Impact of hybrid potato

The future of hybrid potato from a systems perspective

edited by:
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Wageningen Academic Publishers

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Sponsored by KIT Royal Tropical Institute and Dutch Research Council - Applied and Engineering Sciences (NWO-TTW).

Photo cover: © Solynta 2022

EAN: 9789086863921
e-EAN: 9789086869466
ISBN: 978-90-8686-392-1
e-ISBN: 978-90-8686-946-6
DOI: 10.3920/978-90-8686-946-6

First published, 2023

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Foreword

The emergence of hybrid potato breeding is discussed in this book as a radical innovation with potentially far-reaching implications for global food security and its related dimensions of poverty release and nutritional security. The present potato cultivars already show high yields under favourable growing conditions. Yet, farmers in Africa and beyond still struggle with a large yield gap. This large yield gap is partly due to the low quality of farm-saved seed potato tubers as the informal system of seed tuber production is still dominant in low-income countries. When introducing hybrids with the aim to reduce this yield gap, including high-quality starting material and well adapted cultivars, we also need to address the production system as a whole. Can we have a system that allows smallholder farmers to grow into emerging entrepreneurs with potato as a base crop? Food and nutritional security require food that is affordable for the urban poor while offering income for the rural poor. This is only possible with an efficient organisation of the food chain as a whole. The challenge is to help farmers realise the potential of the potato crop.

A crucial issue from the economic point of view is how to breed potato cultivars that fit both small- and large-scale producers. As a wide range of potato cultivars are needed to serve the potato sector everywhere, hybrid breeding as a new approach can help diversify the seed system to make it suitable for every set of biophysical and socio-economic conditions. Overall, the introduction of hybrid seed requires an integrated chain approach and coordination at different policy-making levels. So, partnerships are essential, no single stakeholder can do this alone. Looking forward to the longer term, potato may serve many uses in the biobased economy and also play a role in replacing animal proteins. These modern uses need to be translated into new breeding goals.

This volume addresses these various issues both at a comprehensive systems level and in more detailed and rich discussions of hybrid potato variety development and the organisation of seed value chains. Its contents clearly indicate the need for joint efforts and common platforms, aiming to advance hybrid potato breeding initiatives and to exchange lessons learned on innovation and business models that work.

Sjoukje Heimovaara
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Chapter 1. Introduction

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Abstract

Potato is an important crop for food security. However, it is very vulnerable to diseases and pests and these are partly seed-borne and therefore transmitted from one generation to the next. Breeding is cumbersome while multiplication is slow. These issues can be solved by a new technology: hybrid breeding based on true potato seed. This book gives an overview of relevant developments in creating new opportunities making use of this technology. This introductory chapter describes the aims of the book, provides a main agenda for debate on this new technology and outlines the structure of the book and briefly indicates the contents of its chapters.

Keywords: hybrid breeding, true potato seed, *Solanum tuberosum*, agro-industrial context, international development context

1.1 Preamble

Potato (mainly *Solanum tuberosum* L.) is arguably the world's third food crop for human consumption and grown all over the world. Accordingly, there is an important role for the potato in achieving global food security today and in the future. However, as a vegetatively propagated tuber crop the potato is highly vulnerable to diseases and pests, and its bulky and water-rich produce is difficult to transport and store. On a global level, propagation, storage and distribution of high-quality seed tubers is one of the main constraints that limit production (Tadesse *et al.*, 2020; Schulte-Geldermann *et al.*, 2022). In developing countries, the yield per hectare is often low, mainly due to the use of poor starting material and sub-optimal cultivation methods (Gildemacher *et al.*, 2009; Thomas-Sharma *et al.*, 2016). With the abundant use of chemical crop protection products, potato cultivation also has a high environmental impact. Therefore, there is a pressing need for potato varieties that can be grown in more sustainable ways, with higher yields in different climate zones and under diverse agro-ecological conditions (Edelenbosch and Munnichs, 2020).

Compared with other major crops, breeding of the common tetraploid potato is a cumbersome and time-consuming process and genetic improvement has been slow. This is partly caused by the large number of traits for which breeders need to select (especially for potatoes that are grown as table potatoes or for the food processing industry), but partly also due to the tetrasomic inheritance. In the last decade there has been a concerted effort to develop a novel approach in potato breeding

Paul C. Struik, Peter R. Gildemacher, Dirk Stemerding and Pim Lindhout (eds.)

DOI: 10.3920/978-90-8686-946-6_1, © D. Stemerding *et al.* 2023

which makes available potato starting material for cultivation in the form of diploid hybrid true potato seed (Lindhout *et al.*, 2011; Jansky *et al.*, 2016; Lindhout *et al.*, 2018). This seed is devoid of (almost all) contaminating pathogens and pests and can be rapidly propagated, and easily transported and stored. The diploid hybrid potato also promises to significantly accelerate the process of breeding compared to conventional practices today (Lindhout *et al.*, 2018; Su *et al.*, 2020). As a result, this new hybrid potato may provide a highly promising response to the global challenges of food security, sustainability and climate change.

1.2 Aims of the book and main agenda for debate

The promises of hybrid potato breeding, the topic of this book, strongly resonate with a more general debate in the literature about the role of plant breeding in responding to the United Nations Sustainable Development Goals (SDGs) (Zimmer and De Haan, 2019). Especially relevant in this context is SDG 2, with the achievement of global food security, improved nutrition and promotion of sustainable agriculture as its major aims. How could hybrid potato breeding contribute to these goals? In order to better understand the potential of this innovation, this book focuses on the societal goals and system conditions that may guide and shape the future of hybrid potato. In considering this future, two issues can be identified as the main topics for debate:

- Hybrid breeding will be an important driver for rapid variety development, creating new added value, both commercially and from a societal point of view. This raises questions about the needs to which this variety development should respond. How to connect commercial interests and values with innovation that contributes to the common good, responding to food security, sustainability and climate change as major societal challenges expressed in the global sustainable development goals?
- Hybrid varieties will become available as true potato seeds that can be propagated, stored and transported as a commercial (or public) source of clean and high-quality planting material, but with less growth vigour than the commonly used seed tubers. This creates new opportunities and challenges for the organisation of potato value chains, with cultivation systems that may vary from direct sowing by farmers, to using plantlets or (mini)tubers produced in special nurseries. What would be the implications of these various system choices for different stakeholders in the potato sector?

To discuss these issues, this book brings together the visions, knowledge and experiences from a wide community of scholars and professionals, representing the worlds of breeding, business, international development, policy making and a variety of disciplines ranging from the natural to the social sciences. Most contributions to this book stem from an international online conference about the future of hybrid potato, organised with support of the Netherlands Food Partnership, that took place on November 30th, 2020, with more than 150 participants worldwide (Stemerding *et al.*, 2020).

1.3 Two system contexts

In this book, the hybrid potato is discussed as a system innovation which may affect almost every step in the potato value chain. Accordingly, hybrid potato breeding and hybrid true potato seed are viewed together as a potentially disruptive and game changing technology, involving all players in the sector. For a further understanding of the impact of this innovation, the hybrid potato is considered in two different global system contexts, including on the one hand the agro-industrial context of Western Europe, and on the other hand the international development context of Africa.

A well-developed agro-industrial system, like the potato sector in Western Europe, may lend itself in many ways to the introduction of a hybrid potato, although it may also have to undergo significant system transformations to enable a successful introduction of hybrid varieties and seed. In developing countries, on the other hand, and in Africa in particular, we find a mostly informal potato sector dominated by smallholder farmers. In this international development context, a hybrid potato offers new opportunities, but the conditions for potato cultivation with commercially sourced hybrid seed are much more challenging. By considering the future of hybrid potato in both system contexts, the agenda for debate is elaborated in this book in more concrete, context-specific ways.

