome-editing-offers-tantalizing-possibilities-but-without-clear-guidelines-many-ethical-questions-still-remain-200983 [Accessed 21st November 2024].

228. Almeida M, Ranisch R. Beyond safety: Mapping the ethical debate on heritable genome editing interventions. *Humanities and Social Sciences Communications.* 2022;9(1): 139. https://doi.org/10.1057/s41599-022-01147-y.

229. Guttinger S. Trust in science: CRISPR–cas9 and the ban on human germline editing. *Science and Engineering Ethics.* 2018;24(4): 1077–1096. https://doi.org/10.1007/s11948-017-9931-1.

230. *Māori engagement & advancement rōpu hui: Minutes.* He Kāmaka Waiora, Waitematā District Health Board, Auckland District Health Board; 2021.

231. Benatar J, Evile T, Wihongi H, The Whānau. Hui: a partnership in practice in familial hypercholesterolemia. *New Zealand Medical Journal.* 2020;133(1522): 63–70.

232. Bunn HF. Erythropoietin. *Cold Spring Harbor Perspectives in Medicine.* 2013;3(3): a011619. https://doi.org/10.1101/cshperspect.a011619.

233. Aghadi A, Dybała E, Cuber I, Mazurek M, Białowąs E. Erythropoietin as banned substance in professional sports: Effects on maximal aerobic capacity, endurance and detection methods - a

review. *Journal of Education, Health and Sport.* 2023;13(3): 331–336. https://doi.org/10.12775/JEHS.2023.13.03.042.

234. McFadden BR, Rumble JN, Stofer KA, Folta KM. U.S. public opinion about the safety of gene editing in the agriculture and medical fields and the amount of evidence needed to improve opinions. *Frontiers in Bioengineering and Biotechnology.* 2024;12. https://doi.org/10.3389/fbioe.2024.1340398.

235. *What do people think about genome editing?* National Human Genome Research Institute. https://www.genome.gov/about-genomics/policy-issues/Genome-Editing/public-opinion [Accessed 21st November 2024].

236. Jedwab A, Vears DF, Tse C, Gyngell C. Genetics experience impacts attitudes towards germline gene editing: A survey of over 1500 members of the public. *Journal of Human Genetics.* 2020;65(12): 1055–1065. https://doi.org/10.1038/s10038-020-0810-2.

237. Normile D. Chinese scientist who produced genetically altered babies sentenced to 3 years in jail. *Science.* 2019; https://doi.org/10.1126/science.aba7347.

238. Devlin H. Scientist who edited babies' genes says he acted 'too quickly'. *The Guardian [Internet].* 2023 Feb 4. https://www.theguardian.com/science/2023/feb/04/scientist-edited-babies-genes-acted-too-quickly-he-jiankui [Accessed 21st November 2024].

239. Stein R. 2 Chinese babies with edited genes may face higher risk of premature death. *NPR [Internet].* 2019 Jun 3. https://www.npr.org/sections/health-shots/2019/06/03/727957768/2-chinese-babies-with-edited-genes-may-face-higher-risk-of-premature-death [Accessed 21st November 2024].

240. Cohen J. Did CRISPR help—or harm—the first-ever gene-edited babies? *Science.* 2019; https://doi.org/10.1126/science.aay9569.

241. *China's CRISPR babies: Read exclusive excerpts from the unseen original research.* MIT Technology Review. https://www.technologyreview.com/2019/12/03/131752/chinas-crispr-babies-read-exclusive-excerpts-he-jiankui-paper/ [Accessed 21st November 2024].

242. Reardon S. World Health Organization panel weighs in on CRISPR-babies debate. *Nature.* 2019;567(7749): 444–445. https://doi.org/10.1038/d41586-019-00942-z.

243. Raposo VL. The first Chinese edited babies: A leap of faith in science. *JBRA Assisted Reproduction.* 2019;23(3): 197–199. https://doi.org/10.5935/1518-0557.20190042.

244. Normile D. CRISPR bombshell: Chinese researcher claims to have created gene-edited twins. *Science.* 2018; https://doi.org/10.1126/science.aaw1839.

245. Birney E. A society-wide conversation is needed about germline genome editing using CRISPR. *Nature Medicine.* 2024;30(1): 30–32. https://doi.org/10.1038/s41591-023-02681-1.

246. Baltimore D, Berg P, Botchan M, Carroll D, Charo RA, Church G, et al. A prudent path forward for genomic engineering and germline gene modification. *Science.* 2015;348(6230): 36–38. https://doi.org/10.1126/science.aab1028.

