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How seed breeding could reduce farm inputs in the future

Written by:

Lizzie Carr-Archer NSch

July 2025

A NUFFIELD FARMING SCHOLARSHIPS REPORT

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Date of report: July 2025

"Leading positive change in agriculture. Inspiring passion and potential in people."

Title	How seed breeding could reduce farm inputs in the future
Scholar	Lizzie Carr-Archer
Sponsor	Generously supported jointly by The Worshipful Company of Farmers with Savills, and the Central Region Farmers Trust
Objectives of Study Tour	1. Understand the latest plant breeding technical advancements and industry trends. 2. Identify which impacts could be seen on UK (and EU) farmers and ecology. 3. Illustrate examples where plant breeding has been used for good social and environmental benefit.
Countries Visited	Australia, Mexico, Denmark, United Kingdom
Messages	1. Seed breeding is on the edge of the next green revolution. 2. We need to ensure the optimal regulatory and public relations environment exists to ensure the best is made of these advances. 3. British farmers can benefit from these improvements.

EXECUTIVE SUMMARY

Innovations in seed breeding, gene editing and genetically modified organisms (GMOs) continue to have the potential to significantly reduce farm inputs in the future by introducing crops that are more sustainable and economically attractive. Lower levels of chemical use have the potential to lead to environmental benefits and higher profits for farming businesses.

1. **Drought Resistance**: Breeding drought-tolerant crops can reduce the need for irrigation. These crops are better able to survive and thrive in dry conditions, minimising water usage and the associated energy costs of irrigation.
2. **Pest and Disease Resistance**: By breeding crops that are more resistant to pests and diseases, the need for chemical pesticides and herbicides can be reduced or eliminated. This can lower input costs and reduce the environmental impact of chemical use, leading to healthier ecosystems and soils.
3. **Nutrient Efficiency**: Crops can be bred to better utilize soil nutrients, reducing the need for synthetic fertilisers. For example, plants with improved nitrogen uptake can thrive in lower-nutrient soils, reducing the farmer's dependence on nitrogen-based fertilisers, which are both expensive and environmentally taxing.
4. **Higher Yields**: By improving the genetics of crops, seed breeding can result in varieties that produce higher yields with fewer inputs. Higher yields per unit of land or per plant allow farmers to produce more food with less labour, water, and fertiliser.
5. **Climate Adaptation**: Breeding crops that are better suited to specific regional climates can reduce the need for costly inputs such as fertilisers and irrigation. Crops adapted to local conditions are generally more robust and efficient.
6. **Improved Soil Health**: Crops bred to have deeper root systems can improve soil structure and increase organic matter, which in turn can reduce the need for synthetic fertilisers. Plants with deeper roots can access nutrients and water more effectively, reducing the reliance on external inputs.
7. **Reduced Tillage**: Some crop varieties can be bred to tolerate reduced tillage systems. Reduced tillage improves soil health, conserves moisture, and minimises the need for fuel-intensive machinery. These crops can grow effectively without the need for intensive soil disturbance.
8. **Increased Tolerance to Stress**: Breeding crops with enhanced tolerance to environmental stresses (like heat, flooding, or salinity) can reduce the need for irrigation, fertilisers, and pesticides. Stress-tolerant crops are more likely to perform well under adverse conditions, thus saving resources.

Overall, seed breeding can support more sustainable and cost-effective farming by enhancing crop performance while reducing the need for chemical inputs, water, and labour. This leads to both environmental benefits and economic savings for farmers.

TABLE OF CONTENTS

DISCLAIMER

The opinions expressed in this report are those of the author alone and not necessarily those of the Nuffield Farming Scholarships Trust, of the author's sponsor, or of any other sponsoring body.

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CHAPTER 1: INTRODUCTION

Figure 1: The author, Lizzie Carr-Archer.

Most of my life has been deeply rooted in the picturesque county of Oxfordshire, renowned for its rich agricultural heritage and stunning rural landscapes. My connection to farming, however, extends beyond mere geographical ties. I am the proud daughter of a farmer from the Berkshire Downs, an area now known as the Vale of the White Horse. This ancestral link to the land has imbued me with a profound understanding and respect for agriculture from my earliest years, quite literally making farming a part of my DNA.

My upbringing on a farm was more than just a childhood experience; it was an education in itself. I grew up witnessing the rhythms of the seasons, understanding the challenges and rewards of working with the land, and developing a deep appreciation for the vital role farmers play in our society. These formative years laid the foundation for my future career path and my passion for agricultural innovation.

Driven by my love for the environment and my agricultural background, I pursued a degree in Environmental Science at the prestigious University of York. This choice of study was a natural progression from my upbringing, allowing me to explore the scientific aspects of the natural world I had grown up in. It was during my time at York that I met my now-husband.

Upon graduating in 2012, I embarked on my professional career with British Sugar as an Area Manager based in Ely, Cambridgeshire. This role provided me with invaluable insights into the commercial aspects of agriculture and the sugar industry, broadening my understanding of the sector beyond my family farm.

By 2015, the pull of home and family led us back to Oxfordshire. This move wasn't just about proximity to loved ones; it also allowed me to reconnect with my passion for equestrianism. Horses have always been a significant part of my life, offering a balance to the demands of my professional career and a link to my rural roots.

My career took a significant turn when I joined Monsanto, which was subsequently acquired by Bayer. During my tenure I worked in various Sales and Marketing roles, with a particular focus on Oil Seed Rape (OSR) and other key agricultural sectors. This experience was instrumental in deepening my understanding of the seed and agrochemical industry, exposing me to cutting-edge agricultural technologies and global market dynamics.

Currently, I hold a Product Marketing role at Syngenta UK, where I continue to contribute to the advancement of agricultural solutions. This position allows me to leverage my academic background in Environmental Science, my practical knowledge of farming, and my commercial experience to drive innovation in the sector.

On a personal note, February 2022 marked a new chapter in my life with the birth of our first child, a son named Charlie. It's been heartwarming to see him develop a love for tractors at such a young age, echoing my own childhood fascination with farm machinery. As I write this, I'm on the cusp of another life-changing event, being just nine weeks away from welcoming our second child, a baby girl, into our family.

This impending arrival adds another dimension to my perspective on agriculture and sustainability. As a mother, I'm more aware than ever of the importance of producing healthy, sustainable food for future generations. It reinforces my commitment to driving positive change in the agricultural sector, balancing productivity with environmental stewardship.

Figure 2: Oil seed rape crops in the UK are where my love for plant breeding started, stood here with Matthew Clarke, Dekalb breeder. Photo: author's own.

My journey as a farmer's daughter to a professional in agricultural product marketing, all while maintaining my connections to the land through my family and personal interests, has given me a unique, multifaceted perspective on the challenges and opportunities facing modern agriculture. It's this blend of personal history, academic knowledge, professional experience, and now, maternal insight, that fuels my passion for contributing to the evolution of farming practices and technologies in the UK and beyond.

CHAPTER 2: BACKGROUND TO MY STUDY SUBJECT

Agriculture accounts for a significant 63.1% of land use in England, highlighting the sector's importance in the country's landscape and economy. The total croppable area of the UK in 2023 stood at an impressive 6.1 million hectares, which represents roughly one-third of the Utilised Agricultural Area (UAA). To put this into perspective, this area is equivalent to 90% of Ireland's entire land mass and three times that of Wales, underscoring the scale of agricultural operations in the UK.

The UK consistently ranks among the top four producing countries in Europe for most categories of agricultural products. This achievement demonstrates the strength, resilience, and efficiency of the UK farming sector, which has adapted to various challenges over the years, including climate change, market fluctuations, and evolving consumer demands.

As a professional with extensive experience in the UK's agricultural sector, working for some of the largest seed breeding and agro-chemical companies, I have always been keenly interested in farming effectiveness and efficiency. My career has provided me with unique insights into the industry's dynamics, particularly the intriguing disparity between the UK's heavy reliance on agrochemicals compared to its investment in advanced seed technologies.

This imbalance became particularly evident during my time in the oilseed rape (OSR) seed industry, when OSR was a substantial crop in the UK agricultural landscape. Our team was at the forefront of pioneering and breeding top-class hybrid varieties that offered numerous advantages. These hybrids were designed to require fewer fungicides, less nitrogen, and reduced use of pod-stick products. Moreover, they demonstrated superior resilience to the UK's increasingly unpredictable climate and had the potential to produce higher yields with fewer inputs.

However, despite these clear benefits, we faced significant challenges in convincing farmers to invest in these hybrid varieties. The primary obstacle was the higher upfront cost, which often overshadowed the long-term benefits and potential savings in input costs. This experience highlighted a crucial aspect of the UK agricultural sector: the tension between short-term financial considerations and long-term sustainability and efficiency.

Drawing on my personal experience and observations in the UK's agricultural sector, I have identified three key areas that present opportunities for growth and re-imagination:

1. Industry Mindset Shift: There is a pressing need to challenge and ultimately break the overreliance on chemical inputs for short-term success. This dependency raises an important question: Are we perpetuating an industry heavily focused on chemistry simply because it's the path our forebears took? This shift requires not only technological advancements, but also a fundamental change in how we perceive agricultural productivity and sustainability.
2. On-Farm Expertise Enhancement: There is significant room for improvement in the overall level of on-farm expertise, particularly concerning the most effective use of plant breeding advancements and seed traits. This includes understanding the long-term benefits of investing in higher-quality seeds and how to optimise their performance in various conditions.
3. Supportive Environment Creation: The UK agricultural sector would greatly benefit from the creation of a stable, innovative, and positive public relations, regulatory, and policy environment. Such an environment should encourage trait-based research and productivity enhancements. This involves not only governmental support but also public understanding and acceptance of agricultural innovations.