1.4 Structure of the book and chapter contents

The chapters in this book cover three related thematic subjects. In the second and third chapter the hybrid potato breeding system is introduced and different scenarios are discussed as possible futures for this system, including the implications of these futures for food security, sustainability, and public policy making. The next two chapters focus on the prospects and impacts of hybrid potato innovation for the Dutch potato sector as a vibrant centre in the international potato world, and discuss ensuing policy challenges in the field of international seed regulation. These two chapters specifically relate to the agro-industrial system context in which hybrid breeding must gain a foothold as a potentially disruptive innovation. In the next five chapters the focus of the book shifts to the international development system context. These chapters include discussions of the potential impact of hybrid potato in Sub-Saharan Africa, the role and responsibilities of corporations in this context, and the different ways in which public-private partnerships may help to harness hybrid potato breeding for smallholder farmers. On the basis of these contributions, the final chapter of this book addresses the major findings, in particular regarding the complex nature of hybrid potato innovation, the goals of hybrid variety development, and the organisation and inclusiveness of hybrid potato seed and production chains.

In Chapter 2, the approach and potential of hybrid potato breeding is discussed in comparison with traditional potato breeding (Lindhout and Struik). By generating and selecting inbred homozygous diploid parent lines, a hybrid diploid potato breeding programme can be established which enables faster and more predictable breeding than traditional tetraploid breeding. The multiplication of uniform hybrid seeds can be done under strict phytosanitary conditions and is much more efficient than the multiplication of seed tubers. Thus, hybrid breeding and hybrid true potato seeds have great potential to contribute to global food and nutrient security. However, the introduction of hybrid breeding is also challenging as it involves a potentially disruptive system innovation, changing many steps in the seed and potato production chain.

Chapter 3 focuses on the wider system conditions that may shape the future of hybrid potato (Edelenbosch and Stemerding). It describes how this future has been explored in an interactive process with a variety of stakeholders from the potato sector and beyond. The aim of this process was to foster responsible innovation by seeking ways in which innovation in potato breeding can respond to major societal challenges. With the input of the participants, scenarios were developed showing how the future of hybrid potato may take different directions in a complex interplay of technological and societal developments, with different implications for food security and sustainability on a global level. The participants discussed both the plausibility and desirability of these different scenarios and the major lessons that could be drawn from this scenario exercise.

In Chapter 4, the position of the Netherlands as the largest exporter of seed potato tubers worldwide is put in historical perspective (Louwaars). The chapter explains how the geographical location of the Netherlands in combination with political, institutional and technological developments have resulted in the unique position of the country in the area of seed potato tubers. These developments include public support for potato breeding science, collaboration between farmer-breeders, companies and the government, an early operating system for the protection of plant breeders' rights, and seed quality controls and phytosanitary services as important policy issues of concern. The chapter also discusses the implications of new technological developments like hybrid breeding for the leading position of the Netherlands.

Chapter 5 addresses the global regulatory frameworks that have been established in the agro-industrial context for registration, protection and commercialisation of potato as a crop that is commercialised via seed tubers (Meijerink). The chapter discusses in a systematic mode to what extent existing frameworks apply to new hybrid varieties and true seed, and to what extent these frameworks need to be adjusted or even newly created. In considering these issues the chapter also refers to established requirements and rules for hybrid vegetable crops belonging to the same nightshade family as potato. Although current systems for these hybrid vegetables could be used as examples to legislate hybrid true potato seeds, the routes to do so may not be easy.

Chapter 6 discusses the potential significance of the hybrid potato for potato cultivation in Sub-Saharan African (Gildemacher and Ter Steeg). In this international development context, access to high-quality seed potato tubers remains a most important barrier for intensification of smallholder potato production. On the basis of a seed potato and value chain analysis, the chapter explores how hybrid breeding and seed could improve the availability and use of high-quality planting material and break the deadlock of stagnating productivity levels. Internationally and commercially produced hybrid potato seed can be made available to smallholder farmers through a decentralised system of local multiplication, producing plantlets or tubers as high quality and clean planting material. Another major opportunity of hybrid breeding is variety development tailored to the needs of African smallholder farmers.

Chapter 7 also focuses on the opportunities offered by hybrid true potato seed to foster the development of the different potato sectors in East Africa (Den Braber, De Vries, Kacheyo, Struik and Descheemaeker). For a better understanding of the merits of hybrid potato seed in an international development context, this chapter takes the earlier experiences with True Potato Seed

(TPS) as a starting point, showing that TPS-based potato production systems are feasible in a wide variety of agroecological and socioeconomic circumstances. However, a crucial requirement for an effective and inclusive introduction of the novel hybrid true potato seed, is the mutual alignment between the technological characteristics of this innovation and the diverse needs, preferences and realities of African potato farmers. Therefore, the chapter emphasises the involvement of farmers and other stakeholders as a precondition for responsible innovation in potato breeding.

Chapter 8 highlights recent experiences of Dutch vegetable seed companies with the introduction and marketing of improved hybrid varieties in an international development context, focusing on tomato in Tanzania and shallot in Indonesia (Ter Steeg and Gildemacher). By considering the – seed, farm and market – system transformations that were required for a successful introduction of hybrid varieties in these cases, the authors draw lessons for hybrid potato seed innovation. The success of the introduction of hybrid potato will depend on the entire systemic context, and the magnitude of the systemic changes required for the introduction of hybrid seed and varieties is an important indicator of the chance of success. The promises of hybrid potato may fuel the necessary change of the seed, farm and market system, but the challenge is to find a balance between disruption and integration.

Chapter 9 focuses on Dutch potato breeding companies who are world leaders in the export of certified seed potato tubers and are also in the position to play a pivotal role in hybrid breeding (Swart and Van de Poel). The chapter explores how these companies perceive their responsibility with regard to food security and sustainability as Sustainable Development Goals (SDGs). It shows that firms indeed keep these goals in focus from a Corporate Social Responsibility (CSR) point of view. However, whereas firms connect breeding as their private core business with CSR and SDGs in a quite straightforward way, the chapter emphasises that food security and sustainability are complex societal challenges, whereby hybrid breeding needs to be considered as a common good, and CSR requires a collective effort, with cooperation between firms, public institutions, civil society and farmers' organisations.

Chapter 10 again addresses the issue of cooperation, arguing that neither the private nor the public sector can fully harness the potential of hybrid diploid breeding alone (Beumer and Almekinders). The central question of this chapter is how public-private collaborations can best be organised to enable access for smallholder farmers to the benefits of hybrid potato breeding. It explores – from a commons perspective – four models for institutionalising public-private partnerships and assesses the potential of each model for overcoming the challenges of access for smallholder farmers. A better understanding of the strengths and weaknesses of these different models might serve as a starting point for the public and private sectors to come together and discuss how they can combine their forces for the benefit of smallholder farmers around the world.

Chapter 11 summarises the major findings from the different chapters for both the agro-industrial and international development context, focusing on hybrid variety and seed value chain development as the major topics for debate (Stemerding, Struik, Lindhout and Gildemacher). In the agro-industrial context, hybrid potato may transform as well as strengthen established business models and also creates a need for adjustment of global regulatory frameworks. In the international development context, the introduction of hybrid potato will require either transformation of existing seed, farm and market systems, or integration in these systems. Public-private collaboration will be needed to facilitate the development and dissemination of varieties that are suited to the specific conditions and needs of smallholder farmers, also responding to the challenges of poverty, food security and climate change.

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Chapter 2. Hybrid potato breeding and production systems

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Abstract

In this chapter, we describe the technical aspects of hybrid potato breeding, the implications for cultural practices, cropping systems, product development and global food security. Diploid hybrid breeding allows the breeders to focus on selecting the right combination of parents instead of selecting the right clone. Combining the most suitable parents results in homogeneous hybrids that can be tested in different environments. It allows to stack resistance genes, stack complex traits, create uniform offspring, makes breeding results more predictable, the production of a new cultivar much faster and the possibilities for innovative products and value creation much more abundant. However, diploid breeding followed by a seed system based on true potato seed may cause disruptive change, for breeders, regulators and policy makers, seed growers, ware growers, traders, and consumers. The biggest bottlenecks are in the agronomy of growing a crop from very tiny true potato seeds (TPS). Options include direct sowing, producing transplants or producing seedling tubers. A paradigm shift in the production system must create the conditions for a successful hybrid TPS value chain. Many companies and research institutes are now developing hybrid breeding programmes in potato, mostly based on diploid breeding. The potential is huge, including potato production in tropical lowlands on the basis of heat and drought tolerant hybrids, resistance against bacterial diseases and viruses, and high-quality, healthy and innovative potato products, thus contributing to a sustainable, food-secure, productive potato production value chain.