247. Brown J. Editing fetal genomes is on the horizon – a medical anthropologist explains why ethical discussions with the target communities should happen sooner rather than later. *The Conversation.* http://theconversation.com/editing-fetal-genomes-is-on-the-horizon-a-medical-anthropologist-explains-why-ethical-discussions-with-the-target-communities-should-happen-sooner-rather-than-later-229257 [Accessed 12th November 2024].

248. Science Media Centre. *Call for moratorium on human genome editing - Expert Reaction.* https://www.sciencemediacentre.co.nz/2019/03/14/call-for-moratorium-on-human-genome-editing-expert-reaction/ [Accessed 3rd July 2025].

249. Ledford H. WHO should lead on genome-editing policy, advisers say. *Nature.* 2021; https://doi.org/10.1038/d41586-021-01922-y.

250. WHO Expert Advisory Committee on Developing Global Standards for Governance and Oversight of Human Genome Editing. *Human genome editing: Recommendations.* 2021.

251. WHO Expert Advisory Committee on Developing Global Standards for Governance and Oversight of Human Genome Editing. *Human genome editing: A framework for governance.* 2021.

252. WHO Expert Advisory Committee on Developing Global Standards for Governance and Oversight of Human Genome Editing. *Human genome editing: Position paper.* 2021.

253. Liu S. Legal reflections on the case of genome-edited babies. *Global Health Research and Policy.* 2020;5(1): 24. https://doi.org/10.1186/s41256-020-00153-4.

254. Baylis F, Darnovsky M, Hasson K, Krahn TM. Human germline and heritable genome editing: The global policy landscape. *The CRISPR Journal.* 2020;3(5): 365–377. https://doi.org/10.1089/crispr.2020.0082.

255. National Health Research Ethics Council. *South African ethics in health research guidelines: Principles, processes and structures.* 2024. https://www.health.gov.za/wp-content/uploads/2024/05/NDoH-2024-Health-Research-Guidelines-3rdEdition-v0.1.pdf

256. Wild S. Will South Africa become first country to accept controversial form of human genome editing? *Nature.* 2024; https://doi.org/https://doi.org/10.1038/d41586-024-03643-4.

257. Cheng X, Li H, Tang Q, Zhang H, Liu T, Wang Y. Trends in the global commercialization of genetically modified crops in 2023. *Journal of Integrative Agriculture.* 2024;23(12): 3943–3952. https://doi.org/10.1016/j.jia.2024.09.012.

258. *Hazardous Substances and New Organisms*

*Act 1996.* https://www.legislation.govt.nz/act/public/1996/0030/latest/whole.html#DLM381222 [Accessed 20th November 2023].

259. Ministry for Primary Industries – Manatū Ahu Matua. *Mycoplasma bovis National Pest Management Plan.* https://www.mpi.govt.nz/biosecurity/exotic-pests-and-diseases-in-new-zealand/long-term-biosecurity-management-programmes/mycoplasma-bovis-national-pest-management-plan/ [Accessed 22nd May 2025].

260. Dudek K, Nicholas RAJ, Szacawa E, Bednarek D. Mycoplasma bovis infections—occurrence, diagnosis and control. *Pathogens*. 2020;9(8): 640. https://doi.org/10.3390/pathogens9080640.

261. Ministry for Primary Industries – Manatū Ahu Matua. *Imported bovine semen testing compensation Mycoplasma bovis (M. bovis) eradication programme.* 2023. https://www.mpi.govt.nz/dmsdocument/59575/direct

262. Shadbolt N, Saunders C, Paskin R, Cleland T. *The Mycoplasma bovis programme: An independent review 2021.* 2021 Sept.

263. A timeline of the *Mycoplasma bovis* spread around NZ. *RNZ [Internet]*. 2018 May 22. https://www.rnz.co.nz/news/country/357908/a-timeline-of-the-mycoplasma-bovis-spread-around-nz [Accessed 22nd May 2025].

264. *Finding Mycoplasma bovis (M. bovis).* Ospri. https://www.ospri.co.nz/our-programmes/the-mycoplasma-bovis-programme/how-the-mycoplasma-bovis-programme-works/finding-mycoplasma-bovis/ [Accessed 22nd May 2025].

265. Royal Society Te Apārangi. *The impact of the Hazardous Substances and New Organisms (HSNO) Act on research in New Zealand.* 2013. https://www.royalsociety.org.nz/assets/documents/RSNZ-HSNO-consultation-paper.pdf

266. Dikmen S, Khan FA, Huson HJ, Sonstegard TS, Moss JI, Dahl GE, et al. The SLICK hair locus derived from Senepol cattle confers thermotolerance to intensively managed lactating Holstein cows. *Journal of Dairy Science.* 2014;97(9): 5508–5520. https://doi.org/10.3168/jds.2014-8087.