In this evolving context, it is crucial for British farmers to understand and embrace the potential being introduced by new plant breeding techniques, particularly CRISPR-Cas9 (gene editing). This revolutionary technology offers unprecedented precision in crop improvement, potentially addressing challenges such as climate resilience, pest resistance, and nutritional enhancement.

Figure 3: Lizzie Carr-Archer with a host farmer, Denmark. Photo: author's own.

The adoption of these new breeding techniques could be a game-changer for UK agriculture, potentially reducing the reliance on chemical inputs while improving crop yields and quality. However, this transition requires not only technological advancements, but also a shift in farmer mindset, regulatory frameworks, and public perception.

CHAPTER 3: STUDY TOUR DETAILS

I visited the following countries during my Study Tour:

- Australia - CSIRO
- Mexico – CIMMYT
- Denmark – DAKOFO, Copenhagen
- United Kingdom – John Innes Centre, Rothamsted, BSPB

Mexico - CIMMYT

Figure 4: Lizzie Carr-Archer with a statue of Norman Borlaug, outside CIMMYT headquarters at El Batán, Texcoco, Mexico. Photo: author's own.

CIMMYT, the International Maize and Wheat Improvement Centre, is a global leader in agricultural research and development. Based in Mexico, this non-profit organisation is dedicated to enhancing food security and alleviating poverty worldwide through innovative maize and wheat production techniques. At the core of CIMMYT's mission is the genetic improvement of maize and wheat. The Centre employs both traditional breeding methods and cutting-edge biotechnology to develop crop varieties that are more resilient, productive, and adaptable to diverse environmental conditions. This work is particularly crucial in regions where maize and wheat are dietary staples, such as Sub-Saharan Africa, South Asia, and Latin America. Sustainability is a key focus for CIMMYT. The organisation strives to create crop varieties that are not only high-yielding but also require fewer inputs like water and pesticides. This approach is especially vital in the face of climate change, as CIMMYT works to develop crops that can withstand increasingly unpredictable weather patterns.

CIMMYT's impact extends beyond crop development. The Centre provides valuable training and resources to farmers, scientists, and policymakers, enhancing their knowledge and skills in crop production and research. Additionally, CIMMYT plays a crucial role in preserving maize and wheat genetic

diversity, maintaining vast seed banks that safeguard valuable traits for future breeding efforts.
Collaboration is central to CIMMYT's approach. The Centre partners with a wide range of organisations, including the FAO, CGIAR, and numerous national and regional agricultural research institutions. These partnerships enable CIMMYT to extend its reach and impact globally.

The improved maize and wheat varieties developed by CIMMYT have significantly boosted global food production, particularly in regions where these crops are essential staples. By focusing on food security, sustainability, and poverty reduction, CIMMYT continues to play a vital role in addressing some of the world's most pressing agricultural challenges.

CIMMYT's research has led to the development of improved maize and wheat varieties that have had a significant impact on global food production, particularly in regions where these crops are essential staples. Their work is aligned with the goals of food security, sustainability, and poverty reduction.

Australia – CSIRO and farmers.

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) is Australia's premier scientific research institution, playing a pivotal role in plant breeding and agricultural advancement. CSIRO's plant breeding programme is comprehensive, encompassing a wide range of crops crucial to Australian agriculture and global food security.

At the forefront of CSIRO's efforts are grains such as wheat, barley, and oats, as well as pulses like lentils and chickpeas. The organisation's breeding initiatives aim to develop crop varieties that excel in productivity, resilience, and adaptability to Australia's unique and often challenging environmental conditions.

CSIRO's approach to crop improvement is multifaceted, focusing on enhancing traits such as disease resistance, drought tolerance, and nutritional content. This holistic strategy ensures that new varieties not only yield more but also withstand biotic and abiotic stresses while providing improved nutritional value.

Figure 4: The author. Photo: author's own.

Wheat research is a particular strength of CSIRO, with the organisation having developed numerous high-performing wheat varieties. These varieties often feature enhanced resistance to devastating diseases like rust and improved tolerance to environmental stressors, contributing significantly to the robustness of Australia's wheat industry.

In response to climate change, CSIRO is intensifying its efforts to breed crops adapted to emerging environmental challenges. This includes developing heat-tolerant and drought-resistant varieties capable of thriving in increasingly variable and extreme weather conditions.

CSIRO's impact extends beyond research, with a strong focus on commericalisation. By bringing its crop varieties and technologies to market, CSIRO ensures that its scientific advancements translate into tangible benefits for farmers and the broader agricultural sector.

Central to CSIRO's success is its close collaboration with farmers. By actively engaging with the agricultural community, CSIRO gains valuable insights into on-the-ground challenges and priorities. This farmer-centric approach ensures that CSIRO's crop varieties are not just scientifically advanced but also practically suited to the real-world needs of Australian agricultural producers.

UK – John Innes centre, Rothamstead, NIAB, BSPB and plant breeders

While the John Innes Centre is not a plant breeding company per se, its research and contributions are instrumental in advancing our understanding of plant genetics and in providing the scientific foundations for plant breeding programmes in the UK and beyond. The knowledge generated by the Centre is critical for addressing global challenges related to food security, climate change, and sustainable agriculture. While the John Innes Centre is primarily known for its plant science research, it is not a plant breeding company in the traditional sense. Instead, it focuses on fundamental research and the development of scientific knowledge that underpins plant breeding and crop improvement.

Rothamsted Research is one of the oldest and most well-respected agricultural research institutions in the world. Located in Harpenden, Hertfordshire, in the UK, Rothamsted Research has a long history of conducting pioneering research in various fields of agriculture and crop science. While it is not a plant breeding company, it plays a significant role in providing valuable scientific knowledge and genetic resources that are used by plant breeders to develop improved crop varieties. Rothamsted Research was founded in 1843 and is known for its rich history of agricultural research. It is home to the famous Rothamsted Experimental Station, where long-term agricultural experiments, known as the Broadbalk experiment; whick looks at the effects of different fertilizers and manures on long-term wheat yields, soil health, carbon sequestration, and sustainable agriculture. Rothamsted Research maintains genetic resources and germplasm collections for various crops. These collections serve as valuable sources of genetic diversity for plant breeders looking to develop improved crop varieties.

The British Society of Plant Breeders (BSPB) is an organisation in the UK that represents the interests of plant breeding companies. BSPB plays a key role in the regulation and promotion of plant breeding activities in the UK.

BSPB works closely with government authorities to ensure that new plant varieties meet regulatory standards. It is responsible for conducting national listing trials for new crop varieties, ensuring that they are distinct, uniform, and stable.

BSPB administers the Plant Variety Rights (PVR) system in the UK. Plant breeders can apply for PVR to protect their new plant varieties, giving them exclusive rights to produce, market, and sell these varieties for a set period of time. BSPB may be involved in supporting research and development efforts related to plant breeding and crop improvement. This can include collaborative efforts with plant breeding companies, research institutions, and universities.

Denmark – DAKOFO, Copenhagen University, Seges, farmer

Figure 5: Lizzie Carr-Archer and Danish hosts, Anders Christensen and Lars Ipsen. Photo: author's own.

DAKOFO (Danish Grain and Feed Trade Association) is a key industry organisation representing companies in the grain and feed trade in Denmark. It serves as a platform for collaboration and advocacy for its members, which include grain traders, feed manufacturers, and other related businesses. DAKOFO works to promote the interests of the grain and feed industry, facilitate trade, and engage with regulatory bodies on issues affecting the sector.

Copenhagen University, one of the oldest and most prestigious universities in Denmark, has a strong presence in agricultural and plant science research. The University's Department of Plant and Environmental Sciences conducts cutting-edge research in areas such as plant genetics, crop improvement, and sustainable agriculture. Their work contributes significantly to the scientific knowledge underpinning modern plant breeding and agricultural practices.

SEGES is an agricultural knowledge and innovation centre that plays a crucial role in supporting Danish agriculture. It is part of the Danish Agriculture & Food Council and focuses on providing research-based knowledge and innovative solutions to farmers and the broader agricultural industry. SEGES conducts applied research, offers advisory services, and develops tools and technologies to improve agricultural productivity and sustainability.

CHAPTER 4: PLANT BREEDING METHODS

Introduction to plant breeding

Plant breeding has been one of the foundations for the success of organised human society for millennia. The length of the original full cultivation process using traditional methods is still debated but archaeological data indicates that the establishment of a tough rachis (rachis is the central stalk of the wheat spike to which the spikelets are attached) in wheat may have taken 1,500 years and perhaps 2,000 or more in barley.[1] Ultimately, we have been selecting preferences in our plants from the early days to create products that suit our ever-changing needs.

Some typical examples of traits that have been breed into our domesticated cereals over preceding millennia include:

Traits associated with harvesting:

- Non-shattering of seed/pods at maturity
- A general reduction in hairiness and the awns being reduced or absent
- Determinate and compact growth habit during the lifecycle
- Reduction in axillary branching
- Synchronisation of maturation

Traits associated with seedling competition:

- Seedling vigour
- Rapid germination
- Tolerance of climatic conditions
- Resistance to diseases or pests

Traits associated with seed production and use:

- Larger, denser or more compact inflorescence structure
- Larger seed size
- Naked kernels
- Longer storage or retention periods

[1] Tansley Review, A comparative view of the evolution of grasses under domestication, Sylain Glemin and Thomas Bataillon, Universite Montpellier, 2009.

