WPC SPECIAL: ADVANCEMENTS IN POTATO BREEDING

Transforming potato genetics from challenging tetraploid tubers to manipulable and predictable diploids

Gregor Mendel, 19th Century Austrian-Czech polymath, might have spent most of his life as a monk in a monastery, but he was still well ahead of his time. The significance of his painstaking experiments with pea plants were not appreciated until more than 30 years after their publication. However, it was these pioneering experiments that established the fundamental laws of genetics. They also proved what farmers had known for millennia, namely that crossbreeding could be used to improve desirable traits.

While Mendel knew nothing of DNA, the discovery of its role and structure confirmed his conclusions. It also revolutionised biology, revealing how genetic information is stored and transmitted.

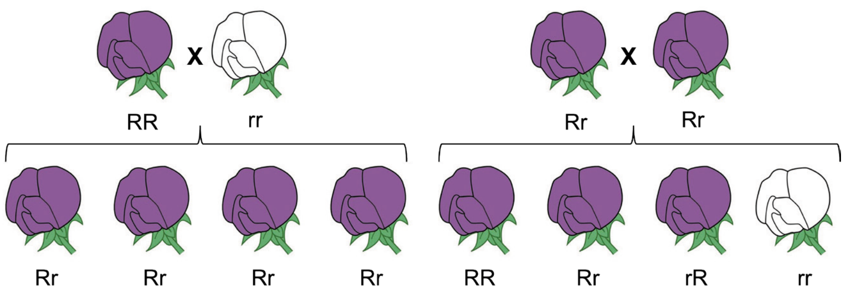
These breakthroughs paved the way for the development of DNA sequencing technologies in the 1970s. For the first time, this allowed us to directly map the entire genetic code of an organism. Modern plant breeding has since harnessed these advances, identifying and incorporating beneficial genes with unprecedented precision. Just as artificial intelligence has transformed computing power, gene sequencing has massively accelerated the development of improved crop varieties.

The potato was genetically unravelled in 2011. Since then, research groups from around the world have been studying the incredible 39,000 genes that it contains. For comparison, humans contain a mere 19,900 genes. In other words, the potato is surprisingly genetically complicated.

KEY SCIENTIFIC TERMS USED IN THIS ARTICLE

- **Tetraploid:** An organism with four sets of chromosomes, which can lead to complex genetic recombination.
- **Diploid:** An organism with two sets of chromosomes, often used in hybrid breeding for its simpler genetic structure.
- **Diplodisation:** The process of converting a polyploid (for example a tetraploid potato) to a diploid
- **Genome sequencing:** The process of determining the exact order of nucleotides within a DNA molecule.
- **Hybrid vigour (heterosis):** The improved performance of hybrid offspring compared to their parents, often due to the combination of beneficial genes.
- **Inbreeding depression:** Reduced biological fitness in a population due to inbreeding, which can lead to weaker offspring.
- **True seed:** Seeds produced through sexual reproduction, offering a disease-free starting material for propagation.
- **F1 Hybrid:** The first generation of offspring produced by crossing two genetically distinct inbred lines, often exhibiting enhanced traits

RECESSIVE AND DOMINANT GENES



Gregor Mendel's famous pea experiments revealed the nature of dominant (R) and recessive (r) genes as well as the concepts of genotype (the genes of an organism) and phenotype (how the organism actually looks).

In this example, the pea plant is a diploid. This means there are two genes determining flower colour: purple, which is dominant, and white which is recessive. If white flowers are desirable, then two white-flowered parents are required. The blue (r) and brown (R) eye colours of humans is an often-used example of this phenomenon.

Because traditional tetraploid potatoes have four variations of each gene, it becomes much more complicated to predict the appearance and qualities of offspring - see Figure 1.

While this complexity is one of the reasons for its productivity and adaptability, it also makes breeding better varieties all the more challenging.

CHALLENGES IN POTATO BREEDING

You, me, and Mendel's pea plants are all heterozygous; we carry both dominant (visible) and recessive (hidden) copies of each gene. This is what makes us all different.

In contrast, modern crop production, whether lettuce, wheat, tomato or soybean, commonly uses F1 hybrids. F1 hybrids are produced by crossing two guaranteed pure breeding lines. These pure lines are generated by repeated inbreeding, producing individuals that are genetically stable with uniform genetics – 'homozygous'.

While we still do not fully understand why F1 hybrids perform so well, they reliably outperform both their parents. Hybridisation appears to overcome any harmful genes or 'bad traits', promoting the beneficial ones. Just like Mendel's hybrid pea plants, F1 plants are virtually genetically identical, resulting in a uniform crop with consistent quality and yield.