267. Donkersloot EG, Worth GM, Yeates AF, Littlejohn MD, McNaughton LR, Davis SR. The benefit of a slick hair coat for heat tolerance in New Zealand dairy cattle. *Proceedings of the Association for the Advancement of Animal Breeding and Genetics.* 2021;24: 94–97.

268. Royal Society Te Apārangi. *Gene editing: Scenarios in the primary industries.* 2019. https://www.royalsociety.org.nz/assets/Uploads/Gene-Editing-Summary-Primary-Industries-DIGITAL.pdf [Accessed 20th November 2024].

269. Fuglie K. *More than half of harvested U.S. cropland uses seed varieties with at least one genetically modified trait.* Economic Research Service U.S. Department of Agriculture. https://www.ers.usda.gov/data-products/charts-of-note/chart-detail?chartId=107037 [Accessed 2nd October 2025].

270. Tuncel A, Pan C, Sprink T, Wilhelm R, Barrangou R, Li L, et al. Genome-edited foods. *Nature Reviews Bioengineering*. 2023;1(11): 799–816. https://doi.org/10.1038/s44222-023-00115-8.

271. Tuncel A, Pan C, Clem JS, Liu D, Qi Y. CRISPR–Cas applications in agriculture and plant research. *Nature Reviews Molecular Cell Biology.* 2025;26(6): 419–441. https://doi.org/10.1038/s41580-025-00834-3.

272. Modrzejewski D, Hartung F, Lehnert H, Sprink T, Kohl C, Keilwagen J, et al. Which factors affect the occurrence of off-target effects caused by the use of CRISPR/cas: A systematic review in plants. *Frontiers in Plant Science.* 2020;11: 574959. https://doi.org/10.3389/fpls.2020.574959.

273. Sturme MHJ, van der Berg JP, Bouwman LMS, De Schrijver A, de Maagd RA, Kleter GA, et al. Occurrence and nature of off-target modifications by CRISPR-cas genome editing in plants. *ACS Agricultural Science & Technology*. 2022;2(2): 192–201. https://doi.org/10.1021/acsagscitech.1c00270.

274. Kempton HR, Qi LS. When genome editing goes off-target. *Science.* 2019;364(6437): 234–236. https://doi.org/10.1126/science.aax1827.

275. Chen F, Chen L, Yan Z, Xu J, Feng L, He N, et al. Recent advances of CRISPR-based genome editing for enhancing staple crops. *Frontiers in Plant Science.* 2024;15. https://doi.org/10.3389/fpls.2024.1478398.

276. Jiang Y, Sun K, An X. CRISPR/cas system: Applications and prospects for maize improvement. *ACS Agricultural Science & Technology.* 2022;2(2): 174–183. https://doi.org/10.1021/acsagscitech.1c00253.

277. Human Foods Program. FDA concludes consultation on pink flesh pineapple. *FDA.* 2024; https://www.fda.gov/food/hfp-constituent-updates/fda-concludes-consultation-pink-flesh-pineapple

278. Fraser RZ, Shitut M, Agrawal P, Mendes O, Klapholz S. Safety evaluation of soy leghemoglobin protein preparation derived from pichia pastoris, intended for use as a flavor catalyst in plant-based meat. *International Journal of Toxicology.* 2018;37(3): 241–262. https://doi.org/10.1177/1091581818766318.

279. Waltz E. GABA-enriched tomato is first CRISPR-edited food to enter market. *Nature Biotechnology.* 2022;40: 9–11. https://doi.org/d41587-021-00026-2.

280. Kwon CT, Heo J, Lemmon ZH, Capua Y, Hutton SF, Van Eck J, et al. Rapid customization of Solanaceae fruit crops for urban agriculture. *Nature Biotechnology.* 2020;38(2): 182–188. https://doi.org/10.1038/s41587-019-0361-2.

281. Tripathi L, Ntui VO, Tripathi JN. Application of genetic modification and genome editing for developing climate-smart banana. *Food and Energy Security.* 2019;8(4): e00168. https://doi.org/10.1002/fes3.168.

282. Qi Y, Sangarwut N, Tongmark K, Chakhonkaen S,

Wang L, Muangprom A. Effects of GS3 editing in japonica rice 'Nipponbare' on grain morphology, yield components, and response to heat stress at the reproductive stage. Plants. 2025;14(18): 2897. https://doi.org/10.3390/plants14182897.