Traditional or convention breeding

Traditional plant breeding involves two primary techniques both of which are time consuming and the results are unpredictable.

Figure 6: Plant crossing of old wheat races, CIMMYT. Photo: author's own.

The first technique is simple selection, typically based on phenotypical traits desired. Ultimately, plants with desirable characteristics are propagated and those with less desirable characteristics are culled. Continue this over many generations and we have breed into the cultivated version of the species the desired characteristics.

The second technique is natural but deliberate crossing or interbreeding of related individuals in an attempt to produce new crop varieties or lines with desirable properties. This could also be referred to as classical hybridisation or crossbreeding.

In both cases, the plant breeder is relying on the ability of natural processes to guide and generate the genetic diversity intended.

It is possible in both of these approaches to use Marker Assisted Selection (MAS). This technique ultilises genetic markers, specific DNA sequences associated with particular traits, to identify and select plants carrying desired genes or quantitative trait loci (QTLs). By leveraging these markers, breeders can more efficiently and accurately select plants with desired characteristics compared to traditional breeding methods.

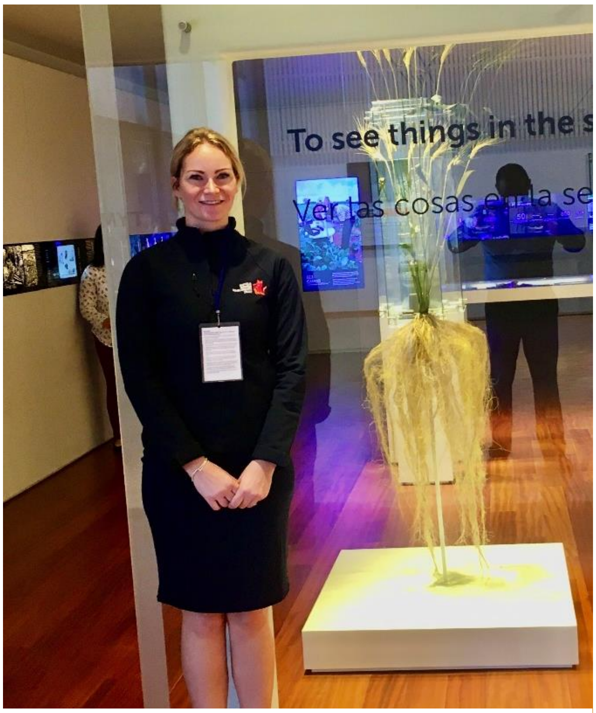

Figure 7: Lizzie Carr-Archer stood by a wheat plant showing the potential root mass of one plant. Photo: author's own.

The concept of MAS relies on the close linkage between genetic markers and genes of interest. This linkage allows breeders to indirectly select for desired traits without the need to grow plants to maturity or observe the phenotype. Various types of genetic markers are employed in MAS including Simple Sequence Repeats (SSRs), Single Nucleotide Polymorphisms (SNPs), Restriction Fragment Length Polymorphisms (RFLPs), and Amplified

Fragment Length Polymorphisms (AFLPs).

The advantages of MAS in plant breeding are numerous. It significantly increases efficiency by enabling early selection of desired traits, thereby reducing the time and resources required for breeding programmes. MAS also improves accuracy by minimising the influence of environmental factors on trait selection. Furthermore, it allows for simultaneous selection of multiple traits and facilitates the introgression of traits from wild relatives or across species, overcoming traditional breeding barriers.

In practice, MAS finds applications across various aspects of plant breeding. It is particularly useful in selecting for disease resistance genes, identifying plants with improved abiotic stress tolerance (such as drought, salt, or heat tolerance), and breeding for quality traits like enhanced nutritional content, flavour, or processing qualities. MAS also plays a crucial role in yield improvement by helping identify plants with genes associated with higher yield potential.

The process of implementing MAS in a breeding programme involves several steps. Initially, breeders must identify markers linked to traits of interest and develop reliable and cost-effective marker assays. They then screen breeding populations using these markers, select plants carrying desired marker alleles, and advance these selected plants in the breeding programme.

MAS is often integrated with other breeding techniques to maximise its effectiveness. It complements approaches such as genomic selection, speed breeding, and doubled haploid technology, creating powerful synergies in modern plant breeding programmes.

Despite its many advantages, MAS does face some challenges and limitations. The cost of developing and applying markers can be significant, and the technique requires specialised equipment and expertise. Additionally, MAS may have limited effectiveness for highly complex traits controlled by many genes. There's also the potential for linkage drag, where undesired genes are carried along with the desired ones due to their proximity on the chromosome.

Genetic Modification (GMOs)

This method involves directly altering a plant's DNA using techniques like recombinant DNA technology to introduce new traits. GMOs may have genes inserted from different species (transgenics) or edited within the same species (cisgenics).

- **Transgenic Plants**: Genes from another species are inserted into the plant's genome. For example, Bt cotton, which produces a toxin to repel pests, is a transgenic plant.
- **Cisgenic Plants**: Genes are transferred from one plant variety to another within the same species. This is similar to traditional breeding but involves more precise gene transfer.

Genetically Modified Organisms (GMOs) have been a topic of intense debate and scientific research since their introduction in the 1990s. These organisms, which have had their genetic material altered using genetic engineering techniques, represent a significant advancement in biotechnology and have far-reaching implications for agriculture, medicine, and the environment.

In the context of agriculture, GMOs are primarily crops that have been modified to express desirable traits such as resistance to pests, diseases, or environmental conditions, or to improve nutritional content. The process involves inserting specific genes from one organism into another, often crossing species barriers that would not occur in nature or through traditional crossbreeding methods.

The development of GMOs began with the discovery of DNA structure and the subsequent advancements in molecular biology. Scientists realised they could isolate genes responsible for specific traits and transfer them between organisms. This led to the creation of the first genetically modified plants in the 1980s, with the first commercial GMO crop, the Flavr Savr tomato, hitting the market in 1994.

Proponents of GMO technology argue that it offers numerous benefits. GMOs can increase crop yields, reduce the use of pesticides, enhance nutritional content of foods, and create crops that are more resistant to adverse environmental conditions such as drought or salinity. For example, Bt cotton, which produces its own insecticide, has significantly reduced the need for chemical pesticides in many regions. Golden Rice, enriched with beta-carotene, was developed to address vitamin A deficiency in developing countries.

However, GMOs have also faced significant controversy and opposition. Critics raise concerns about potential health risks, environmental impact, and ethical implications. Some worry about the long-term effects of consuming GMO foods, although scientific consensus suggests that approved GMOs are as safe as their conventional counterparts. Environmental concerns include the potential for GMOs to cross-pollinate with non-GMO crops or wild relatives, potentially leading to the development of 'superweeds' or affecting biodiversity.

The regulation of GMOs varies significantly across the world. In the United States, GMOs are regulated by the FDA, USDA, and EPA, focusing on the product rather than the process used to create it. The European Union, on the other hand, has stricter regulations, requiring rigorous testing and labelling of GMO products. Many developing countries have their own regulatory frameworks, often influenced by their trade relationships and domestic agricultural policies.

The impact of GMOs extends beyond agriculture. In medicine, genetic modification techniques are used to produce insulin for diabetics and to develop new vaccines. In industry, GMOs are employed to create enzymes for various manufacturing processes. Environmental applications include the development of bacteria for bioremediation of polluted sites.

Public perception of GMOs remains mixed, with opinions often divided along cultural, political, and geographical lines. This has led to ongoing debates about labelling requirements for GMO products and has influenced consumer behaviour and market trends. The rise of 'Non-GMO' labels on food products reflects the consumer demand for transparency and choice in this area.

As technology advances, new techniques like CRISPR gene editing are blurring the lines between traditional GMOs and more precise genetic modifications. These developments are prompting reassessments of regulatory frameworks and public perceptions.

Gene Editing (CRISPR and other techniques)

Figure 8: Lizzie Carr-Archer stood outside John Innes centre, Norwich. Photo: author's own.

Gene editing can be understood to be the process whereby scientists make precise changes to a plant's existing DNA to promote or reduce traits. This powerful tool allows scientists to make precise modifications to DNA sequences within living organisms, opening up unprecedented possibilities in fields ranging from medicine and agriculture to environmental conservation. It is best thought of as techniques to re-programme or edit the existing DNA of a plant by using natural immune system response processes. Older techniques for gene editing involved time-consuming processes to create a whole new sequence, introduce and test this new protein – overall this remains haphazard and difficult to do.

The latest advance in the field of gene editing is known as CRISPR-Cas9 or more colloquially "genetic scissors". The discoverers, Emmanuelle Charpentier (French Professor from the Max Planck Unit for the Science of Pathogens in Berlin) and Jennifer Doudna (American Professor from the University of California, Berkeley) first published their technique in a landmark paper in 2012. They were subsequently both awarded the Nobel Prize for chemistry in 2020 – the first award in this field granted solely to women.[2]

This technique is faster, more accurate and cheaper to utilise. Plant breeders have the possibility to introduce beneficial traits or correct genetic defects with far greater precision and speed than has been possible for the preceding two millennia.

[2] Two women share chemistry Nobel in historic win for "genetic scissors", 7 October 2020, BBC News - https://www.bbc.co.uk/news/science-environment-54432589

The process of gene editing using CRISPR is remarkably precise and efficient compared to earlier methods. Once the DNA is cut, the cell's natural repair mechanisms kick in, allowing scientists to either disable a gene, correct a mutation, or insert new genetic material. This level of precision and ease of use has made CRISPR a game-changer in genetic research and applications.

