



Plant breeding – from cross breeding to genome editing

Climate change, emerging pests and scarce resources – sustainable production of sufficient food of high quality requires plant varieties to be continuously adapted to current and future production systems. Regardless of the crop, the basic principle of plant breeding always remains the same: it is based on genetic diversity, which either arose naturally or was created by humans using various methods. The resulting plants are then characterised in detail, evaluated in the field over many years, and ultimately registered in the catalogue of varieties after being officially approved. Over the past decades, the range of methods available for plant breeding has continually been extended. Mutation breeding can be used to increase genetic diversity, and genetic engineering makes it possible to introduce genes across the species barrier. Genome editing, the latest set of tools, can be used to make directed changes at a specific position in the genome of a crop species.

Plant breeding helps to secure and improve the yield and quality of plant products.¹ It aims to develop plants that combine resistance to diseases and pests with high quality and a stable yield. Nowadays, climate change and resource scarcity pose additional challenges.² That is why, for example, efforts are being made to develop plant varieties that can better tolerate periods of drought, heat or nutrient deficiency. Together with the global goods trade, climate change can also result in new plant diseases and pests spreading more quickly and becoming established in places where they had not previously been found. That is why resistance to pathogens and pests is also an important breeding goal to reduce the use of pesticides.

Efficient nutrient and water use have also become a major focus of plant breeding in order to reduce the need for mineral fertilisers.^{3,4} Finally, the needs of consumers and the market also have to be considered in plant breeding.

Regardless of the crop and the breeding goal, the principle of plant breeding is always the same: if a specific trait is to be changed, the corresponding genetic diversity is first identified or created. Plants with the desired characteristics are then selected and further optimised with the aim of them being approved as new varieties after passing an independent variety test.⁵

Genetic material

Wild plant ●

Crop ●

Other organism ●

Change

Desired ●

Not desired ●

1 Generation of genetic variation

Genetic diversity is the foundation of all breeding. Since the beginning of agriculture, humans have selected plants with desired traits from the existing diversity and propagated them in a targeted manner. In modern plant breeding, genetic diversity is increased as the first step of the breeding process. Existing gene variants are recombined e.g. through crossing with other plants from the same or similar species. Mutations also help to increase genetic diversity. They arise spontaneously or are induced by environmental influences (sun, stress). However, they can also be intentionally introduced in large numbers. Mutations often do not have any benefits, but new and valuable characteristics are occasionally created. Classical genetic engineering can be used to combine desired characteristics both within a species (cisgenic) and across species barriers (transgenic). Finally, the recently developed genome editing tools can be used in different ways to change the genetic material in a specific manner.

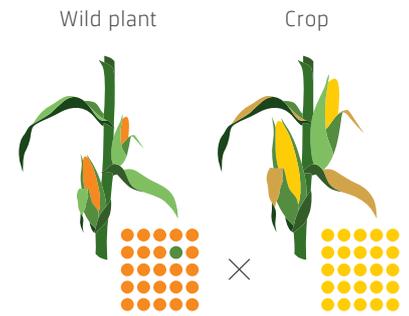
2 Selection and optimisation

During the breeding process, plants with a desired trait (e.g. resistance to disease) are progressively selected. The progeny is evaluated under controlled conditions or in the field (phenotyping) and selected for the next breeding cycle. Individual or even thousands of genetic markers are used to determine which individuals carry the desired genetic information. This is referred to as marker-assisted or genomic selection. Depending on the method, the progeny must be optimised through additional crossings, whereby desired traits are fixed and undesired ones are eliminated. If the new trait is adequately combined in the progeny with other positive features, a potential new variety is developed.

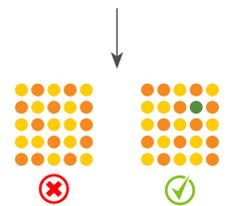
3 Testing and approval of varieties

After a long selection process with several years of field testing, the best performing varieties are tested by an independent testing facility on behalf of the Federal Office for Agriculture (FOAG). In order to be approved and registered in the National Catalogue of Varieties by the FOAG, the variety candidate must differ from other varieties and be homogenous and genetically stable. In addition, new arable crop varieties are also tested in terms of their suitability for cultivation and use.⁹ Nowadays, only varieties created through cross breeding or mutation breeding are approved for cultivation in Switzerland. There has been a moratorium on growing genetically modified plants since 2005. In Switzerland and the European Union, varieties created by genome editing are currently considered to be genetically modified plants and are therefore subject to the same regulatory oversight. In Switzerland, it is currently under discussion as to whether these regulations should be adapted for certain applications of genome editing.