283. Tripathi L, Ntui VO, Tripathi JN. Application of CRISPR/Cas-based gene-editing for developing better banana. *Frontiers in Bioengineering and Biotechnology.* 2024;12: 1395772. https://doi.org/10.3389/fbioe.2024.1395772.

284. Guiltinan MJ, Landherr L, Maximova SN, DelVecchio D, Sebastian A, Albert I. Reduced susceptibility to Phytophthora in non-transgenic cacao progeny through CRISPR–Cas9 mediated TcNPR3 mutagenesis. *Plant Biotechnology Journal*. 2025;0: 1–13. https://doi.org/10.1111/pbi.70365.

285. Karlson D, Mojica JP, Poorten TJ, Lawit SJ, Jali S, Chauhan RD, et al. Targeted mutagenesis of the multicopy myrosinase gene family in allotetraploid Brassica juncea reduces pungency in fresh leaves across environments. *Plants.* 2022;11(19): 2494. https://doi.org/10.3390/plants11192494.

286. Do PT, Nguyen CX, Bui HT, Tran LTN, Stacey G, Gillman JD, et al. Demonstration of highly efficient dual gRNA CRISPR/Cas9 editing of the homeologous GmFAD2–1A and GmFAD2–1B genes to yield a high oleic, low linoleic and α-linolenic acid phenotype in soybean. *BMC Plant Biology.* 2019;19(1): 311. https://doi.org/10.1186/s12870-019-1906-8.

287. Okuzaki A, Ogawa T, Koizuka C, Kaneko K, Inaba M, Imamura J, et al. CRISPR/Cas9-mediated genome editing of the fatty acid desaturase 2 gene in Brassica napus. *Plant Physiology and Biochemistry.* 2018;131: 63–69. https://doi.org/10.1016/j.plaphy.2018.04.025.

288. Abe K, Araki E, Suzuki Y, Toki S, Saika H. Production of high oleic/low linoleic rice by genome editing. *Plant physiology and biochemistry: PPB.* 2018;131: 58–62. https://doi.org/10.1016/j.plaphy.2018.04.033.

289. Zhao X, Jayarathna S, Turesson H, Fält AS, Nestor G, González MN, et al. Amylose starch with no detectable branching developed through DNA-free CRISPR-Cas9 mediated mutagenesis of two starch branching enzymes in potato. *Scientific Reports.* 2021;11(1): 4311. https://doi.org/10.1038/s41598-021-83462-z.

290. Tuncel A, Corbin KR, Ahn-Jarvis J, Harris S, Hawkins E, Smedley MA, et al. Cas9-mediated mutagenesis of potato starch-branching enzymes generates a range of tuber starch phenotypes. *Plant Biotechnology Journal.* 2019;17(12): 2259–2271. https://doi.org/10.1111/pbi.13137.

291. Japan embraces CRISPR-edited fish. *Nature Biotechnology.* 2022;40(1): 10. https://doi.org/10.1038/s41587-021-01197-8.

292. The Curiosity Company. *Latest data shows three quarters of New Zealanders know nothing about the Gene Technology Bill.* 2025.

293. Dort EN, Tanguay P, Hamelin RC. CRISPR/cas9 gene editing: An unexplored frontier for forest pathology. *Frontiers in Plant Science.* 2020;11. https://doi.org/10.3389/fpls.2020.01126.

294. Thapliyal G, Bhandari MS, Vemanna RS, Pandey S, Meena RK, Barthwal S. Engineering traits through CRISPR/cas genome editing in woody species to improve forest diversity and yield. *Critical Reviews in Biotechnology.* 2023;43(6): 884–903. https://doi.org/10.1080/07388551.2022.2092714.

295. *World-leading gene editing research will benefit NZ.* Scion Research. https://www.scionresearch.com/news-and-events/news/2025-news-and-media-releases/world-leading-gene-editing-research-will-benefit-nz [Accessed 3rd June 2025].

296. Meyer F. They said it couldn't be done: Gene editing breakthrough preempts new law. *Newsroom [Internet].* 2025 May 21. http://newsroom.co.nz/2025/05/21/gene-editing-breakthrough-ahead-of-new-law/ [Accessed 4th June 2025].

297. Callahan AM, Srinivasan C, Dardick C, Scorza R. Rapid cycle breeding: Application of transgenic early flowering for perennial trees. In: *Plant Breeding Reviews, Volume 40.* John Wiley & Sons, Ltd; 2016. p. 299–334. https://doi.org/10.1002/9781119279723.ch7. [Accessed 8th July 2025].