In medicine, CRISPR holds enormous potential for treating genetic disorders. Scientists are exploring its use in correcting mutations responsible for diseases like sickle cell anaemia, cystic fibrosis, and certain types of cancer. Clinical trials are already underway for some of these applications, with promising early results. Additionally, CRISPR is being used to develop new therapies for infectious diseases, including potential treatments for HIV and strategies to combat antibiotic-resistant bacteria.

Agriculture is another field where CRISPR is making significant inroads. Unlike traditional genetic modification techniques, CRISPR allows for more precise and often simpler alterations to plant genomes. This has led to the development of crops with enhanced nutritional profiles, improved resistance to pests and diseases, and better tolerance to environmental stresses like drought. For instance, researchers have used CRISPR to create wheat varieties resistant to powdery mildew, a common fungal disease, and to develop tomatoes with enhanced vitamin C content.

In the realm of environmental conservation, gene editing offers new tools for protecting endangered species and controlling invasive ones. Scientists are exploring the use of CRISPR to increase the genetic diversity of endangered populations, potentially improving their resilience to environmental changes. There are also controversial proposals to use gene drives – a technique that can rapidly spread genetic modifications through a population – to control disease-carrying mosquitoes or invasive species.

Figures 9 & 10: Gene edited wheat plants in their infancy, John Innes Centre. Photo: author's own.

Despite its enormous potential, CRISPR and gene editing technology also raise significant ethical concerns. The possibility of creating 'designer babies' by editing human embryos has sparked intense debate within the scientific community and beyond. In 2018, the announcement of the birth of twin girls in China whose embryos had been gene-edited to confer HIV resistance caused international outcry and calls for stricter regulation of human germline editing.

The regulatory landscape for gene-edited organisms varies widely across the globe. Some countries, like the United States, have taken a relatively permissive approach, particularly for applications in agriculture. Others, including many European nations, have stricter regulations, often treating gene-edited organisms similarly to traditional GMOs. This regulatory divergence has implications for international trade and the global adoption of gene-editing technologies.

As CRISPR and other gene-editing techniques continue to advance, new challenges and opportunities emerge. Researchers are working on improving the precision of CRISPR to minimise off-target effects and developing new Cas enzymes with different capabilities. The development of base editing and prime editing techniques, which allow for even more precise genetic modifications without cutting the DNA, represent the next frontier in this rapidly evolving field.

CHAPTER 5: RESEARCH INSTITUTIONS AND BREEDING COMPANIES

Summary

- Due to the lower cost and accuracy of gene editing techniques it is possible that some disruption to the traditional plant breeding companies could occur given smaller or less known players can be highly innovative and fast acting in improving plant traits
- Coupled with this the best results are likely to come from strong collaborations between private sector companies and international research institutions

Breeding Companies

Breeding companies, also known as seed or genetics companies, are pivotal in shaping modern agriculture through the development and commercialisation of new crop varieties. These organisations dedicate substantial resources to research and development, focusing on creating plants with enhanced traits such as improved disease resistance, higher yield potential, and superior quality. Their work is instrumental in addressing critical global challenges including food security, agricultural sustainability, and adaptation to climate change.

The landscape of plant breeding companies has undergone significant transformation in recent years, marked by notable mergers and acquisitions. Events such as Bayer's acquisition of Monsanto and the merger of Dow and DuPont have reshaped the industry, concentrating resources and expertise while also raising concerns about market consolidation.

Figure 11: Lizzie Carr-Archer stood in Ciudad Obregón, Sonora CIMMYT – Situated in the arid Yaqui Valley, focused on heat and drought tolerance in wheat; also part of the famed shuttle-breeding system established by Norman Borlaug. Photo: author's own.

In the current era, plant breeding has become increasingly sophisticated and data-driven. Companies now leverage advanced technologies like genomics and bioinformatics to analyse vast datasets, enabling more targeted and efficient breeding processes. This shift towards data-centric approaches has accelerated the pace of innovation and improved the precision of trait selection.

The global nature of agricultural challenges has fostered increased international cooperation among breeding companies. Collaborations span across continents, with organisations working together to address food security issues, share genetic resources, and develop crops suited to diverse climatic conditions. This global perspective is crucial in creating varieties that can thrive in different environments and meet the needs of farmers worldwide. Partnerships between plant breeding companies and other entities in the biotechnology ecosystem have become commonplace. Collaborations with biotechnology firms, research institutions, and universities allow breeding companies to tap into specialised expertise in genomics, genetics, and trait development. These synergies accelerate innovation and bring diverse perspectives to the breeding process.

The perception and approach to genetic modification technologies have evolved over time. While genetically modified organisms (GMOs) were often associated with multinational corporations, gene editing (GE) is viewed as a more collaborative effort between private sector companies and public institutions. This shift in perception has implications for public acceptance and regulatory approaches.

It's important to note that gene editing, unlike some earlier biotechnology approaches, is not dominated by a monopoly. While there are significant players in the field, the technology is characterised by a diverse landscape of contributors. From academic researchers and innovative startups to established biotech and pharmaceutical companies, a wide range of actors are involved in developing and applying gene editing technologies.

Research Institutions

Universities, research institutions, and non-profit organisations are pivotal in driving the advancement of gene editing technology. These entities are often at the forefront of groundbreaking discoveries and fundamental research that lay the foundation for practical applications. Their work is crucial in expanding our understanding of genetic mechanisms and developing new techniques that push the boundaries of what's possible in gene editing.

The gene editing landscape is characterised by a vibrant ecosystem of startups and small biotech companies. These agile organisations are often spin-offs from academic research or founded by innovative scientists and entrepreneurs. They bring fresh perspectives and specialised expertise to the field, focusing on niche applications or novel approaches to gene editing. Their presence in the market fosters healthy

Figure 12: Water absorption vs root mass, Copenhagen University. Photo: author's own.

competition and drives rapid innovation, challenging larger established players to stay at the cutting edge.

Gene editing is truly a global endeavour, with research and development occurring across numerous countries and continents. This international nature of the field creates a rich tapestry of diverse approaches, ideas, and applications. Scientists and organisations from different cultural and academic backgrounds collaborate, sharing insights and methodologies that might not emerge in a more homogeneous research environment. This global network of researchers and institutions ensures that gene editing technology benefits from a wide range of perspectives and expertise.

The spirit of collaboration in gene editing extends beyond geographical boundaries. Many researchers and organisations actively participate in data sharing initiatives and contribute to open-source platforms. This openness promotes a non-monopolistic environment where knowledge and tools are accessible to a broader community. Collaborative efforts, such as international research consortia or multi-institutional projects, pool resources and expertise to tackle complex challenges that might be beyond the scope of any single entity.

This collaborative and diverse ecosystem in gene editing helps prevent the concentration of power or knowledge in the hands of a few large corporations or institutions. It ensures that the field remains dynamic, with multiple players contributing to its advancement and shaping its future direction. As gene editing continues to evolve, this diverse and collaborative approach will likely play a crucial role in addressing ethical concerns, navigating regulatory challenges, and realising the technology's full potential across various applications.

CHAPTER 6: GMO VS GENE EDITING

Summary

- Genetically Modified Organisms' (GMO) social acceptance varies hugely but could be said to have a tarnished reputation
- The opportunity exists to explain the power and benefits of gene editing and its distinguishing characteristics in order to create a positive public perception of this technique and its outcomes
- Governmental organisations should play an active and open role in cementing trust and understanding of this technique

Societal acceptance of gene editing technologies is heavily influenced by public awareness and understanding. The complex nature of genetic modification and its potential implications can be challenging for the general public to grasp, leading to misconceptions and fears. To address this, education and public engagement initiatives are crucial. These efforts aim to demystify the science behind gene editing, explain its potential applications across various fields, and openly discuss the ethical considerations involved. By fostering a more informed public discourse, these initiatives can help bridge the gap between scientific advancement and societal acceptance.

The regulatory landscape for GMOs varies significantly across different countries and regions. This diversity in approach reflects differing cultural attitudes, political climates, and economic considerations. Some nations have implemented strict regulatory frameworks that govern every aspect of GMO development, from initial research to commercial cultivation and marketing. These stringent regulations often require extensive safety testing and environmental impact assessments before approval. In contrast, other countries have adopted more permissive approaches, viewing GMOs as a continuation of traditional plant breeding methods and regulating them similarly to conventional crops.

The United States and Canada are examples of countries with relatively high acceptance and widespread commercial cultivation of GMO crops. These nations have embraced the technology as a means to enhance agricultural productivity and address various challenges in food production. Their regulatory systems focus on the end product rather than the process used to create it, which has facilitated the adoption of GMO crops.

On the other hand, many European countries have taken a more cautious stance towards GMOs. The European Union, in particular, has implemented strict regulations that require rigorous safety assessments and mandatory labelling of GMO products. This approach reflects a stronger emphasis on the precautionary principle and responds to public concerns about potential long-term effects on health and the environment.

Public understanding plays a pivotal role in the acceptance of GMOs. The complexity of genetic modification techniques and their potential implications can be difficult for non-experts to grasp, leading to misunderstandings and fears. To address this, various stakeholders, including scientists, policymakers, and industry representatives, have initiated education and awareness campaigns. These efforts aim to provide accurate, accessible information about the science behind GMOs, their potential benefits, and associated risks. By fostering a more informed public discourse, these initiatives can help alleviate unfounded fears and promote evidence-based decision-making.