However, it is not always easy to produce a pure breeding line. It is particularly difficult when plants are not self-compatible.

In the case of potatoes, add self-incompatibility to an unusually complex genome, and you have a major challenge.

Most plants and animals have two sets of chromosomes; 'diploid.' These carry dominant and/or recessive traits, combining to make the plant, animal or person that we see.

The ancestors of modern potatoes were diploid, just like other plants. However most of our current commercial potato varieties have four sets of chromosomes; 'tetraploid.' This may be one of the reasons potatoes are the world's most productive food crop. However, it also makes breeding an attribute lucky-dip.

If considering a trait such as blight resistance, there is only one possible outcome in an F1 hybrid, three to four possible outcomes from two non-uniform diploid parents, but 16 potential outcomes from each cross of tetraploid parents.

Add the multi-generational lead time between producing a seed and growing a potato crop, and it is no wonder that it can take up to 50 years to develop a new potato variety.

It seems somewhat ironic that the new buzz on the block is transforming our modern, clonally propagated tetraploid potatoes back into old school diploids. However, the ability to do this is taking potato breeding by storm, transforming our ability to manipulate the potato genome and massively reducing the lead time in breeding new potato varieties.

However, this is not easy. Most diploids are self-incompatible. If they *can* be self-pollinated, there are often serious mutations that limit the number of generations that the line can be selfed. This makes it difficult to develop the genetically stable, homozygous, lines that are needed, especially as male sterility can be almost 100%.

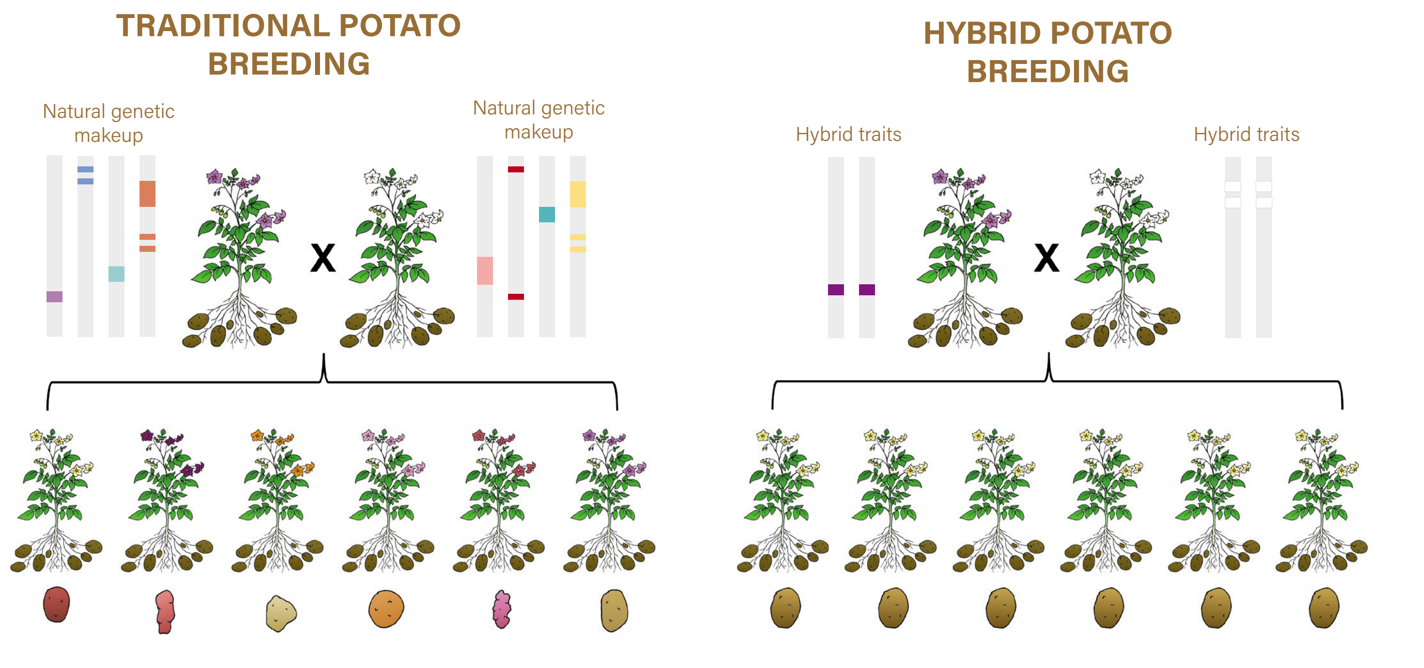


Figure 1. Complexity of crossing tetraploids that produce offspring with very variable and unpredictable traits versus the simplicity of potato breeding with hybrids that produce offspring with predicable traits (adapted from Solynta, WPC presentation)