298. Flachowsky H, Le Roux PM, Peil A, Patocchi A, Richter K, Hanke MV. Application of a high-speed breeding technology to apple (Malus × domestica) based on transgenic early flowering plants and marker-assisted selection. *New Phytologist.* 2011;192(2): 364–377. https://doi.org/10.1111/j.1469-8137.2011.03813.x.

299. Wanga MA, Shimelis H, Mashilo J, Laing MD. Opportunities and challenges of speed breeding: A review. *Plant Breeding.* 2021;140(2): 185–194. https://doi.org/10.1111/pbr.12909.

300. Vega Rodríguez A, Rodríguez-Oramas C, Sanjuán Velázquez E, Hardisson de la Torre A, Rubio Armendáriz C, Carrascosa Iruzubieta C. Myths and realities about genetically modified food: A risk-benefit analysis. *Applied Sciences.* 2022;12(6): 2861. https://doi.org/10.3390/app12062861.

301. Nordlee JA, Taylor SL, Townsend JA, Thomas LA, Bush RK. Identification of a Brazil-nut allergen in transgenic soybeans. *New England Journal of Medicine.* 1996;334(11): 688–692. https://doi.org/10.1056/NEJM199603143341103.

302. Chakraborty A, Wylie SJ. Gene editing for allergen amelioration in plants – A review. *Plant Gene.* 2024;40: 100476. https://doi.org/10.1016/j.plgene.2024.100476.

303. Nishiguchi M, Futamura N, Endo M, Mikami M, Toki S, Katahata SI, et al. CRISPR/Cas9-mediated disruption of CjACOS5 confers no-pollen formation on sugi trees (Cryptomeria japonica D. Don). *Scientific Reports.* 2023;13(1): 11779. https://doi.org/10.1038/s41598-023-38339-8.

304. Wei J, Wagner S, Maclean P, Brophy B, Cole S, Smolenski G, et al. Cattle with a precise, zygote-mediated deletion safely eliminate the major milk allergen β-lactoglobulin. *Scientific Reports.*

2018;8(1): 7661. https://doi.org/10.1038/s41598-018-25654-8.

305. Jabed A, Wagner S, McCracken J, Wells DN, Laible G. Targeted microRNA expression in dairy cattle directs production of β-lactoglobulin-free, high-casein milk. *Proceedings of the National Academy of Sciences.* 2012;109(42): 16811–16816. https://doi.org/10.1073/pnas.1210057109.

306. Li L, Li M, Qiu Y, Dong Y. A sensitive CRISPR/Cas12a-assisted fluorescent aptasensor for rapid detection of food allergens. *International Journal of Biological Macromolecules.* 2024;274: 133444. https://doi.org/10.1016/j.ijbiomac.2024.133444.

307. Goldson S, Bourdôt G, Brockerhoff E, Byrom A, Clout M, McGlone M, et al. New Zealand pest management: Current and future challenges. *Journal of the Royal Society of New Zealand.* 2015;45(1): 31–58. https://doi.org/10.1080/03036758.2014.1000343.

308. Gault AA, Welsh SA, Paewai A, Drysdale P, Wilkinson SP, Morris H, et al. Promoting community-led monitoring of taonga (treasured) species and freshwater health through eDNA metabarcoding. *Environmental DNA.* 2025;7: e70098. https://doi.org/10.1002/edn3.70098.

309. De Brauwer M, Clarke LJ, Chariton A, Cooper MK, de Bruyn M, Furlan E, et al. Best practice guidelines for environmental DNA biomonitoring in Australia and New Zealand. *Environmental DNA.* 2023;5(3): 417–423. https://doi.org/10.1002/edn3.395.

310. *Kākāpō breeding season 2026.* Conservation blog. 2025. https://blog.doc.govt.nz/2025/06/27/kakapo-breeding-season-2026/ [Accessed 3rd July 2025].

311. Clout MN, Merton DV. Saving the Kakapo: The conservation of the world's most peculiar parrot. *Bird Conservation International.* 1998;8(3): 281–296. https://doi.org/10.1017/S0959270900001933.

312. *Kākāpō125+gene sequencing.* Department of Conservation. https://www.doc.govt.nz/our-work/kakapo-recovery/what-we-do/research-for-the-future/kakapo125-gene-sequencing/ [Accessed 3rd July 2025].

313. *Rangitāne o Manawatū become the first indigenous community to name a genome sequence*. Plant & Food Research. https://www.plantandfood.com/en-nz/article/rangitane-o-manawatu-become-the-first-indigenous-community-to-name-a-genome [Accessed 11th August 2025].