Media coverage significantly influences public perception of GMOs. The way genetic modification is portrayed in news articles, documentaries, and social media can shape public opinion, sometimes more powerfully than scientific evidence. Sensationalised or negative media stories can amplify fears and misconceptions, potentially leading to widespread rejection of GMO technologies. Conversely, balanced and accurate reporting can provide a more nuanced perspective, helping the public understand both the potential benefits and legitimate concerns associated with GMOs.

It's important to note that while GMOs and gene editing are related concepts in biotechnology, they are distinct. GMOs typically involve the introduction of foreign DNA into an organism, often crossing species barriers. Gene editing, particularly techniques like CRISPR, allows for more precise modifications within an organism's existing genome. This distinction is becoming increasingly important in public discourse and regulatory considerations, as some argue that certain gene-edited organisms should be regulated differently from traditional GMOs.

Worldwide Examples

Different cultures and ethical belief systems have varying perspectives on the acceptability of gene editing. Some may embrace it as a tool for improving human health and well-being, while others may have concerns related to tampering with the natural order or altering the human germline.

One of the most prominent examples is Golden Rice, developed to combat vitamin A deficiency in developing countries. This genetically engineered rice produces beta-carotene, a precursor of vitamin A, aiming to reduce childhood blindness and mortality in regions where rice is a staple food. It has been approved for cultivation in several countries, including the Philippines and Bangladesh.

While primarily an agricultural advancement, Bt Cotton has indirect health benefits. By reducing pesticide use, it leads to fewer pesticide-related health issues among farmers. This GMO has been widely adopted in countries like India, China, and the United States. In the medical field, genetically modified bacteria are used to produce human insulin for diabetics, replacing earlier methods that used animal-derived insulin and reducing allergic reactions. This technology is now used globally, providing a more consistent and safer insulin supply.

The Hepatitis B vaccine, produced using genetically modified yeast cells, offers a safer and more efficient alternative to vaccines derived from human blood plasma. It is widely used in national immunisation programmes worldwide. In Bangladesh, Bt Brinjal (eggplant) has been developed to resist the fruit and shoot borer pest, reducing pesticide use and leading to health benefits for both farmers and consumers.

Omega-3 enhanced soybean oil, derived from genetically modified soybeans, aims to provide a sustainable, plant-based source of heart-healthy omega-3 fatty acids. This product has been approved for use in the United States and other countries. Low-acrylamide potatoes, genetically modified to produce less of the potential carcinogen acrylamide when fried, have been approved for cultivation in the United States and Canada.

Research is ongoing to develop allergen-reduced peanuts, which could potentially decrease the prevalence and severity of peanut allergies. Although still in development stages, this innovation shows promise for addressing a significant health concern. Biofortified cassava, genetically modified to enhance nutritional content including iron and zinc, targets malnutrition in regions where cassava is a staple food. Research and field trials are ongoing in several African countries.

Drought-resistant maize, while primarily offering agricultural benefits, indirectly supports food security and nutrition by helping maintain crop yields in drought-prone regions. This GMO has been approved for cultivation in the United States and is under consideration in several African countries.

UK Public and Market Anticipation

In the United Kingdom, the anticipation of gene editing technologies in both public perception and market dynamics reflects a unique blend of scientific ambition, regulatory caution, and post-Brexit policy considerations.

Public perception in the UK has been shaped by a history of debate surrounding GMOs and biotechnology. However, gene editing is generally viewed more favourably than traditional GMOs. The UK public tends to be more accepting of gene editing applications in medicine compared to those in agriculture or food production. This is partly due to the UK's strong reputation in medical research and the National Health Service's central role in public health.

The UK government has shown increasing interest in gene editing, particularly in the wake of Brexit. In January 2021, the Department for Environment, Food and Rural Affairs (DEFRA) launched a consultation on the regulation of genetic technologies, signalling a potential shift towards a more permissive approach to gene editing in agriculture and food production. This move has been seen as an attempt to diverge from EU regulations and position the UK as a leader in biotechnology innovation.

In the medical field, the UK has been at the forefront of gene editing research. The Francis Crick Institute in London was the first in the world to receive approval for editing genes in human embryos for research purposes in 2016. This has placed the UK at the centre of both scientific advancement and ethical debates surrounding gene editing.

The market anticipation in the UK is characterised by cautious optimism. The biotechnology sector, including companies focused on gene editing, has seen growth and investment. However, this is tempered by regulatory uncertainties, particularly in the agricultural sector. The outcome of the DEFRA consultation and subsequent policy decisions will likely have a significant impact on market dynamics.

UK research institutions and biotech companies are actively exploring gene editing applications in various fields:

1. In agriculture, there's interest in developing crops with improved traits, such as disease resistance or enhanced nutritional profiles. The Rothamsted Research institute, for instance, has been working on gene-edited wheat with reduced levels of asparagine, which could lower acrylamide formation during baking.
2. In medicine, UK-based companies and research institutions are exploring gene editing for treating genetic disorders. For example, Great Ormond Street Hospital has been involved in developing gene therapies for rare immune disorders.
3. In livestock breeding, there's research into using gene editing to improve animal welfare and productivity. The Roslin Institute, famous for cloning Dolly the sheep, is at the forefront of this research.

The UK's regulatory approach to gene editing is evolving. While still aligned with EU regulations that treat gene-edited organisms as GMOs, there are indications of a potential shift. The government has expressed interest in adopting a more science-based approach to regulation, potentially distinguishing between gene editing and traditional GMOs.

Public engagement and education initiatives are crucial in shaping public perception. Organisations like the Royal Society and the Nuffield Council on Bioethics have been active in promoting public dialogue and providing balanced information on gene editing technologies.

The market response in the UK has been cautiously positive. Investment in gene editing research and companies has increased, but full market potential remains constrained by current regulations. Many in the industry are watching closely for regulatory changes that could open up new opportunities, particularly in agriculture and food production.

CHAPTER 7: REGULATORY ENVIRONMENT

Summary

- The UK is still very early in its regulatory journey with regards to gene editing in plants and other agricultural utilities but the primary legislation introduced is a positive step forward

UK Breeding Bill and Legislation

The UK has recently taken significant steps to establish a renewed legal framework that will enable researchers and plant breeders to advance seed breeding and gene editing in agriculture. This initiative has culminated in the Precision Breeding Act 2023.

Precision Breeding Act 2023

The Genetic Technology (Precision Breeding) Act 2023, passed in March 2023, marks a pivotal shift in the UK's approach to genetic technologies in agriculture. This legislation introduces a crucial distinction between gene-edited organisms and traditional genetically modified organisms (GMOs). The Act's primary purpose is to facilitate the development of crops with enhanced traits through gene-editing techniques.

Key aspects of the Act include:

1. Legal differentiation: It legally distinguishes gene-edited organisms from GMOs, potentially streamlining the regulatory process for gene-edited crops.
2. Focus on agriculture: The Act aims to unlock the potential of gene editing in crop improvement, potentially leading to more resilient and productive plant varieties.
3. Limited scope: Currently, the Act's scope is confined to plants and their by-products in food and feed. It explicitly excludes applications in animals and humans.
4. Pending implementation: While the Act has been passed, its practical implementation awaits the introduction of necessary secondary legislation. This additional step is required to fully enable companies to leverage the benefits of gene editing in England.
5. Regulatory framework: The Act sets the stage for a new regulatory system that could potentially accelerate the development and commercialisation of gene-edited crops.

This legislation represents a significant departure from the UK's previous alignment with EU regulations on GMOs. It reflects the country's post-Brexit ambition to position itself as a leader in agricultural innovation and biotechnology.

However, it's important to note that the full impact of this Act is yet to be realised. The agricultural and biotechnology sectors are eagerly awaiting the secondary legislation that will provide the detailed guidelines and procedures for implementing gene editing technologies under this new framework.

The Precision Breeding Act 2023 has generated both excitement and debate. Proponents see it as a crucial step towards enhancing food security, improving crop resilience, and boosting agricultural productivity. Critics, however, raise concerns about potential long-term environmental impacts and the need for robust safety assessments.

As the UK moves forward with this new approach to genetic technologies in agriculture, it will be crucial to monitor its implementation, assess its impact on the agricultural sector, and evaluate public acceptance of gene-edited products. The success of this legislation could potentially influence similar regulatory changes in other countries, particularly those seeking to balance technological innovation with environmental and safety considerations in agriculture.

Considerations and Challenges

The UK Precision Breeding Act 2023 presents a complex array of considerations and challenges as it moves towards implementation. One of the primary hurdles is the development of comprehensive secondary legislation to operationalise the Act, including establishing clear guidelines for research, development, and commericalisation. This process must ensure that regulatory bodies are adequately equipped to handle new assessment procedures.

From a scientific and technical standpoint, defining precise criteria for what constitutes "precision breeding" and addressing potential off-target effects of gene editing techniques are crucial challenges. Additionally, developing robust methods for detecting and identifying gene-edited organisms will be essential for regulatory compliance and monitoring.

The Act has significant market and trade implications. Potential trade barriers may arise with EU countries that still regulate gene-edited organisms as GMOs. Navigating different international regulatory frameworks for gene-edited products and addressing labelling and traceability requirements will be ongoing challenges.

Public perception and acceptance remain critical factors. Educating the public about the differences between gene editing and traditional GMOs, addressing concerns about safety and environmental impact, and managing public trust and transparency in the development and use of gene-edited crops will be essential for the Act's success.