ADVANCEMENTS PRESENTED AT THE WPC

Creating hybrids

Dr Chunzhi Zhang, a leading potato geneticist at the Agricultural Genomics Institute in Shenzhen, China, is at the forefront of efforts to transform potato breeding. Her presentation at the congress highlighted the progress her team has made in producing vigorous F1 hybrid potato lines.

Developing the highly homozygous (genetically uniform) inbred lines necessary for breeding hybrid potatoes has been difficult due to both harmful mutations and issues of self-incompatibility. In a paper published in 2021[1], Zhang and her team described how they used genome editing to create a generation of pure and fertile potato lines. These could then be crossed, resulting in uniform and vigorous F1 hybrids.

With many advanced molecular techniques are their disposal they could measure several factors, including the percentage of genome homozygosity and the number of harmful mutations in the starting material. They could then separate beneficial and harmful genes.

This approach transforms potato breeding from a slow, random and non-accumulative process into a fast and increasingly targeted one.

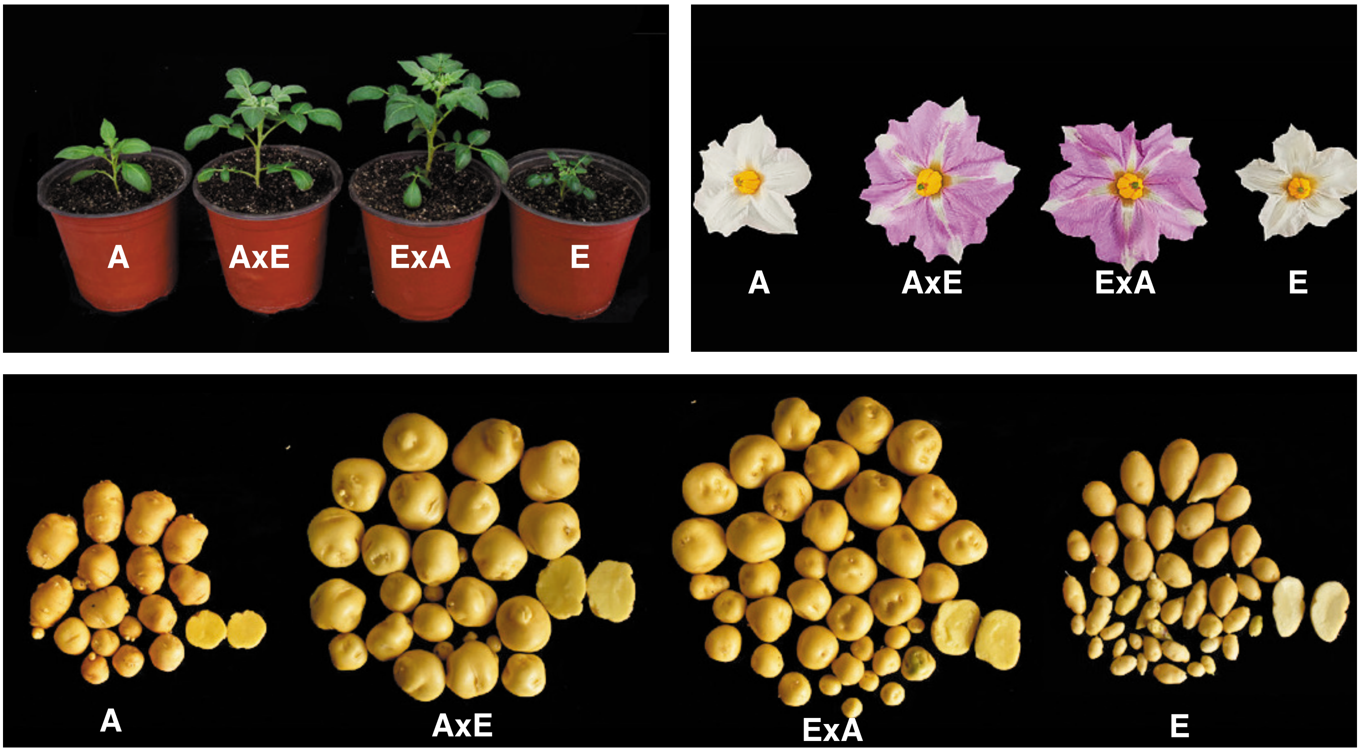


Figure 2. The two highly homozygous (genetically uniform lines) A and E were crossed to produce the F1 hybrids AxE and ExA. The F1 hybrid plants were more vigorous than either of their parents (top left) and produced more and larger tubers (bottom). The F1 flowers were larger and purple (top right), whereas the parental lines were both white. This shows that the parental lines interacted in the hybrids, producing a new flower colour. Images from Li et al., 2021[2]