Keywords: cropping system, production hybrid seeds, logistics

2.1 Introduction

Hybrid breeding is an advanced breeding system, whereby inbred lines are generated through repeated selfings and crossed to generate hybrids. The inbred lines allow breeders to better control genetics and this results in more efficient breeding. Many food crops have been adapted to hybrid breeding (Ter Steeg *et al.*, 2022). Potato has been recalcitrant as the tetraploid nature of commercial potato cultivars and inbreeding depression have hampered the development of pure inbred lines. Moreover, potato is traditionally propagated via seed tubers, while the product of hybrid breeding is true seed. This different type of starting material further complicates the application of

DOI: 10.3920/978-90-8686-946-6_2,

hybrid cultivars in potato tuber production, although it strongly increases the multiplication rate, thereby reducing the number of years between making the cross and producing enough seed for commercial use. The limitations caused by tetrasomic inheritance and inbreeding depression have been overcome and at present, there are hybrid potato breeding programmes in the Netherlands, USA and China (Jansky *et al.*, 2016; Lindhout *et al.*, 2011, 2018; Zhang *et al.*, 2021).

In this chapter, the technical aspects of hybrid potato breeding and the implications for cultivation technologies and product development are briefly outlined. Attention is also paid to additional changes in the potato production systems, when implementing hybrid potato cultivars. Finally the potential impact on the global food security is addressed.

2.2 Traditional potato breeding

Traditional potato breeding starts with making crosses between tetraploid cultivars that have four sets of chromosomes (Figure 2.1A). As both parents have a wide genetic variation of genes per sister chromosome (are 'heterozygous'), the offspring will segregate into a very wide collection of genetic recombinations. So, all individuals of the progeny are genetically different. The art of breeding is to identify the best genotype in this progeny, as a potentially new cultivar; such a new genotype is subsequently multiplied clonally.

In a typical breeding programme, some ten to hundred thousands seeds are generated, sown and seedlings are produced to produce first-year tubers, designated 'F1 clones'. These clones are grown in the field to evaluate the plants and tubers in the first year. This is repeated five to ten years, while selections are done in each generation to remove clones with unacceptable quality, low yields or high susceptibilities for diseases. Advanced technologies like marker assisted selection can also be applied, mainly to select for the presence of disease resistance genes. The number of selected clones is gradually diminished to only a few and the numbers of plants per clone that are tested in the field, gradually increase. Finally, the most advanced clones are tested at several locations in repeated field trials, with larger plot sizes (Stockem *et al.*, 2022). When such selected clones have shown added value compared with existing cultivars in the market, they can be considered as a potentially new cultivar that are going to be commercialised. Such a clone is then registered at national seed lists (Chapter 5) and tubers are propagated in the field for five to ten generations to produce sufficient numbers of seed tubers to serve the farmers as starting material for the production of ware potatoes. The reproduction factor of potato tubers is about ten. So, to produce one million seed tubers (enough to plant 20 ha), starting from one single seed tuber, will take six years.

The ware potato tubers are produced as a fresh product to consumers' markets or as a bulk product to processing plants, where they are processed into fries, chips, or other products. Usually, specialised companies produce the seed tubers. They are experts in avoiding contaminations with seed-borne viruses, bacteria, fungi and other pathogens, as well as seed-borne pests, such as nematodes, to maintain a high quality level of the seed tubers. However, it is unavoidable that some contamination occurs. Many countries have a severe governance system in place that monitors seed tuber quality and provides certification based on strict criteria, on continuous

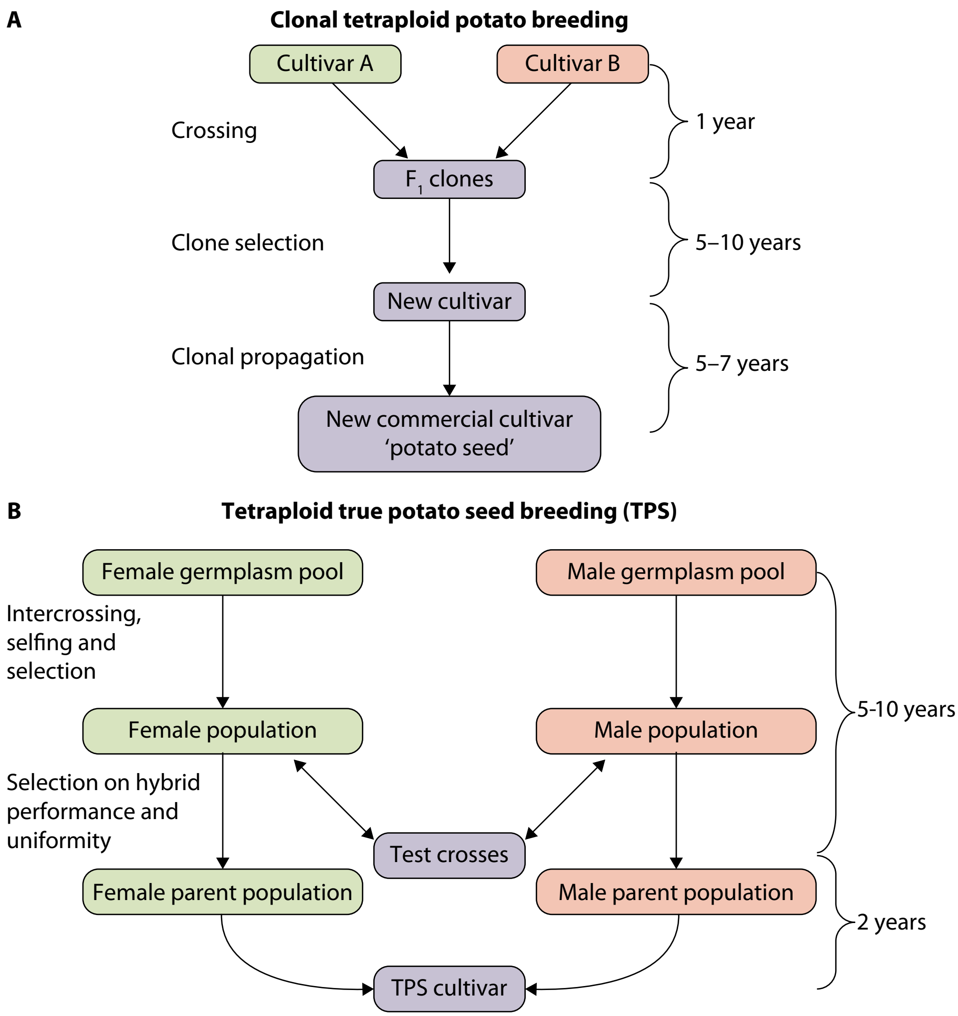

Figure 2.1. Schematic representation of two contrasting potato breeding systems. (A) traditional potato breeding; (B) hybrid potato breeding.

degradation to a lower level of certification and on a flush-out scheme. After several generations of seed tuber multiplication, the quality may drop below the level that is required for the lowest grade of certification, and the multiplication of this badge will stop (it will be flushed out). Usually, each year breeding companies start a fresh multiplication round for each cultivar with *in vitro* plantlets that are completely free of any pathogen or pest. Breeding companies may produce large quantities of mini-tubers per plant in the greenhouse, to give a boost to the production of clean seed tubers, that are subsequently multiplied as described above.