314. North HL, McGaughran A, Jiggins CD. Insights into invasive species from whole-genome resequencing. *Molecular Ecology.* 2021;30(23): 6289–6308. https://doi.org/10.1111/mec.15999.

315. Sethuraman A, Janzen FJ, Weisrock DW, Obrycki JJ. Insights from population genomics to enhance and sustain biological control of insect pests. *Insects.* 2020;11(8): 462. https://doi.org/10.3390/insects11080462.

316. Barnes MA, Turner CR. The ecology of environmental DNA and implications for conservation genetics. *Conservation Genetics.* 2016;17(1): 1–17. https://doi.org/10.1007/s10592-015-0775-4.

317. Goldberg CS, Sepulveda A, Ray A, Baumgardt J, Waits LP. Environmental DNA as a new method for early detection of New Zealand mudsnails (Potamopyrgus antipodarum). *Freshwater Science.* 2013;32(3): 792–800. https://doi.org/10.1899/13-046.1.

318. Waters JM, Ni S, McCulloch GA. Freshwater eDNA reveals dramatic biological shifts linked to deforestation of New Zealand. *Science of The Total Environment.* 2024;908: 168174. https://doi.org/10.1016/j.scitotenv.2023.168174.

319. David BO, Fake DR, Hicks AS, Wilkinson SP, Bunce M, Smith JS, et al. Sucked in by eDNA – a promising tool for complementing riverine assessment of freshwater fish communities in Aotearoa New Zealand. *New Zealand Journal of Zoology.* 2021;48(3–4): 217–244. https://doi.org/10.1080/03014223.2021.1905672.

320. Bird S, Wilkinson S, McGaughran A. Wetland biodiversity in Aotearoa New Zealand: An eDNA perspective on exotic and non-exotic species. *New Zealand Journal of Zoology.* 2024; 1–18. https://doi.org/10.1080/03014223.2024.2359685.

321. Westbrook JW, Malukiewicz J, Zhang Q, Sreedasyam A, Jenkins JW, Lakoba V, et al. *Improving American chestnut resistance to two invasive pathogens through genome-enabled breeding.* 2025; Preprint. https://doi.org/10.1101/2025.01.30.635736.

322. Powell WA, Newhouse AE, Coffey V. Developing blight-tolerant American chestnut trees. *Cold Spring Harbor Perspectives in Biology.* 2019;11(7): a034587. https://doi.org/10.1101/cshperspect.a034587.

323. Bergner LM, Jamieson IG, Robertson BC. Combining genetic data to identify relatedness among founders in a genetically depauperate parrot, the Kakapo (Strigops habroptilus). *Conservation Genetics.* 2014;15(5): 1013–1020. https://doi.org/10.1007/s10592-014-0595-y.

324. Piaggio AJ, Segelbacher G, Seddon PJ, Alphey L, Bennett EL, Carlson RH, et al. Is it time for synthetic biodiversity conservation? *Trends in Ecology & Evolution.* 2017;32(2): 97–107. https://doi.org/10.1016/j.tree.2016.10.016.

325. van Oosterhout C, Supple MA, Morales HE, Birley T, Tatayah V, Jones CG, et al. Genome engineering in biodiversity conservation and restoration. *Nature Reviews Biodiversity.* 2025;1(8): 543–555. https://doi.org/10.1038/s44358-025-00065-6.

326. Phelps MP, Seeb LW, Seeb JE. Transforming ecology and conservation biology through genome editing. *Conservation Biology.* 2020;34(1): 54–65. https://doi.org/10.1111/cobi.13292.

327. Bose S, Kumar PS, Vo DVN, Rajamohan N, Saravanan R. Microbial degradation of recalcitrant pesticides: A review. *Environmental Chemistry Letters.* 2021;19(4): 3209–3228. https://doi.

org/10.1007/s10311-021-01236-5.

328. Kumar A, Saxena P, Kisku GC. Recent advancements in environmental biodegradation of organochlorine pesticides: A review. *Environmental Sustainability.* 2024;7(4): 461–476. https://doi.org/10.1007/s42398-024-00331-x.

329. Brooijmans RJW, Pastink MI, Siezen RJ. Hydrocarbon-degrading bacteria: The oil-spill clean-up crew. *Microbial biotechnology.* 2009;2(6): 587–594. https://doi.org/10.1111/j.1751-7915.2009.00151.x.