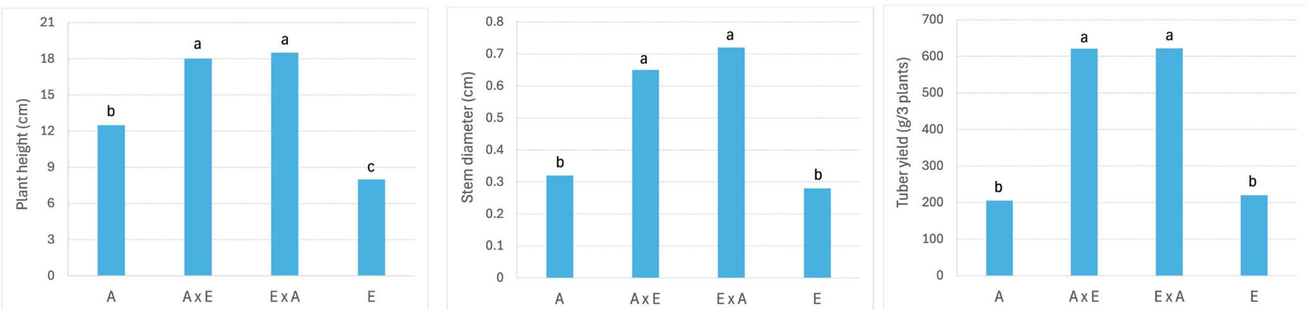


Figure 3. Hybrid plants (AxE and ExA) were significantly taller(left) and had stems more than twice as thick (centre) as either of their parents (A and E). Total yield was approximately tripled compared to the parental lines (right). Derived from Li et al., 2021[2]

Potatoes with hybrid vigour

Zhang's group are investigating the molecular characteristics of their new varieties using a combination of advanced analysis techniques. These are providing insights into the 'hybrid vigour' created by crossing different potato varieties. This research is crucial for developing new varieties that are both high-yielding and resilient to environmental stresses.

For example, a study from her group in 2022 combined data from multiple analyses to examine the genetic and molecular factors behind hybrid vigour of potatoes at three developmental stages.

They found that the initial boost in growth was mainly due to 'dominant complementation'. This occurs when genes from each parent complement each other and, presumably, reduce any negative traits. Traits like flower colour, male fertility, and starch and sucrose metabolism all benefited from gene complementation. This meant that hybrids used more energy for primary metabolism, promoting faster growth.

The group found about 2,700 genes that are active in different ways at each growth stage. These genes likely help make the hybrids stronger, with specific changes in DNA (Figure 2, 3)[2].

Building a library

Of more than 100 tuber-bearing Solanum species, a mere seven are currently cultivated. This points to a huge, virtually untapped, gene pool.

Professor Dave Douches, from Michigan State University (MSU), has already released more than 30 new potato varieties in over 36 years of breeding potatoes.

During the last 10 years his team has focused on reinventing the potato as a diploid, inbred line-based crop. Such lines are propagated from true potato seed using some of the novel genes in different potato species.

Their primary aim is to breed hybrid potatoes with improved resistance to disease and insect attack. Targets include common scab, Potato Virus Y (PVY), late blight, and the Colorado potato beetle. By developing potatoes with natural resistance, breeders aim to reduce the reliance on chemical treatments, reducing costs and improving crop health.

In addition to disease resistance, storability and processing quality, particularly for chip production, are critical traits. Stabilising the potato starch:sugar profile is essential for maintaining potato quality during low temperature storage. Developing varieties which can be stored for eight months or more at low temperatures, without accumulating sugars, is a key breeding target, as is resistance to blackspot bruising.

Figure 4. True F1 hybrid potato plants, produced by crossing *S. verrucosum* with *S. tuberosum*. Image: Presentation by Professor Douches.

To support these breeding goals, the MSU research team has been collecting and maintaining a wide range of genetic material. This germplasm base acts like a library, providing a broad pool of genes from which they can select desirable traits. These include resistance to viruses and diseases, but also suitability for processing and high specific gravity.