These formal systems are in place in the higher income economies. Farmers in low- and middle-income economies in Asia, Africa and South America usually produce their own seed tubers, which is considered as an informal system without external quality control or certification. The multiplications of seed tubers may continue for ten to twenty generations or more (Africa: Gildemacher *et al.*, 2009; South America: Navarrete *et al.*, 2022). As these conditions are not optimal, the seed tubers will rapidly accumulate diseases (so-called seed degeneration), which reduces the yield of the crop produced from these seed tubers. The yields in the informal systems are usually about ten tons per ha, about five times lower than the productions in formal systems. This yield gap is caused by low quality seed tubers and low-tech cultivation systems. Globally, 90-95% of seed tubers are produced in the informal system (Thomas-Sharma *et al.*, 2016).

2.3 Hybrid true potato seed: hybrid potato breeding, principle and practice

Hybrid potato breeding starts with the generation of inbred lines from the breeders' germplasm. After several rounds of inbreeding all genes on sister chromosomes are identical. Such a parent line is considered 'homozygous' and the genes are 'fixed': the parent line can only pass a unique and fixed composition of genes to the progeny. When both parents are fixed, the genetic make-up of their progeny can reliably be predicted from the characteristics of the parent inbred lines. Each individual plant has an identical chromosome set of both parents and is heterozygous but all progeny plants are genetically identical, which results in a uniform phenotype (Figure 2.1B).

So, in a hybrid breeding programme, most emphasis is on the selection of superior inbred lines that are generated by repeated selfings. This is efficiently done with diploid genotypes that have one pair of each chromosome, as in each selfing generation the frequency of heterozygotes is halved. For some typical pictures, see Figure 2.2. The development of homozygous inbred lines via repeated selfings takes many more generations in a tetraploid genotype with four sets of chromosomes (Lindhout *et al.*, 2018). This is the main reason why hybrid potato breeders prefer to use diploid genotypes.

A hybrid potato breeder can take advantage of genetics by studying the inheritance of the most important traits. For instance, the heritability of crisp frying quality is high. This means that the performance of the hybrids can be predicted from the performance of the parents (Figure 2.3). The heritability of most of the qualitative traits of potato tubers is high (Adams *et al.*, 2022). Inbred lines are thoroughly tested to select parent lines with good combining abilities (i.e. lines that show the ability to combine well with each other during the hybridisation process), thus allowing that desired genes or features are efficiently passed down to their progenies. This selection process is so efficient that the number of hybrids tested can be limited to merely several hundreds per season. So, where in a traditional breeding programme most emphasis is on the selection of clones that are clonally propagated, in a typical hybrid breeding programme, most emphasis is on the selection of the right combination of parent lines. New hybrids are tested in the field and the best ones are repeatedly tested at several locations and environments to eventually select the most robust hybrids for registration and commercialisation (Stockem *et al.*, 2020). However, the hybrid true potato seed technology has certain consequences for breeding and multiplication that need to be described in more detail below.

Figure 2.2. Some examples of hybrid potato: (A) The size of true potato seeds compared with the size of a seed tuber and of potato berries; (B) diploid potato growing in the field, the weaker plants at the front are inbred progenies and the vigorous plants at the back are hybrid plants; (C) inbred lines growing in the greenhouse; (D): harvesting a plot with advanced hybrids; (E) tuber yield of a promising hybrid (photos: Solynta, 2019, 2022).

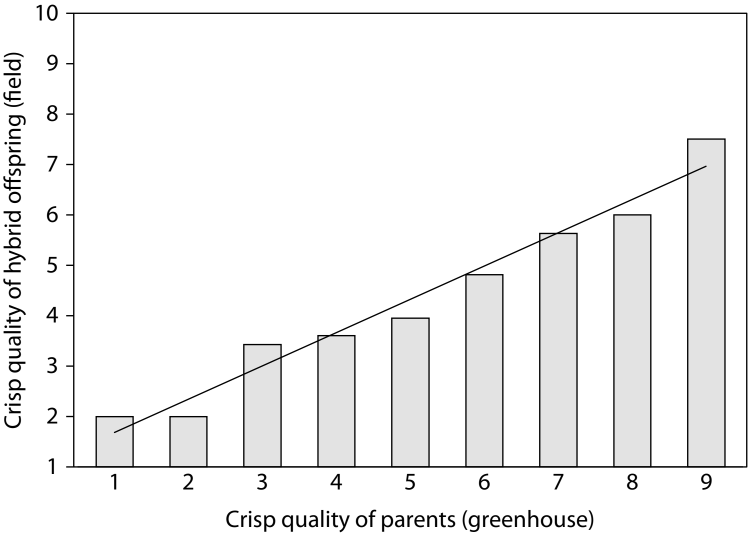

Figure 2.3. Illustration of the high heritability of quality traits in hybrid breeding. Diploid potato inbred lines were grown in the greenhouse and crossed to produce hybrid progeny seeds. The seeds were sown, seedlings raised and transplanted into the field and cultivated as a crop to produce ware potato tubers. The tubers of the parent lines and of the hybrid progenies were assessed for crisp quality. There is a close association between the crisp quality of the offspring and the crisp quality of the parents. Similar associations for conventional tetraploid cultivars would demonstrate a much poorer relationship between crisp quality of the offspring and that of the parents.

2.4 Specific aspects of the hybrid true potato seed technology

As stated above, hybrid breeding takes advantage of knowledge on the inheritance of traits, by efficiently selecting parent lines and combining or stacking desirable (either monogenic or polygenic) traits in uniform offspring. Moreover, hybrid true potato seed (HTPS) allows rapid multiplication of desirable genotypes without degeneration of the planting material and with low costs of storage and transport. Some relevant aspects are explained below.

2.4.1 Uniformity

Hybrids are generated by crosses between inbred parents. Molecular markers may be helpful to select the most homozygous parent lines (Zhang *et al.*, 2021). When inbred parents are not completely homozygous, this may result in genetically not completely uniform hybrid seeds. As it takes much more generations to generate homozygous tetraploid lines, usually hybrids generated from tetraploid inbred plants or populations lack uniformity (Lindhout *et al.*, 2018). The initial TPS cultivars generated by the International Potato Center (CIP) were tetraploid and hence lacked good uniformity (Table 2.1). The present trend is to generate fully homozygous diploid lines and hence the hybrids generated from these lines are uniform (Stockem *et al.*, 2020).

Table 2.1. Main potato breeding systems.[1,2]

	Vegetative system	TPS (CIP system)	HTPS
Ploidy level	tetraploid	tetraploid	diploid
MAB introduction one gene	10-20 years	10-20 years	2-3 years
MAB introduction two genes	>25 years	>25 years	3-4 years
Multiplication	tubers (5-10 years)	seeds (one season)	seeds (one season)
Seed health	high chance of contamination	clean	clean
Uniformity	high	low	high
Commercial interest	proven	limited	growing
Conclusion	Dominant system: Russet Burbank is leading cultivar for >140 years	CIP introductions: mainly in developing world, area is declining	Potential: dynamic introductions of innovative products, value creation, disruptive change

[1] For comparison, traditional TPS is included that is not further outlined in this chapter, as it is hardly used anymore.

[2] CIP = International Potato Center; HTPS = hybrid true potato seed; MAB = marker assisted backcrossing; TPS = true potato seed.

2.4.2 Qualitative tuber traits

In traditional breeding, most emphasis is on the selection of qualitative tuber traits, as these traits segregate in the progeny populations (see above). In contrast, due to the fixation of genes in homozygous potato inbreds, the genes for qualitative traits in diploid inbred parents are fixed and the quality traits of hybrids can well be predicted from the performance of the parent lines (Adams *et al.*, 2022). So, the majority of the tuber traits is selected in the inbred parents and the hybrids are just checked to guarantee that the high tuber quality is maintained.