Ethical considerations must also be addressed, including balancing innovation with precautionary principles, addressing concerns about biodiversity and ecological impact, and considering the socio-economic implications for farmers and the agricultural sector.

The current limitations of the Act, particularly the exclusion of animals, may face pressure for expansion in the future. Harmonising the new framework with existing food safety and environmental protection laws, as well as ensuring consistency with international obligations and treaties, will be ongoing tasks.

Intellectual property rights present another challenge, requiring the development of appropriate patent and plant variety protection frameworks for gene-edited crops while balancing innovation incentives with access to genetic resources.

Establishing systems for long-term monitoring of gene-edited organisms in the environment and developing protocols for assessing unintended consequences over time will be crucial for the Act's long-term success and public trust.

Capacity building in terms of scientific and regulatory expertise, as well as investment in research and development infrastructure, will be necessary to effectively implement the new framework.

The UK's divergence from EU regulations on this matter presents its own set of challenges, including managing the implications for trade and addressing potential obstacles in data sharing and collaborative research with EU countries.

Ensuring coexistence of gene-edited crops with organic and conventional farming, and addressing potential concerns about cross-contamination, will be important for maintaining diversity in agricultural practices.

Consumer choice and transparency issues, including determining appropriate labelling requirements for gene-edited products and ensuring consumers have access to clear information, will need careful consideration.

Finally, international collaboration and engagement in developing global standards for safety assessment and regulation of gene-edited organisms will be crucial for the UK to maintain its position in the global agricultural and biotechnology sectors.

Addressing these multifaceted challenges will require ongoing dialogue between policymakers, scientists, industry stakeholders, and the public to ensure a balanced and effective implementation of the new regulatory framework established by the Precision Breeding Act 2023.

CHAPTER 8: WORLD EXAMPLES OF CHEMICAL REDUCTION

Fungicides

One compelling global example demonstrating the potential for reducing fungicide use through advanced breeding techniques comes from the development of disease-resistant wheat varieties in Europe and North America.

The Wheat Rust Resistance Project, a collaborative effort involving researchers from multiple countries, has made significant strides in developing wheat varieties resistant to various strains of rust, particularly stem rust. Stem rust is a devastating fungal disease that can cause significant yield losses in wheat crops worldwide. Traditionally, controlling rust outbreaks has relied heavily on fungicide applications, which can be costly and environmentally problematic.

By utilising advanced breeding techniques, including marker-assisted selection and more recently, gene editing, scientists have successfully identified and incorporated rust-resistant genes into commercial wheat varieties. One notable success story is the development of wheat varieties resistant to Ug99, a particularly virulent strain of stem rust that emerged in Uganda in 1999 and threatened wheat production across Africa and Asia.

The International Maize and Wheat Improvement Centre (CIMMYT), in collaboration with national research programmes, has released several high-yielding, Ug99-resistant wheat varieties. These varieties have been widely adopted in countries like Kenya, Ethiopia, and India, where they have significantly reduced the need for fungicide applications to control stem rust.

For instance, in Kenya, where stem rust has been a persistent threat, the adoption of resistant varieties has allowed farmers to reduce fungicide applications by up to 50% in some regions. This reduction not only lowers production costs for farmers but also minimises the environmental impact of chemical fungicides.

In North America, similar efforts have led to the development of wheat varieties resistant to Fusarium head blight, another fungal disease that can cause significant economic losses and contaminate grain with harmful mycotoxins. The use of these resistant varieties has enabled farmers in the United States and Canada to reduce their reliance on fungicides for controlling this disease, particularly in high-risk areas.

The success of these projects demonstrates the potential of advanced breeding techniques, including precision breeding methods, to develop crop varieties with enhanced disease resistance. By reducing the need for fungicide applications, these innovations contribute to more sustainable agricultural practices, lower production costs, and reduced environmental impact.

As precision breeding techniques continue to advance, there is potential for even more targeted and efficient development of disease-resistant crop varieties. This could lead to further reductions in fungicide use across various crops and regions, contributing to global efforts to promote sustainable agriculture and food security while minimising environmental impacts.

The UK's Precision Breeding Act 2023 aims to facilitate similar innovations in crop improvement, potentially accelerating the development of disease-resistant varieties suited to local conditions and reducing the reliance on chemical fungicides in British agriculture. As this legislation is implemented, it may pave the way for new success stories in sustainable crop protection, building on the global examples of rust-resistant wheat and other disease-resistant crop varieties.

Herbicides

In Argentina, the adoption of no-till farming practices combined with cover crops has led to substantial reductions in herbicide use. Farmers implementing these methods have reported up to 30% decrease in herbicide applications. Cover crops like rye and vetch suppress weed growth naturally, reducing the need for chemical interventions. This approach not only cuts herbicide use but also improves soil health and reduces erosion.

Within the UK there is a compelling example with its development of herbicide-tolerant OSR and sugar beet varieties. While initially this might seem counterintuitive, these varieties allow farmers to use fewer, more targeted herbicide applications. The Clearfield OSR system, for instance, has enabled reductions in herbicide use by up to 40% compared to conventional varieties, as reported by some UK farmers. This system allows for more effective weed control with less environmental impact.

In Europe, particularly in countries like Denmark and Sweden, integrated weed management strategies have shown promising results. These approaches combine mechanical weeding, crop rotation, and precision spraying technologies. Some Danish farmers have reported herbicide reductions of up to 50% by implementing these integrated strategies. The use of robotic weeders, which can distinguish between crops and weeds, has been particularly effective in reducing herbicide use in high-value crops like sugar beets.

Japan offers an interesting case study in herbicide reduction through alternative weed management in rice cultivation. The "Aigamo" method, which involves raising ducks in rice paddies, has gained popularity among organic farmers. The ducks eat weeds and insects, fertilise the rice with their droppings, and oxygenate the water as they move around. Farmers using this method have eliminated the need for herbicides entirely in their rice production.

In the United States, the development of drought-tolerant corn varieties has indirectly contributed to herbicide reduction. These varieties, developed through both conventional breeding and genetic modification, allow for earlier planting and faster crop establishment. This gives the corn a competitive advantage over weeds, reducing the need for herbicide applications. Some studies have shown up to 25% reduction in herbicide use in drought-tolerant corn fields compared to conventional varieties under similar conditions.

Brazil has made significant strides in reducing herbicide use through the adoption of integrated crop-livestock systems. By rotating crops with pasture, farmers have been able to break weed cycles naturally, reducing the need for chemical control. Some Brazilian farmers implementing these systems have reported herbicide reductions of up to 60% compared to conventional monoculture systems.

In India, the System of Rice Intensification (SRI) has gained traction as a method to reduce inputs, including herbicides, while increasing yields. This system involves wider spacing of rice plants, which allows for mechanical weeding. Farmers adopting SRI have reported significant reductions in herbicide use, with some eliminating herbicides entirely.

These global examples demonstrate that reducing herbicide use is achievable through a combination of innovative breeding, integrated management practices, and technological advancements. As precision breeding techniques continue to evolve, there's potential for developing crop varieties with enhanced competitive abilities against weeds or with traits that allow for more targeted and reduced herbicide applications.

Insecticides

A notable global example of reducing insecticide use comes from the widespread adoption of Bt cotton around the world, most notably in India, which has led to significant decreases in chemical insecticide applications while improving yields and farmer incomes.

Bt cotton, genetically engineered to produce a protein from Bacillus thuringiensis (Bt) that is toxic to certain insect pests, was first introduced in India in 2002. The primary target was the bollworm complex, particularly the American bollworm (Helicoverpa armigera), which had been causing substantial crop losses and necessitating heavy insecticide use. The resulting mature plant has the Bt gene in all its cells and expresses the insecticidal protein in its leaves. Caterpillars ingest the toxin, which fatally damages the lining of the gut. The EPA considered 20 years of human and animal safety data before registering Bt corn (Ostlie et al, 1997)

The impact of Bt cotton adoption on insecticide use in India has been dramatic:

1. Reduction in insecticide use: Studies have shown that Bt cotton adoption has led to a 41% decrease in insecticide use on average. In some regions, the reduction has been even more significant, with reports of up to 80% decrease in insecticide applications.
2. Environmental benefits: The reduction in insecticide use has had positive effects on non-target organisms, including beneficial insects and birds. It has also reduced pesticide runoff into water bodies and soil contamination.
3. Economic impact: Farmers have benefited from reduced input costs due to lower insecticide use, as well as increased yields due to better pest control. Some studies estimate that Bt cotton has increased yields by 30-40% and profits by 50-60%.
4. Health benefits: The decrease in insecticide applications has reduced farmers' exposure to harmful chemicals, leading to fewer pesticide-related health issues.
5. Pest resistance management: While there have been concerns about pest resistance development, the overall reduction in insecticide use has helped in managing resistance to other chemical insecticides.

However, it's important to note that the success of Bt cotton in India has not been without challenges. There have been issues with the development of secondary pests, concerns about the long-term ecological impacts, and debates about the socio-economic effects on small-scale farmers. Additionally, there have been reports of bollworms developing resistance to Bt cotton in some areas, highlighting the need for ongoing research and integrated pest management strategies.

Between 1992 and 2019, Australian cotton growers have also been using Bt technology, reducing their use of insecticides as measured in grams/bale by 97%. Australian use of all types of pesticides went down by 18.2% in just five years between 2014 and 2019(Australian Cotton Sustainability Report 2019)

Despite these challenges, the adoption of Bt cotton remains a significant example of how advanced breeding techniques can contribute to substantial reductions in insecticide use.