330. Amobonye A, Bhagwat P, Singh S, Pillai S. Plastic biodegradation: Frontline microbes and their enzymes. *Science of The Total Environment.* 2021;759: 143536. https://doi.org/10.1016/j.scitotenv.2020.143536.

331. Karlson B, Bellavitis C, France N. Commercializing LanzaTech, from waste to fuel: An effectuation case. *Journal of Management & Organization.* 2021;27(1): 175–196. https://doi.org/10.1017/jmo.2017.83.

332. Cowl VB, Comizzoli P, Appeltant R, Bolton RL, Browne RK, Holt WV, et al. Cloning for the twenty-first century and its place in endangered species conservation. *Annual Review of Animal Biosciences.* 2024;12(1): 91–112. https://doi.org/10.1146/annurev-animal-071423-093523.

333. Callender C. On the horns of a dilemma: Let the northern white rhino vanish or intervene? *Ethics, Policy & Environment.* 2023;26(2): 318–332. https://doi.org/10.1080/21550085.2021.1961199.

334. Hildebrandt TB, Hermes R, Colleoni S, Diecke S, Holtze S, Renfree MB, et al. Embryos and embryonic stem cells from the white rhinoceros. *Nature Communications.* 2018;9(1): 2589. https://doi.org/10.1038/s41467-018-04959-2.

335. *Dire wolf.* Colossal. 2025. https://colossal.com/direwolf/ [Accessed 11th June 2025].

336. Kluger J. The return of the dire wolf. *TIME [Internet].* 2025 Apr 8. https://time.com/7274542/colossal-dire-wolf/ [Accessed 11th June 2025].

337. Le Page M. No, the dire wolf has not been brought back from extinction. *New Scientist.* 2025; https://www.newscientist.com/article/2475407-no-the-dire-wolf-has-not-been-brought-back-from-extinction/ [Accessed 11th June 2025].

338. Ilic D. Engineered proxies and the illusion of de-extinction. *Stem Cell Reports.* 2025;20(6). https://doi.org/10.1016/j.stemcr.2025.102505.

339. IUCN SSC. *IUCN SSC guiding principles on creating proxies of extinct species for conservation benefit.* 2016. https://portals.iucn.org/library/efiles/documents/Rep-2016-009.pdf [Accessed 9th July 2025].

340. *Moa.* Colossal. 2025. https://colossal.com/moa/ [Accessed 9th July 2025].

341. Science Media Centre. *Moa 'de-extinction' plans announced - Expert Reaction.* 2025. https://www.sciencemediacentre.co.nz/2025/07/09/moa-de-extinction-plans-announced-expert-reaction/ [Accessed 9th July 2025].

342. Klassen W, Curtis CF, Hendrichs J. History of the sterile insect technique. In: *Sterile insect technique: principles and practice in area-wide integrated pest management.* Second. Boca Raton, Florida, USA: CRC Press; 2021. p. 1–44.

343. Carvalho DO, McKemey AR, Garziera L, Lacroix R, Donnelly CA, Alphey L, et al. Suppression of a field population of Aedes aegypti in Brazil by sustained release of transgenic male mosquitoes. *PLOS Neglected Tropical Diseases.* 2015;9(7): e0003864. https://doi.org/10.1371/journal.pntd.0003864.

344. Shelton AM, Long SJ, Walker AS, Bolton M, Collins HL, Revuelta L, et al. First field release of a genetically engineered, self-limiting agricultural pest insect: Evaluating its potential for future crop protection. *Frontiers in Bioengineering and Biotechnology.* 2020;7. https://doi.org/10.3389/fbioe.2019.00482.

345. Elorriaga E, Klocko AL, Ma C, du Plessis M, An X, Myburg AA, et al. Genetic containment in vegetatively propagated forest trees: CRISPR disruption of LEAFY function in Eucalyptus gives sterile indeterminate inflorescences and normal juvenile development. *Plant Biotechnology Journal.* 2021;19(9): 1743–1755. https://doi.org/10.1111/pbi.13588.

346. Nagle MF, Nahata SS, Zahl B, Niño de Rivera A, Tacker XV, Elorriaga E, et al. Knockout of floral and meiosis genes using CRISPR/Cas9 produces male-sterility in Eucalyptus without impacts on vegetative growth. *Plant Direct.* 2023;7(7): e507. https://doi.org/10.1002/pld3.507.

347. Beach SJ, Maselko M. Recombinant venom proteins in insect seminal fluid reduce female lifespan. *Nature Communications.* 2025;16(1): 219. https://doi.org/10.1038/s41467-024-54863-1.