2.4.3 Plant vigour and tuber yield

The growth and tuber yield of potato plants are very sensitive to (fluctuations in) the environmental conditions. Moreover, there is a large genotype by environment (G×E) interaction. In general, the conditions in a greenhouse, where potato plants of the parents are grown in pots, are very different from the natural field conditions where the offspring is selected. Therefore, the growth and tuber yield of the offspring plants are not well predicted by growth and tuber yield of the parents. This requires that these traits are evaluated in the natural conditions of a potato field. So, the growth and tuber yield of potato hybrids are assessed in the field, preferably in randomised, repeated trials under different conditions, locations and years (Stockem *et al.*, 2020).

2.4.4 Trait stacking

In potato, there are many traits, that inherit as one locus or gene. Good examples are resistances and genes involved in the synthesis of pigments, like anthocyanins and carotenoids (Haynes *et al.*, 2011; Van Eck *et al.*, 1994). These genes can relatively easily be mapped on the potato genome by genetic studies using molecular markers (Korontzis *et al.*, 2020; Meijer *et al.*, 2018). These genes, often identified in wild species, can be introduced into potato parent lines by a process designated 'marker assisted backcrossings'. This is done by crossing the resistant donor with one of the inbred parent lines of the hybrid), followed by two backcrosses to the same inbred parent line and finally the cross with both original parent lines to reconstitute the hybrid, but now with one or two additional resistance genes. In this way, a susceptible hybrid can be converted into a resistant hybrid with maintenance of the genetic composition, but with an additional resistance gene (Figure 2.4; Su *et al.*, 2020).

2.5 Hybrid true potato seed: seed production

The multiplication of hybrid seeds is very fast: a female inbred line is manually pollinated with pollen from a male parent and each berry may contain hundred seeds, while a female plant may produce dozens of berries and, thus, thousands of seeds. This can be done in a greenhouse, allowing two cycles per year. Like with vegetable seeds, this can also be done in remote locations, where the conditions for the production of clean hybrid seeds are favourable, like at high altitudes

Figure 2.4. Trait stacking in hybrid potato. Note that R1, Susceptible, R1 + R2 and R2 refer to the resistance levels of the rows in which these codes appear. Field trial of potato hybrids with one or two resistance genes to late blight (caused by *Phytophthora infestans*) and the susceptible control. Wild potato species carrying a single resistance gene were crossed in 2015 with the parent plants of a susceptible hybrid. In 2016, the F1s were backcrossed to the recurrent parent plants and the two parent lines with resistance genes were crossed to reconstitute the hybrids with one (R1 or R2) or two resistance genes (R1 + R2). The susceptible original hybrid was added as control. The susceptible control shows a high frequency of diseased plants, some hybrids with one resistance gene (R1 or R2) show some diseased plants, while nearly all plants of the double stack resistant hybrids (R1 + R2) are healthy at the end of the season (photo Solynta, 2017).

in tropical regions. There are only ten true-seedborne pathogens known in potato (Chapter 5, Table 5.3). This is in great contrast to tuber-borne diseases as over 200 pathogens are listed as tuber-borne (Gildemacher *et al.*, 2009). Hybrid potato seeds are produced in greenhouses with high phytosanitation conditions, principally hybrid potato seeds are devoid of any pathogen. These greenhouses are usually existing facilities and the technology of producing these hybrid potato seeds is comparable to common production techniques. In this way, millions of clean hybrid seeds can be produced in one year. The shipment to the regions where the seeds are grown is technically simple as one kg may contain two million seeds. The most important limitations are the legal restrictions for import and export of potato seeds (Chapter 5).

2.6 Hybrid true potato seed: agronomy of potato cultivation from true seeds

True potato seeds are very small: there are about 2,000 seeds in one gram. Upon sowing, the seed germinates into a seedling that grows into a plant that is similar to plants raised from seed tubers. A farmer may start with true seeds and sow them in the field. Sowing needs to be done shallow, followed by delicate construction of the ridges. However, direct sowing is risky as the young, delicate seedlings have a low early vigour, have difficulty in acquiring the necessary resources (such as light, water and nutrients), may not be competitive enough against weeds, may suffer from pathogens (dying off) or may suffer from extreme conditions: heat, frost, drought, wind erosion, etc. Alternatively, a farmer may sow the seeds in a protected environment like in a greenhouse or nursery, where the conditions are favourable: no weeds and conducive environmental conditions. At five to six weeks after sowing, the seedling is transplanted into the field. This is another risky step as the seedling has to cope with a transplant shock and has to compete with weeds and deal with different field conditions (van Dijk *et al.*, 2021, 2022a,b). When established, the seedling grows into a plant that is similar to a tuber raised plant (Kacheyo *et al.*, 2021). In conclusion, the technical systems to implement HTPS are in place, but the seed and ware potato growers, the packers and processors, as well as the retailers will have to adopt these technologies.

2.7 Hybrid true potato seed: paradigm shift in the potato production system

The entire potato production system consists of a chain of activities from research and breeding to the final consumption of the fresh or processed products (Figure 2.5). Upon the implementation of HTPS, many technologies have to be adapted. This goes for the breeding, production of true hybrid seeds, sowing seeds, raising seedlings and transplanting into the field to produce seed tubers or ware potatoes. For all these steps, the present stakeholders in the potato systems will have to adopt these technologies and new stakeholders may take their positions in these steps. The HTPS system is very similar to the systems of field grown vegetables, where also hybrid seeds and transplanting technologies are used. It is expected that growers and seed companies, who and which are experts in these technologies will easily adopt HTPS as it is just a new crop in their portfolio of vegetables.

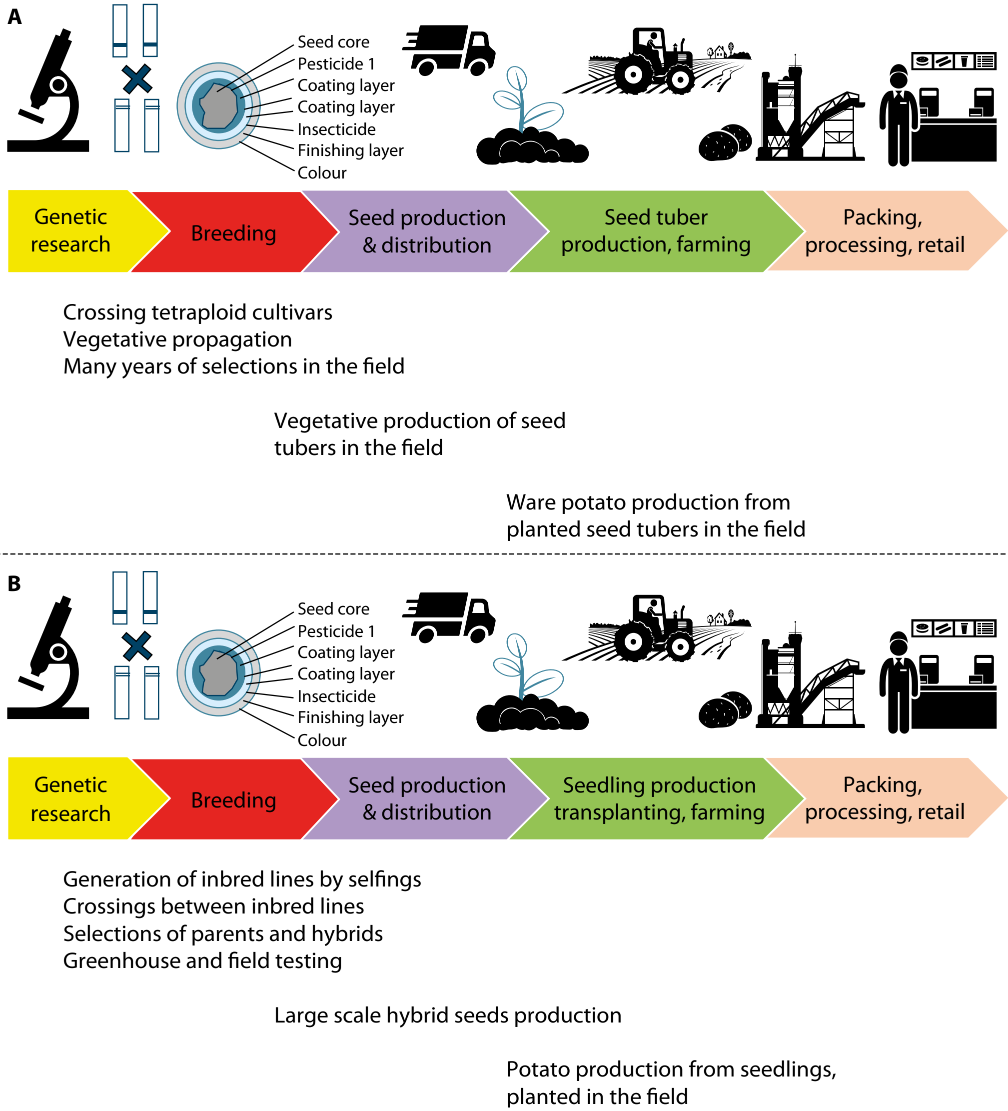

Figure 2.5. Schematic representation of potato systems with the main technologies used: (A) the traditional potato system; (B) the hybrid potato system.