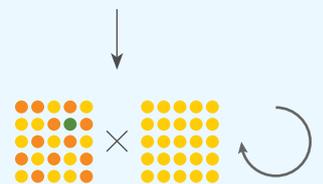
Cross breeding



A desired trait (e.g. resistance to disease) from crops or wild progenitors, or a related species, is crossbred into an existing variety.



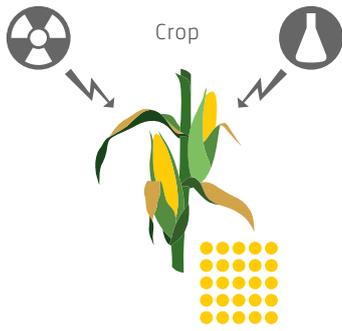
The genetic materials of the parental plants mix and create random, new combinations of desired and undesired characteristics in the progeny.



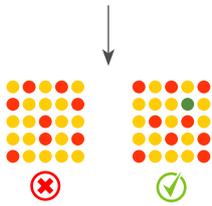
The selected progeny is then further optimised through multiple backcrossings with the original variety.



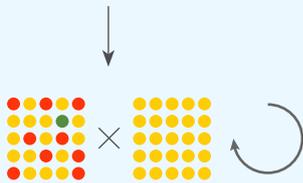
Mutation breeding



Radiation or treatment with chemicals are used to induce random mutations in the genetic material of a crop.



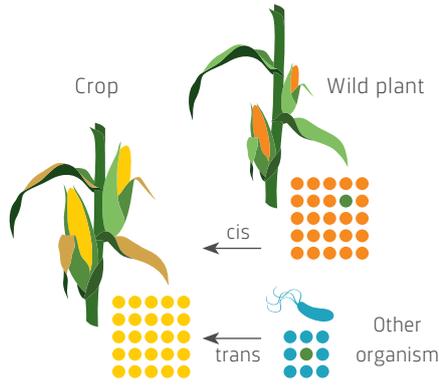
Alongside the randomly created and desired mutations, countless other undesired changes are also introduced in the genome.



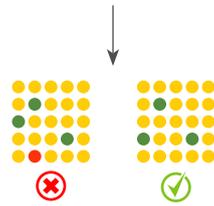
These undesired mutations are then removed from the selected progeny through multiple backcrossings and the progeny is further optimised.



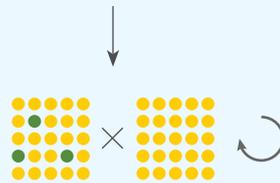
Classical genetic engineering



One or more genes from a plant of the same species (cisgenic) or a different species (transgenic) are introduced into an existing variety using genetic engineering methods.



The new genes are integrated once or several times at a random position in the genome, which can sometimes result in undesired changes.



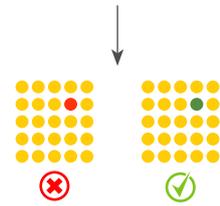
The selected progeny is then optimised through additional crossings.



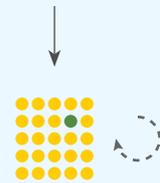
Genome editing



The genetic material of a variety is modified using genome editing tools. Selected genes can be randomly mutated, specifically changed or inserted as a whole.



The desired changes take place at a specific, previously determined location in the genome. This results only in rare cases in additional undesired changes.



The selected progeny must only be optimised through additional crossings in certain cases.