Diploidisation is a critical part of the process. This reduces the number of damaging copies of genes as well as increasing genetic uniformity. Filtering out less desirable genetic material ensures that only the best traits are passed on.

Ongoing research activities include overcoming self-incompatibility among potato varieties. This is vital for successful breeding and consistent crop production. According to Professor Douches: "*The incredible gains in tomato breeding in the last century are only possible because of its reliable self-compatibility and broad intraspecific compatibility*".

Since 1940, improved breeding of new tomato varieties has increased yield by four to five times, as well as incorporated resistance to at least 42 major diseases.

To overcome self-incompatibility in potato, the MSU team has conducted backcross breeding of *S. tuberosum* dihaploids with Solanum species that are self-compatible, such as *S. verrucosum* and *S. chacoense*. With repeated backcrossing, this has produced diploid plants that improve in self-compatibility with each selection cycle.

Using these techniques, the team has established a collection of approximately 1,000 (homozygous) pure breeding lines. These are crossed to produce diploid hybrids, which can be assessed in field trials to measure performance under real-world conditions. Some of the advanced diploid selections have exceeded the yield of current commercial varieties – a very promising result!

Pest resistant potatoes

One such example is the use of *S. chacoense* hybrids when screening for resistance to Colorado potato beetle. A breeding line susceptible to beetles but self-compatible was repeatedly crossed with a line resistant to beetles which was self-incompatible. After five generations, the team were able to isolate a variety which was both self-compatible AND beetle resistant.

This was then crossed with a diploid selection which had desirable tuber traits to achieve a commercially viable variety (Figure 5).

Less thirsty potatoes

Another example is selection for drought tolerance genes from wild potato species. Wild potatoes possess unique genetic traits that allow them to survive in harsh, relatively arid conditions. Incorporating drought tolerance genes into cultivated potato varieties can help develop crops less impacted by low water availability. This could potentially improve the resilience of potatoes to climate variability as well as yield and stability in drought-prone regions.

Unfortunately, an effect found with drought tolerance in other crop plants is that these varieties may yield less than water-hungry varieties when conditions are good. Growers therefore have to take a gamble; plant the drought tolerant variety with lower yield, or hope that it rains. However, field trials with drought tolerant potato lines at MSU from 2019 to 2023 did not find any yield penalty. Rather, both total yield and specific gravity were actually increased in these lines relative to commercial variety Ranger Russet.

Potatoes that can take the cold

The team at MSU recently achieved a significant milestone in potato breeding with the development of the Kal91.3 potato variety. This breakthrough, which has been in the making for about a decade, is on the fast track to commercialisation, thanks to extensive research and testing.

The Kal91.3, bred from the MSU Kalkaska variety, does not contain active vacuolar invertase – the enzyme that converts starch to sugars. This means it can be stored at cool temperatures for extended periods without accumulating reducing sugars like fructose and glucose. This stability prevents browning when potato crisps are cooked (Figure 6).

From 2016 to 2023, Douches and his team tested the Kal91.3's agronomic characteristics, confirming its good shape, size, and specific gravity. Traditional chipping potatoes are stored at around 10°C, increasing moisture loss and leaving them vulnerable to storage rots. In contrast, Kal91.3 can be stored at 4°C, allowing longer storage as well as better quality.

The Kal91.3 variety is now approved for commercial production by the USDA/APHIS.

Figure 5. A potato plant resistant to Colorado potato beetle. Image: presentation by Professor Douches.

CONCLUSION

As the challenges of environmental sustainability in a changing climate and food security converge, plant breeding has become a crucial field in the search for solutions. The need to develop crops that can withstand extreme weather conditions, resist pests and diseases, and produce higher yields on less arable land has never been more urgent. Modern plant breeding, using advanced genetic tools and techniques, offers promising pathways to meet these demands.

Look out for future editions of PotatoLink magazine as we explore the potential of True Potato Seed

Figure 6. The newly developed Kal91.3 potato can be stored in cool temperatures (4°C) for 6 months without accumulating reducing sugars (left). In contrast, the parental line Kalkaska (right) is chilling sensitive, browning following storage and chipping. Images: presentation by Professor D. Douches.

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2. Li D, Lu X, Zhu Y, Pan J, Zhou S, Zhang X, Zhu G, Shang Y, Huang S, Zhang C. The multi-omics basis of potato heterosis. J Integr Plant Biol. 2022 Mar;64(3):671-687. doi: 10.1111/jipb.13211. Epub 2022 Feb 28. PMID: 34963038.

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