In addition, where nowadays seed tubers are stored and transported over the globe, in future hybrid seeds may be distributed over the globe, where local players will produce seed tubers and distribute them over the farmers. The storage, transport and handling of HTPS is much more efficient than those of bulky seed tubers. So, the initial steps in the potato systems will change but as soon as seed tubers are produced from HTPS, the farmers' practices will largely remain the same. If farmers see the advantages of HTPS and become familiar with the new technologies, more farmers may follow this route. Still, farmers may have a mixed system whereby they regularly purchase fresh seed tubers from the formal system, followed by a small number of saved seed generations. These systems may go hand in hand and differ dependent on the geographies, agronomic and economic conditions, and farmers' communities and skills.

The driver for these changes is the added value of HTPS. As stated above, the advantages of HTPS are the faster development of new cultivars with new traits that are desired by farmers and by other stakeholders in the potato systems.

In conclusion: HTPS is a new technology with great potential, but the implementation is challenging as it affects many steps in the potato systems.

2.8 Hybrid true potato seed: state of the art in the context of developing countries

The first publication about the development of HTPS appeared in 2011 (Lindhout *et al.,* 2011). The first hybrid field trials were done in 2015 and repeated in 2016 in the Democratic Republic of Congo (DRC), Africa (De Vries *et al.*, 2016; Figure 2.6). These field trials in the DRC were caried out in an international context of developing countries with often a dominance of an informal seed potato system and a high rate of seed degeneration of traditional seed potato production. Although the genetic composition of the potato hybrids at that time did not meet the market demands (e.g. in terms of uniformity of the hybrids and their produce), the added value of clean true potato seeds was already so high that local farmers wanted to use these HTPS cultivars. Still, legal regulations did not permit to use these hybrid cultivars and some more breeding was needed to further improve these cultivars genetically. Similarly, already in 2017, a hybrid potato cultivar was generated with two resistance genes against *Phytophthora infestans*. These 'double stack' cultivars showed a strong resistance during the entire growing season (Su *et al.*, 2020). But these cultivars were meant for demonstration and were not genetically good enough for commercialisation.

One of the main challenges is the regulation of HTPS (see also Chapter 5). The breeding pipelines of the HTPS breeding companies are very promising, but it takes some years before the added value is proven in the field and in demonstration plots and before all regulations are in place to transport and import HTPS over the globe, certify the quality of seeds and the progeny seed tubers, and register the hybrid cultivars.

2.9 Hybrid true potato seed: global food security

HTPS has great potential to contribute to the global food and nutrient security (Global Development Goal II: zero hunger; FAO, IFAD, UNIUCEF, WFP and WHO, 2019; FAO, 2021). At present, all HTPS breeding programmes are executed in the northern hemisphere at mild climatic conditions (Aardevo[1]; HZPC[2]; Solynta[3]; Jansky *et al.*, 2016; Zhang *et al.*, 2021). The HTPS products are well suited for these mild climates and at high altitudes in tropical regions,

1 https://www.aardevo.com/en/.
2 https://tinyurl.com/yckv742w.
3 https://www.solynta.com/about-solynta/.

Figure 2.6. First hybrid potato cultivation in Africa: (A) raising seedlings; (B) seedlings two weeks after transplanting in the field; (C) harvested potato tubers; (D) relative yields of nine hybrids (S1…S10) compared to a local control (photos: Solynta, 2016).

the centre of origin of potato. Implementation of HTPS requires technical adaptations that can only successfully be implemented when this is supported by training and capacity building programmes of the main stakeholders in the potato systems. This is a great challenge that is only achievable by cooperations and coalitions: breeding companies will develop new HTPS cultivars that are tested in the target markets over the globe, where local users can participate in selecting the best adapted cultivars. These activities have to be embedded in the local potato systems with active involvement of these stakeholders. Government bodies should implement the new rules and regulations on HTPS. When these systems around HTPS are well organised and function well, all stakeholders will benefit. This is crucial for the sustainability of this system. This means that additional funding, including public funding, is required to set up the HTPS potato system, but when it is established, no more funding is needed.

The long-term aim of this new technology is to develop HTPS cultivars that are adapted to cultivation in the tropical lowlands. As no cultivated potato is adapted to tropical lowland conditions, a completely new breeding programme – and in fact a new crop – has to be generated. This requires a considerable investment, even higher than the present investment in the development of HTPS, as the (diploid) hybrid breeding germplasm is well adapted to grow in the regions where potato is already cultivated. Given the very large genetic variation in wild related *Solanum* species that are crossable with cultivated potato (*Solanum tuberosum*), such a tropical lowland HTPS breeding programme is feasible and realistic. This requires strong public private partnership where inputs and results are shared (Beumer and Stemerding, 2021; Beumer *et al.*, 2020).

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Chapter 3. The future of hybrid potato: responsible innovation with future scenarios

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Abstract

This chapter explains how scenarios were used to guide the responsible innovation of hybrid potato breeding. Innovators, societal stakeholders and policy makers were involved in a process of mutual learning about how innovation can respond to major societal challenges like food security and sustainability. Focusing on the future of hybrid potato in 2040, three scenarios were elaborated that differed in control over the value chain, consumer demand, technology trends and dominant developments in agriculture. The question how to combine business opportunities for breeders with variety development that serves global food security in sustainable ways was identified as one of the main challenges emerging from this scenario exercise. This chapter also offers a critical reflection on the plausibility and desirability of the three different scenarios.

Keywords: breeding, food security, sustainability, mutual learning

3.1 Introduction

Hybrid potato breeding offers a way to rapidly develop new potato varieties, with true potato seed as a new resource for potato cultivation. Potentially, this could lead to more sustainable farming and food security on a global scale. However, such desirable impacts of technology are by no means a given (Morozov, 2013). Stakeholder expectations on the impact of this technology vary greatly, from the innovation having no impact at all, to the technology being a game changer (Beumer and Edelenbosch, 2019). Technological innovations raise a diversity of technical and societal issues, involving stakeholders with different interests, and uncertainties abound. Can hybrid true seeds provide yields that are competitive with those of seed tubers? How will this technology be embedded in, and match with, different agricultural systems? If hybrid breeding shakes up the potato value chain, who will be winners or losers?

In this chapter we consider the future of hybrid potato breeding from the perspective of 'responsible research and innovation' (RRI), taking into account the complexities and uncertainties of innovation, while seeking ways in which innovation can respond to major societal challenges (Owen *et al.*, 2012). In the past decade, RRI has made its way in various fields of research and

DOI: 10.3920/978-90-8686-946-6_3, © R. Edelenbosch and D. Stemerding, 2023

innovation, including agricultural research (Asveld *et al.*, 2015; Bronson and Knezevic, 2016; Bruce and Bruce, 2019; Bruijnis *et al.*, 2015; Eastwood *et al.*, 2019; Gremmen *et al.*, 2019; Klerckx and Rose, 2020; Macnaghten, 2016; Macnaghten *et al.*, 2014; Wigboldus *et al.*, 2016). The approach of RRI is different from more conventional ethical assessments of technology, because it not only takes into account potentially problematic aspects of a new technology, but also aims to identify and stimulate desirable opportunities for innovation (Edelenbosch, 2014).