Fertilisers

Reducing fertiliser use while maintaining crop productivity is a global challenge that many countries are addressing through innovative approaches. The European Green Deal, in particular, has set ambitious targets for reducing fertiliser use across the European Union. Several global examples demonstrate successful strategies for fertiliser reduction.

In China, the government launched a nationwide campaign in 2015 to achieve zero growth in fertiliser use by 2020. This initiative promoted precision agriculture techniques, soil testing, and improved nutrient management. As a result, China reported a 1.6% reduction in chemical fertiliser use between 2015 and 2018 while maintaining grain production growth.

India has been promoting the use of neem-coated urea since 2015. This approach slows down the release of nitrogen, reducing losses and improving nutrient uptake efficiency. Studies have shown that neem-coated urea can reduce nitrogen application by up to 20% without compromising crop yields.

In the United States, precision agriculture technologies have played a significant role in optimising fertiliser use. GPS-guided applicators, variable rate technology, and soil mapping have allowed farmers to apply fertilisers more efficiently. Some studies have reported fertiliser use reductions of 10-15% through these technologies while maintaining or even improving yields.

Brazil has made significant strides in reducing fertiliser use through biological nitrogen fixation in soybeans. By developing and widely adopting soybean varieties that efficiently fix atmospheric nitrogen, Brazil has dramatically reduced the need for nitrogen fertilisers in soybean production. This approach has been estimated to save over $10 billion annually in fertiliser costs.

In Australia, the development and adoption of enhanced efficiency fertilisers (EEFs) has helped reduce overall fertiliser use. These fertilisers release nutrients more slowly or in sync with crop demand, reducing losses to the environment. Some studies have shown that EEFs can reduce nitrogen application rates by up to 25% while maintaining yields.

Coming closer to home, The European Green Deal, launched in 2019, is a set of policy initiatives aimed at making the European Union climate-neutral by 2050. A key component of this deal is the Farm to Fork Strategy, which directly addresses agricultural sustainability, including fertiliser use. The Farm to Fork Strategy sets a target to reduce nutrient losses by at least 50% while ensuring no deterioration in soil fertility. This is expected to result in a reduction of fertiliser use by at least 20% by 2030.

To achieve these goals, the European Commission has outlined several approaches. These include an Integrated Nutrient Management Action Plan to address nutrient pollution at its source and increase the sustainability of the livestock sector. The EU is also promoting the adoption of precision farming techniques through its Common Agricultural Policy (CAP) and research funding programmes.

The strategy aims to expand organic farming, with a goal of having at least 25% of EU agricultural land under organic farming by 2030, which typically uses less synthetic fertiliser. Improved soil management practices like crop rotation, cover cropping, and reduced tillage are being promoted to improve soil health and reduce fertiliser needs.

The European Green Deal also encourages the circular economy in agriculture, promoting the recycling of organic waste into renewable fertilisers to reduce reliance on synthetic inputs. Significant investments are being made in research to develop new, low-input farming systems and more efficient fertilisers. Additionally, the strategy emphasizes the importance of farm advisory services to help farmers implement sustainable nutrient management practices.

Figure 13: NUE trials, Denmark, SEGES. Photo: author's own.

Within the EU, Denmark is taking significant strides with reducing fertiliser use to incredibly relying almost exclusively on groundwater for its drinking water supply, with about 99% of all drinking water in the country sourced from underground aquifers. This unique situation has led to a strong focus on groundwater protection and sustainable water management practices. Now, when you want to register a fertiliser into the Danish market, there are significant taxes on products which make them almost unpalatable to use.

The implementation of these strategies is expected to not only reduce fertiliser use but also decrease greenhouse gas emissions, improve water quality, and enhance biodiversity across the EU. While the European Green Deal sets ambitious targets, it's important to note that its implementation is still in progress, and the full impact of these measures will become clearer in the coming years. The success of this initiative could provide valuable lessons for other regions looking to reduce fertiliser use while maintaining agricultural productivity.

CHAPTER 9: BREEDING FOR THE GREATER GOOD AND THE ENVIRONMENT

Summary

- There are a large number of research endeavours across the globe that are actively pursuing Plant Trait improvements
- We are still in a stage of making more efficient the practical application of the CRISPR components and protocols in order to optimise research
- This includes the codification of whole genome edited libraries for more crop types whilst extensive progress on this has occurred in soybean, maize, rice and tomatoes many cereal crops remain totally unchartered
- As such the results discussed should be considered as early signs of an impending second green revolution rather than its crescendo

Nutrient Adaption

Breeding for nutrient adaptation with a focus on root length and depth is an important strategy in developing crops that can thrive in nutrient-poor soils, which are common in many developing regions. This approach aims to enhance a plant's ability to explore larger soil volumes and access nutrients that may be scarce or located deeper in the soil profile. Here's an overview of this breeding strategy:

Figure 14: Root columns, Copenhagen University, Denmark. Photo: author's own.

The importance of root architecture in nutrient acquisition stems from the fact that nutrients in soil are often unevenly distributed. Some essential nutrients, like phosphorus, tend to be concentrated in the topsoil, while others, such as nitrogen and water, can be more abundant in deeper soil layers. By modifying root architecture, breeders aim to develop crops that can more efficiently capture these resources.

Root length and depth are key components of root architecture that significantly influence a plant's nutrient acquisition capacity. Longer roots can explore a greater soil volume, increasing the chances of encountering nutrient-rich patches. Deeper roots can access water and nutrients that are beyond the reach of shallow-rooted plants, which is particularly beneficial in drought-prone areas or in soils where nutrients have leached to lower layers.

The breeding process for enhanced root length and depth involves several steps:

- Phenotyping is a crucial first step in this breeding process. Traditional methods involve labour-intensive excavation and measurement of root systems. However, modern techniques have made this process more efficient and accurate. These include:
- Shovelomics: A field-based method where roots are excavated, washed, and analysed for various traits including depth and length.
- Clear pot systems: Seedlings are grown in transparent pots, allowing for non-destructive observation of root development.
- Rhizotrons: These are underground facilities with glass walls that allow direct observation of root growth in soil.
- X-ray computed tomography: This technology enables 3D imaging of roots in soil without disturbing the plant.
- Minirhizotrons: Transparent tubes inserted into the soil allow for repeated observations of root growth over time.

Once phenotyping data is collected, breeders identify genetic sources of desirable root traits. This often involves screening diverse germplasm collections, including landraces and wild relatives, which may have evolved root systems adapted to nutrient-poor conditions.

Drought Resistance Adaption

Plant breeding for drought resistance adaptation is a critical area of agricultural research aimed at developing crop varieties that can maintain productivity under water-limited conditions. This approach is becoming increasingly important as climate change leads to more frequent and severe droughts in many parts of the world.

The process of breeding for drought resistance involves identifying and incorporating traits that allow plants to better cope with water scarcity. These traits can be broadly categorised into three main strategies: drought escape, drought avoidance, and drought tolerance.

Drought escape refers to the ability of plants to complete their life cycle before severe water stress occurs. This often involves breeding for early maturity or shorter growth cycles. For example, breeders have developed wheat varieties that mature earlier, allowing them to complete grain filling before the onset of terminal drought stress.

Drought avoidance involves traits that help plants maintain high water status even under water-limited conditions. This can include developing deeper root systems to access water from lower soil layers, improving water use efficiency, or reducing water loss through transpiration. For instance, rice varieties have been developed with deeper, more extensive root systems that can access water from deeper soil layers during drought periods.

Drought tolerance refers to the plant's ability to maintain physiological functions even under low water potential. This can involve mechanisms such as osmotic adjustment, where plants accumulate solutes in their cells to maintain turgor pressure, or the production of protective compounds like antioxidants. Sorghum, for example, has been bred for improved stay-green traits, allowing leaves to remain photosynthetically active for longer periods under drought stress.

The breeding process for drought resistance typically begins with screening diverse germplasm collections for drought-adaptive traits. This may involve evaluating plants under controlled drought conditions in greenhouses or in field trials in drought-prone areas. Advanced phenotyping techniques, such as thermal imaging to measure canopy temperature (an indicator of drought stress), or root imaging systems, are increasingly being used to assess drought-related traits.

Figure 15: Heat lamps used to identify flag leaf roll in different varieties in adaption to heat stress/drought, CIMMYT. Photo: author's own.

Once promising traits or varieties are identified, breeders use various methods to incorporate these traits into elite cultivars. Traditional crossbreeding remains a cornerstone of drought resistance breeding, but it is increasingly supplemented by molecular breeding techniques. Marker-assisted selection, for instance, allows breeders to identify plants carrying desired drought-resistance genes without having to grow them to maturity or expose them to drought conditions.

Genomic selection is another powerful tool in drought resistance breeding. This approach uses genome-wide markers to predict the breeding value of individuals for complex traits like drought resistance, potentially accelerating the breeding process.

Genetic engineering and gene editing technologies like CRISPR-Cas9 are also being explored to enhance drought resistance. These techniques allow for the precise introduction or modification of genes involved in drought response. For example, researchers have used genetic engineering to enhance the expression of genes involved in osmotic adjustment or antioxidant production in various crops.

It's important to note that breeding for drought resistance often involves trade-offs. For instance, deeper root systems may come at the cost of above-ground biomass, or early maturity might reduce overall yield potential under favourable conditions. Therefore, breeders must carefully balance drought resistance with other important agronomic traits.