348. Naidoo K, Oliver SV. Gene drives: An alternative approach to malaria control? *Gene Therapy.* 2025;32(1): 25–37. https://doi.org/10.1038/s41434-024-00468-8.

349. Buchthal J, Evans SW, Lunshof J, Telford SR, Esvelt KM. Mice against ticks: An experimental community-guided effort to prevent tick-borne disease by altering the shared environment. *Philosophical Transactions of the Royal Society B: Biological Sciences.* 2019;374(1772): 20180105. https://doi.org/10.1098/rstb.2018.0105.

350. Dearden PK, Gemmell NJ, Mercier OR, Lester PJ, Scott MJ, Newcomb RD, et al. The potential for the use of gene drives for pest control in New Zealand: a perspective. *Journal of the Royal Society of New Zealand.* 2018;48(4): 225–244. https://doi.org/10.1080/03036758.2017.1385030.

351. Royal Society Te Apārangi. *Gene editing: Scenarios in pest control.* 2019. https://www.royalsociety.org.nz/assets/Uploads/Gene-Editing-Summary-Pest-Control-DIGITAL.pdf [Accessed 20th November 2024].

352. Brossard D, Belluck P, Gould F, Wirz CD. Promises and perils of gene drives: Navigating the communication of complex, post-normal science. *Proceedings of the National Academy of Sciences.*

2019;116(16): 7692–7697. https://doi.org/10.1073/pnas.1805874115.

353. MacDonald EA, Balanovic J, Edwards ED, Abrahamse W, Frame B, Greenaway A, et al. Public opinion towards gene drive as a pest control approach for biodiversity conservation and the association of underlying worldviews. *Environmental Communication.* 2020;14(7): 904–918. https://doi.org/10.1080/17524032.2019.1702568.

354. Noble C, Adlam B, Church GM, Esvelt KM, Nowak MA. Current CRISPR gene drive systems are likely to be highly invasive in wild populations. *eLife.* 2018;7: e33423. https://doi.org/10.7554/eLife.33423.

355. Annas GJ, Beisel CL, Clement K, Crisanti A, Francis S, Galardini M, et al. A code of ethics for gene drive research. *The CRISPR Journal*. 2021;4(1): 19–24. https://doi.org/10.1089/crispr.2020.0096.

356. Rode NO, Estoup A, Bourguet D, Courtier-Orgogozo V, Débarre F. Population management using gene drive: Molecular design, models of spread dynamics and assessment of ecological risks. *Conservation Genetics.* 2019;20(4): 671–690. https://doi.org/10.1007/s10592-019-01165-5.

357. Noble C, Min J, Olejarz J, Buchthal J, Chavez A, Smidler AL, et al. Daisy-chain gene drives for the alteration of local populations. *Proceedings of the National Academy of Sciences.* 2019;116(17): 8275–8282. https://doi.org/10.1073/pnas.1716358116.

358. Bier E. Gene drives gaining speed. *Nature Reviews Genetics.* 2022;23(1): 5–22. https://doi.org/10.1038/s41576-021-00386-0.

359. Wang JY, Doudna JA. CRISPR technology: A decade of genome editing is only the beginning. *Science.* 2023;379(6629): eadd8643. https://doi.org/10.1126/science.add8643.

360. Webber BL, Raghu S, Edwards OR. Is CRISPR-based gene drive a biocontrol silver bullet or global conservation threat? *Proceedings of the National Academy of Sciences*. 2015;112(34): 10565–10567. https://doi.org/10.1073/pnas.1514258112.

361. Cook F, Bull JJ, Gomulkiewicz R. Gene drive escape from resistance depends on mechanism and ecology. *Evolutionary Applications.* 2022;15(5): 721–734. https://doi.org/10.1111/eva.13358.

362. Esvelt KM, Smidler AL, Catteruccia F, Church GM. Concerning RNA-guided gene drives for the alteration of wild populations. *eLife.* 2014;3: e03401. https://doi.org/10.7554/eLife.03401.

363. Béllo Carvalho R. Between hype and hope: De-extinction is a tool, not a panacea for the biodiversity crisis. *Biological Conservation.* 2025;309: 111307. https://doi.org/10.1016/j.biocon.2025.111307.

364. Lean CH. Synthetic biology and the goals of conservation. *Ethics, Policy & Environment.* 2024;27(2): 250–270. https://doi.org/10.1080/21550085.2023.2298646.

365. Environmental Protection Agency Te Mana Rauhī Taiao. *HSNO application register APP204173. 2024*. https://www.epa.govt.nz/database-search/hsno-application-register/view/APP204173/ [Accessed 20th May 2026].

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