So how to innovate responsibly? What to consider as 'right impacts' of a new technology and how to steer innovation into desirable directions? (Kool *et al.*, 2017; Von Schomberg, 2011 and 2014). These questions have no clear-cut answers. Public values, like sustainability, may have different meanings to different people, and, additionally, values can be at odds with each other. To a degree, the issue is not in defining the right outcomes, but in defining the right problem (Grin and Van de Graaf, 1996). A deeper understanding of these questions requires inclusion, early in the innovation process, of a broad variety of stakeholders and other relevant actors, who can help anticipate potential impacts and reflect on desirable conditions and outcomes of innovation. Accordingly, RRI has been conceptualised in terms of different process dimensions, stimulating mutual learning through anticipation, inclusion, reflexivity, transparency and responsiveness (Groves, 2017; Owen *et al.* 2013; Ravn *et al.*, 2015; Stilgoe *et al.*, 2013). In the following, we will discuss how we have taken up RRI as approach in the context of a multidisciplinary project focusing on the future of hybrid potato (POTAREI 2015-2021).

3.2 Context and outline of this chapter

In the POTAREI project (Dutch) researchers from different scientific backgrounds worked together on the question of how to create optimal conditions for responsible innovation in hybrid potato breeding that benefit the productivity, sustainability and diversity of current potato production systems. Agronomic research into the performance of hybrid potato varieties and their different types of propagules in various cropping systems was conducted side by side with social studies of the wider system conditions that may shape the future of hybrid potato. Another unique aspect of this project was the implementation of a 'valorisation panel', an advisory board consisting of a diverse group of stakeholders and experts active in different domains relevant to our research question, including sector representatives, national policy makers, an environmental organisation, and environmental and breeding researchers.

One of the core activities in our project was an interactive scenario building exercise in which we explored how the future of hybrid potato might be shaped by different and changing system conditions, with different implications for food security and sustainability on a global level. These scenarios were developed in an anticipatory, inclusive, reflexive and responsive manner, involving a broad range of stakeholders (including valorisation panel members). In this chapter, we describe the different steps we have taken in this process and the main findings and lessons relating to the plausibility as well as the desirability of the futures explored.

3.3 Step 1: mapping out expectations

In the early stages of innovation, when future innovation trajectories are still open and uncertain, the behaviour of actors is strongly directed by their expectations about the technology in question. Therefore, we started our exploration by interviewing a diversity of stakeholders within and outside the Dutch potato sector (breeders, seed potato farmers, trading houses, civil society organisations, experts, and policymakers) in order to map their expectations about the impact of hybrid potato on the sector and society at large. A systematic analysis of these expectations helped us better understand what was at stake in diverging claims about the future, which opportunities and hurdles were perceived, and what would drive or inhibit stakeholders to act upon particular expectations (Beumer and Edelenbosch, 2019). On the one hand, this first step in our exploration was about immersing ourselves – as social scientists – in the realities, practices and expectations within the field, on the other hand it was also about pulling key actors into our responsible innovation process.

By mapping our findings along the two dimensions – expected impact of hybrid breeding on the potato sector and expected impact on society – we found three clusters of actors' expectations, with each cluster including a wide variety of stakeholders. We found a cluster of actors who shared the expectation that hybrid potato breeding will meet unsurmountable technical and societal barriers and thus will bring no significant change at all. The second and largest cluster included actors showing higher expectations of the technical feasibility of hybrid breeding, without expecting however more than modest effects on the sector and society at large. Finally, there was a third cluster of actors describing hybrid potato breeding as a game changer that may bring a technological solution to food security and sustainability as urgent societal problems, with potentially disruptive effects for the sector.

Central to the low or moderate expectations about the impact of hybrid breeding was the idea that the potato sector itself is highly unchangeable. Actors in the first two clusters considered innovation mostly in light of established sectoral structures. These structures were perceived as barriers that would be difficult to overcome. Representatives of large potato processing companies for example pointed out that any innovation in breeding should meet the tight-fitting requirements of the processing industry. More in general, interviewees believed that the introduction of new potato varieties is marked by a strong path dependency and also repeatedly mentioned, in this context, the relatively conservative nature of the Dutch potato sector. To the extent that hybrid breeding was deemed technically feasible, it was thus expected to lead to innovation that fits well with established farming and processing systems, and it was seen as unlikely to bring broader sectoral or societal changes.

Actors in the third cluster, on the other hand, were more optimistic about the potential for change. They did not take the existing structures of the potato sector as their starting point, but emphasised urgent sector-wide problems, with implications for food security and sustainability as global challenges and hybrid breeding as a highly promising technology to overcome various constraining obstacles. Nevertheless, these interviewees were also keenly aware of the challenges that such changes would entail.

3.4 Step 2: coming to terms with uncertainty

Societal embedding of new technology requires both aligning the technology with existing needs, and adapting structures that constrain the implementation of a new technology. In order to do so in a responsible way, it is necessary to keep desirable futures in mind. Our findings from the previous step show that it may be difficult to imagine more diverse and wide-ranging futures when current system conditions and daily practices are framing the discussion.

We live in the present, while the future is uncertain. This is where scenarios can help, not as predictions of the future but as a way to explore how multiple versions of the future might enfold. While the future is still open, it is not empty, as it holds manifold connections to the present (Van Asselt *et al.*, 2010). Therefore, scenarios should be informed not only by future expectations, but also by current societal and technological trends that may have a strong impact on the future of hybrid breeding, although in ways that again are open and uncertain.

Accordingly, as a second step in our exploration, we identified from the interviews and a literature review the most relevant uncertainties and trends to take into account in a scenario building exercise. The divergent expectations that we mapped on the basis of our interviews pointed to cognitive or factual uncertainties in particular, referring to aspects of the future we do not know yet. Will the technology work properly and how will it be applied? What will future cropping systems look like? What will the economic and societal impact of the technology be, especially with a view to food security and sustainability? As can be seen from these questions, the future of hybrid potato will take shape in a complex interplay of technological, agronomic, commercial, social and political aims and developments.

To further broaden our perspective, and inspired by responsible innovation as our aim, we also took into account normative uncertainties, which relate to different stakeholders' perspectives on how the technology should be developed and applied (Van Asselt *et al.*, 2010). The main question here is what stakeholders consider to be a desirable future for hybrid potato breeding. What do stakeholders see as important challenges and goals to which hybrid potato breeding should respond? What interests and values are at stake? And what are, in this context, the conditions for a successful development of hybrid breeding?

Thus, we made an overview of major uncertainties and relevant trends playing a role in the future of hybrid potato breeding, global food security and sustainable development. On this basis, we identified four key contingencies shaping the development of hybrid potato breeding that could serve as building blocks for the construction of scenarios (Edelenbosch and Munnichs, 2020). As we aimed to contribute to optimal conditions for a responsible development of hybrid breeding, we took the successful introduction of hybrid true potato seed on the (global) market as a starting point for our scenario building exercise. The four key contingencies we identified were:

1. *Who is in control?* Today, the Dutch potato sector is the world's biggest exporter of seed potato tubers. The question is whether Dutch companies can continue to play a leading role in the sector. A major switch to the use of hybrid true potato seed may offer new revenue models for large multinationals in the seed industry. New powerful players may enter the market who

can monopolise hybrid breeding, also by shielding off the use of genetic material (Bronson, 2015). Whoever has control in the sector will exert influence on the purposes for which hybrid potato breeding is utilised and on the extent to which potato cultivation meets the aims of food security and sustainability.