Moreover, drought resistance is a complex trait influenced by multiple genes and environmental factors. As such, breeding programmes often focus on developing varieties with broad adaptation rather than extreme resistance to severe drought. This approach, known as breeding for yield stability, aims to develop varieties that perform consistently across a range of water-limited environments.

Collaborative international efforts play a crucial role in drought resistance breeding. Organisations like the International Maize and Wheat Improvement Centre (CIMMYT) and the International Rice Research Institute (IRRI) conduct extensive drought resistance breeding programmes and share germplasm and knowledge globally.

Looking ahead, the integration of advanced genomics, phenomics, and data science is expected to accelerate progress in breeding for drought resistance. Techniques like genome editing may allow for more precise and rapid introduction of drought-adaptive traits. Additionally, there's growing interest in exploring the potential of wild relatives and landraces, which may harbour novel drought resistance mechanisms evolved over millennia.

Developing World Needs

Plant breeding for developing world needs is a crucial aspect of global food security and nutrition efforts. This focus area aims to address specific challenges faced by farmers and consumers in low and middle-income countries, including nutrient deficiencies, climate resilience, and productivity in resource-limited conditions. Two notable examples of such breeding efforts are iron-fortified wheat and biofortified purple wheat flour.

Iron-fortified wheat:

Iron deficiency is one of the most common nutritional disorders worldwide, particularly affecting women and children in developing countries. To combat this issue, plant breeders have been working on developing wheat varieties with increased iron content.

The process of breeding iron-fortified wheat involves several steps:

1. Identifying genetic sources of high iron content: Researchers screen diverse wheat germplasm, including wild relatives and landraces, to find lines with naturally high iron levels.

2. Crossing and selection: High-iron lines are crossed with agronomically superior varieties, followed by multiple generations of selection for both iron content and desirable agronomic traits.
3. Bioavailability testing: It's not enough for wheat to contain more iron; the iron must also be in a form that the human body can absorb. Researchers conduct studies to ensure the increased iron is bioavailable.
4. Field testing: Promising lines are tested in various environments to ensure they perform well under different growing conditions.
5. Nutritional impact studies: Before release, the new varieties are evaluated in human studies to confirm their effectiveness in improving iron status.

Successful examples of iron-fortified wheat have been developed by organisations like the International Maize and Wheat Improvement Centre (CIMMYT). These varieties can contain up to 40% more iron than standard varieties and have shown promise in addressing iron deficiency in target populations.

Biofortified purple wheat flour represents another innovative approach to improving nutrition through plant breeding. Purple wheat derives its distinctive colour from anthocyanins, potent antioxidants with potential health benefits. Breeding efforts for purple wheat aim to develop varieties that are both high-yielding and rich in these beneficial compounds.

The development of biofortified purple wheat flour begins with exploring genetic resources to identify wheat lines with genes for purple pigmentation. These genes are then introgressed into high-yielding wheat varieties through crossing and selection. Breeders focus on optimising anthocyanin content while maintaining or improving yield and other agronomic traits.

As the end product is flour, it's crucial to ensure that the purple wheat varieties meet necessary quality standards for milling and baking. The stability of the purple colour and anthocyanin content under various storage and processing conditions is also evaluated. Nutritional analyses are conducted to assess the potential health benefits of the biofortified purple wheat flour.

Purple wheat flour not only offers potential nutritional benefits but also creates opportunities for value-added products in developing countries, potentially providing economic benefits to farmers and local food processors.

Despite their promise, these breeding efforts face several challenges. Adoption barriers may exist if farmers are hesitant to grow new varieties without clear market demand or price premiums. Consumer acceptance, particularly for visually distinct products like purple wheat flour, may require educational efforts. Regulatory hurdles may also arise, especially if genetic engineering techniques are employed in the breeding process.

Maintaining agronomic performance is crucial; nutritional improvements must not come at the cost of yield or disease resistance. Environmental variability is another consideration, as nutrient content can be influenced by soil conditions and climate. Therefore, varieties need to be tested across diverse environments to ensure consistent performance.

CHAPTER 9: CONCLUSIONS

Gene editing technologies like CRISPR are indeed at the forefront of a potential agricultural revolution, offering a promising pathway to creating crops that require fewer inputs - such as water, pesticides, herbicides, and fertilisers - while simultaneously improving overall yield, resilience, and quality. These advancements represent a significant leap forward in our journey towards more sustainable and efficient farming practices. The potential benefits are multifaceted, extending beyond mere input cost reduction for farmers to encompass broader environmental and societal impacts.

The ability to precisely modify plant genomes opens up unprecedented possibilities for crop improvement. For instance, we could develop crops with enhanced natural pest resistance, reducing the need for chemical pesticides. Similarly, plants could be engineered to use water and nutrients more efficiently, decreasing the reliance on irrigation and fertilisers. Drought-tolerant varieties could help farmers maintain productivity in the face of climate change, while crops with improved nutritional profiles could contribute to addressing global malnutrition.

However, it's crucial to temper our optimism with a realistic understanding of the challenges ahead. Significant optimisations and efficiencies related to gene editing protocols and gene trait libraries are still necessary across all major plant species before more widespread innovations become available. This process requires substantial investment in research and development, as well as time to ensure the safety and efficacy of these new varieties.

Moreover, the successful implementation of gene-edited crops will depend on factors beyond the laboratory. Public acceptance, regulatory frameworks, and market dynamics will all play crucial roles in determining the extent to which these technologies are adopted. Education and transparent communication about the benefits and potential risks of gene editing will be essential in gaining public trust and support.

As we look to the future, the potential of gene editing to transform agriculture is immense. We can anticipate breakthroughs that will not only reduce the ecological footprint of farming but also help address some of the most pressing global challenges of our time, including climate change, food security, and environmental conservation. By enabling the development of crops that are more resilient to pests, diseases, and environmental stresses, gene editing could play a pivotal role in ensuring food production keeps pace with a growing global population while minimising environmental impact.

Furthermore, the reduction in input requirements could have far-reaching economic implications for farmers, potentially improving profitability and sustainability of agricultural operations, particularly in developing regions where access to inputs may be limited or costly.

In conclusion, while the road ahead may be complex and challenging, the potential benefits of gene editing in agriculture are too significant to ignore. As we continue to refine these technologies and address the associated challenges, we move closer to a future where agriculture is not only more productive but also more sustainable and environmentally friendly. The journey towards this future will require collaboration between scientists, policymakers, farmers, and the public, but the potential rewards—in terms of food security, environmental protection, and agricultural sustainability—make it a journey well worth undertaking.

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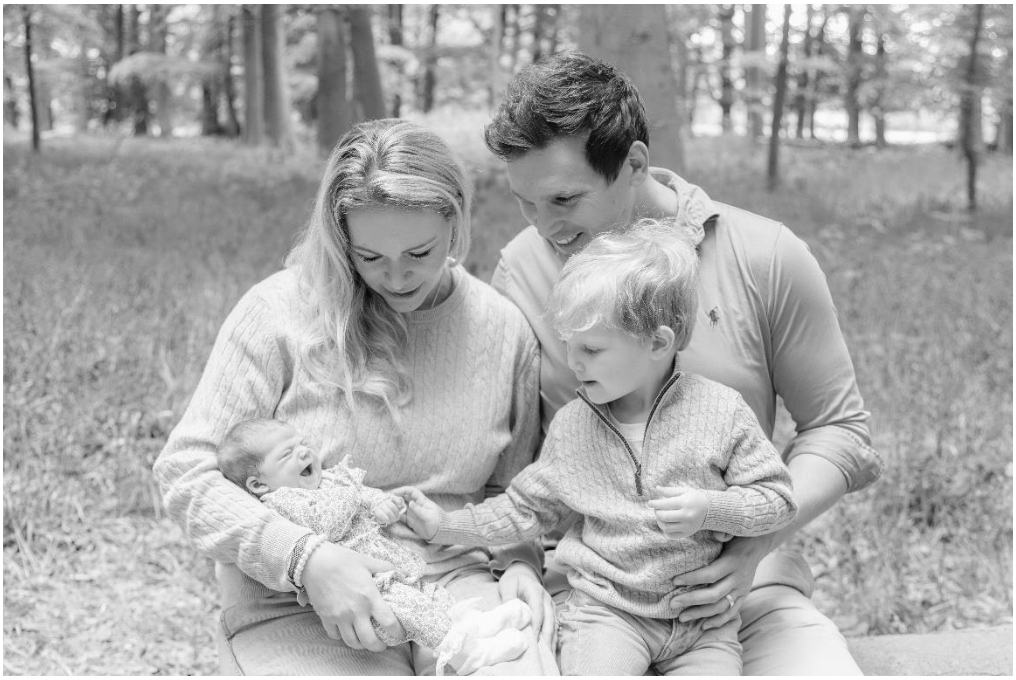

Figure 16: The author with her young family. Photo: author's own.

REFERENCES

1. https://www.gov.uk/government/statistics/land-use-in-england-2022/land-use-statistics-england-2022
2. https://www.gov.uk/government/publications/farming-evidence-pack-a-high-level-overview-of-the-uk-agricultural-industry/farming-evidence-key-statistics-accessible-version
3. https://nph.onlinelibrary.wiley.com/doi/pdf/10.1111/j.1469-8137.2009.02884.x
4. https://www.bbc.co.uk/news/science-environment-54432589
5. https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2023.1247707/full
6. https://onlinelibrary.wiley.com/doi/10.1111/pbi.14320

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