Genome editing – a new tool in plant breeding

Genome editing uses gene scissors such as TALEN, zinc finger nucleases or CRISPR/Cas. For CRISPR/Cas, they are based on bacterial proteins that have been around for millions of years. Gene scissors can be used for different modifications of the genetic material. With the simplest form of genome editing, incorrect repair of the DNA double strand break caused by the gene scissors results in random mutations, which can result in the inactivation of the gene. Another form of genome editing uses a template to specifically change parts of a gene, which can potentially repair a defective gene. Finally, complete genes can be inserted from the same species (cisgenic) or a different species (transgenic) at a specific position in the genome. Genome editing tools are continually being developed further to make the changes more efficient and precise.

Genome editing differs from other methods in terms of its specificity. Individually selected genes or gene segments can be changed without impacting the remaining genome significantly. In contrast, mutation breeding causes many changes at random positions in the genome. Genome editing is also more targeted than classical genetic engineering, as with the latter genes are inserted into the genome at random positions.

The specificity of genome editing makes it possible to introduce individual traits (e.g. resistance to disease) into a variety in a targeted manner without changing the remaining desired characteristics. This can significantly speed up the development of new varieties but is only possible if the genetic mechanism and the underlying genes of the desired trait are known. This requires extensive basic research, particularly for complex traits that are encoded by multiple interacting genes.

Sustainable agricultural production systems take advantage of the highest possible genetic diversity among varieties used for breeding and cultivation, particularly in terms of protection against diseases and pests. Genome editing has the potential to make the gene pool of wild ancestors more accessible,⁷ for example by efficient reintroduction of genes and traits that were lost during domestication.⁸ Yet it is also important to continually extend genetic diversity through crossings and new combinations of whole genomes. A wide

diversity of wild plants and crops must therefore be conserved as an important resource that can also be used for future breedings.

Unintentional genome modifications can occur with all breeding methods. With cross breeding, many undesired gene variants are present that come from the parental plants. With mutation breeding, thousands of mutations arise that could influence other plant traits. Similarly, the random positioning of new genes using classical genetic engineering can have unintended effects. Unintended changes can also occur with genome editing, but these are much less common than with mutation breeding and classical genetic engineering. Although the gene scissors cut at very specific locations in the genome they may, in rare cases, also be active in other regions. However, most of these unintended changes are eliminated through additional crossings or during selection.

Traceability is a challenge with genome-edited plants. Simple forms of genome editing induce mutations that could also arise naturally or are created through mutation breeding. As it is not possible with such mutations to draw conclusions about the method that introduced them, there are open questions about regulation based on the methods used.⁹

Genome editing has quickly become established in research and breeding around the world.⁴ By 2018, around 100 applications of genome editing with potential market relevance had been characterised in 28 different crop varieties.¹⁰ Genome editing is also extensively used in basic research in Switzerland. However, there are currently no known breeding projects to develop genome-edited varieties for Switzerland. Furthermore, only varieties that were created by cross breeding or mutation breeding are currently approved for cultivation in Switzerland. The question of whether, and under which legislation, plants developed by genome editing should have a place in Switzerland in the future is a current matter of political and social debate. In any case, it is critical that Switzerland continues to play a leading role in research with and on genome editing, in order to shape the discussion around this technology and assume its international responsibility.

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PUBLISHER AND CONTACT

Swiss Academy of Sciences (SCNAT) • Forum for Genetic Research
House of Academies • Laupenstrasse 7 • P.O. Box • 3001 Bern • Switzerland
+41 31 306 93 34 • geneticresearch@scnat.ch • geneticresearch.scnat.ch

EDITORS

Luzia Guyer • Sandro Käser • Franziska Oeschger

AUTHORS

Ueli Grossniklaus (University of Zurich) • Monika Messmer (Research Institute of Organic Agriculture FiBL) • Roland Peter (Agroscope) • Jörg Romeis (Agroscope) • Bruno Studer (ETH Zurich)

REVIEWERS

Roland Kölliker (SSA, ETH Zurich) • Adrian Rügsegger (TA-SWISS) • Olivier Sanvido (SECO) • Roman Ulm (University of Geneva) • Michael Winzeler (formerly Agroscope)

TRANSLATION AND CORRECTIONS

CVB International (Valérie Cardona) • Bruno Studer • Jörg Romeis • Roland Kölliker

ILLUSTRATIONS AND LAYOUT

Natascha Jankovski

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