2. *What are the main market and consumer trends?* What will be the future demand for hybrid true potato seed from potato farmers as current purchasers of seed potato tubers? Another important question is how hybrid seed will fit into the informal seed potato markets that are still dominant in large parts of the world. Will small farmers in Africa be able to afford clean hybrid seed? In addition, consumer demand for potato products is changing. Global consumption of French fries is expected to increase. At the same time, Western consumers are increasingly concerned with a healthy 'natural' diet and there is a growing demand for organic farming and regional products (Rabobank, 2016)[4]. The position of hybrid breeding in all this is open to question.
3. *What are the most relevant technological trends?* The potato sector has so far been reluctant to make use of genetic modification (GM) technology because of costly authorisation procedures and looming public resistance. Notable exception is Simplot, a company that has brought several GM potatoes to the US market. Other companies may follow in the future perhaps (Mampuys and Stemerding, 2010). Moreover, there is an important role for gene technology in (hybrid) breeding as a laboratory tool to develop know-how or to speed up analysis of newly developed varieties. The technologisation of agriculture may well continue in other areas too with the development of global positioning systems (GPS), sensor technology, robotisation, vertical agriculture, and 3D food printing (Den Hartog-de Wilde and Poppe, 2017). These parallel technological trends may influence the market as well as consumer choice and may also affect future potato production.
4. *Focus on intensification or extensification?* This raises the question of the extent to which a food production system focusing on reducing costs and increasing yields per hectare is compatible with the pursuit of more sustainable agriculture (Bennett, 2017). Is further intensification of agriculture desirable, so that less land is needed for food production ('sparing' the land)? Or should agriculture instead be made more extensive, while devoting more space to natural processes on farmland, so that food production is less damaging to the environment and biodiversity ('sharing' the land)? By adding different resistance genes to otherwise identical potatoes, hybrid breeding may contribute to sustainable intensification. Could it also serve more extensive low-input practices of agriculture?

3.5 Step 3: co-construction and discussion of scenarios

In the foregoing steps, we articulated major cognitive and normative uncertainties with regard to the future of hybrid potato breeding that were manifest in the diverging claims of individual actors within and outside the sector. In a third step we used these insights as starting point for a more direct exchange of views and a process of mutual learning, by bringing together the different stakeholders (including some of the interviewees and members of our valorisation panel) in a joint scenario building exercise. To structure this stakeholder dialogue, we developed three basic storylines, showing how the embedding of hybrid potato in future food systems may go in different

4 https://tinyurl.com/6w4urph5.

directions, depending on the answers to the issues raised in our scenario building blocks. Each storyline dealt with food security and sustainability as grand societal challenges in a different way, leading to specific internal tensions, with both winners and losers. The three storylines were, as basic scenario frameworks, further elaborated and discussed in two successive stakeholder workshops. In addition, we discussed the main results of our scenario building exercise in four individual consultations with relevant societal stakeholders beyond the conventional sector who had been unable to join the process.

In the first workshop, we invited stakeholders to look forward 25 years and to think out of the box, thus stimulating their imagination and broadening their perspective beyond personal or sectoral interests. Fleshing out the details of the different storylines enabled the participants to gain and share insights into relevant developments, the intricate relationships between them, and their economic and social effects (Dammers *et al.*, 2013). Based on the outcomes of the first workshop, the narrative within each scenario was elaborated further by our research team. The resulting scenarios served as starting point for a second workshop with (for the most part) other sector and non-sector participants, focusing on questions like: Do these scenarios make sense and what else might happen in each of them? The scenarios were also discussed by the participants in terms of plausibility and desirability, including questions about how to strengthen the positive aspects and how to mitigate the negative aspects of each scenario. Finally, thinking about (moderately) distant futures created space to define common lessons and aims (Edelenbosch and Munnichs, 2020).

Summaries of the three scenarios are included in the Appendix. The first scenario – 'Global Duopoly' – is in line with the current dominant trend in agriculture towards increasing scale and intensification of farming. In this scenario, hybrid breeding is in the hands of two large companies, using true potato seeds to grow uniform potatoes in bulk. The second scenario – 'Sustainable and High-Tech' – is inspired by the ecomodernist vision of sustainability. In this scenario, hybrid breeding is part of a highly efficient, technology-driven agriculture, guided by changing environmental and climate policy requirements. In the third scenario – 'Diversified Markets' – hybrid potato breeding is globally supported by the public availability of parental lines, enabling breeders all over the world to develop a broad range of hybrid potato varieties suited to local conditions.

Many workshop participants considered the 'Global Duopoly' scenario as most realistic or even as 'business as usual', focused on scaling-up, intensification and concentration as trends that have been dominant in agriculture for many years. The substantial contribution of the two mega-companies to global food security, thanks to hybrid breeding and modern gene technologies, was seen as a positive, desirable development. At the same time, participants noted that tackling the world food issue is not just a matter of yield increase, but also of distribution, transportation, and trade of food, facilitated by open borders and national distribution networks. In addition, participants were critical about the lack of attention within this scenario for soil fertility, crop diversity and biodiversity. The one-sided focus on scale, intensification and use of chemical crop protection ultimately comes at the expense of agricultural yields in the long term. Although the 'Global Duopoly' scenario is most in line with current dominant trends, participants all agreed that such a large-scale concentration, dominated by a few mega-companies, probably would not come about. It would run up against increasing and widespread criticism, with voices calling for more small-scale and sustainable forms of agricultural production.

The 'Sustainable and High-Tech' scenario is about land sparing and decreasing agricultural emissions and waste by using technology to optimise current food systems, a vision popular in Dutch policymaking. In this scenario, the cultivation of seed tubers has made way for hybrid true potato seed on limited acreage. One of the elements questioned by the workshop participants was the extent to which consumers are willing to pay substantially more for sustainable products. Various participants also had doubts about the degree of sustainability of this scenario. Although the use of high-tech farming methods can reduce the environmental impact of food production, it leads to underutilisation of natural conditions and processes. According to these participants, a more resilient agricultural system would require greater structural attention to soil fertility, crop diversity and biodiversity, taking into account the complex relationship between the cultivation of crops and the natural environment. In this context, the use of natural pest control methods would be more appropriate for example. Another shortcoming in the eyes of the participants was the lack of attention in this scenario for food security as a global challenge, which might lead, in the long run, to increasing tensions in North-South relations.

The future outlined in the 'Diverse Markets' scenario arises from the abolition of patent law, allowing breeders all over the world to participate in hybrid breeding. This scenario offers ample room for global biodiversity, with locally adapted potato varieties contributing to food security. Although several workshop participants saw this as a most desirable future, doubts prevailed about its feasibility. The public availability of parental lines makes it commercially less attractive to invest in the development of new varieties, which may inadvertently inhibit the necessary innovation. The scenario was also deemed unrealistic in light of current power relations in the potato sector. Moreover, participants questioned whether the Netherlands could maintain a strong knowledge position in the potato sector with hybrid breeding and seed production largely relocated abroad.

3.6 Step 4: formulating overarching lessons

Technology alone is never the solution to societal challenges. If hybrid potato breeding is really to benefit the productivity, sustainability and diversity of current potato production systems, we need to understand the complex interplay of societal conditions and goals that shape the future of hybrid potato, in order to find pointers for guiding this innovation in the right direction. This was the aim of our interactive scenario building exercise. In this exercise, we not only discussed the pros and cons of the three different scenarios, but also asked the participants to draw lessons about the necessary conditions for one or more versions of the future, that could help us formulate more robust scenario-transcending strategies for responsible innovation in hybrid potato breeding. Based on the final workshop discussion, our research team has identified three overarching lessons, focusing on various system conditions that may connect the future of hybrid potato more strongly with public interests of food security and ecological sustainability and a promising business model for the Dutch potato sector (Edelenbosch and Munnichs, 2020).

First of all, the scenarios show that innovation in hybrid breeding depends to a significant extent on 'how the breeding market is organised'. In the 'Global Duopoly' scenario, innovative start-ups have little chance of success because multinationals control the entire chain and have monopolised breeding know-how and genetic resources. In the 'Diversified Markets' scenario, parental lines are made publicly available and numerous parties can freely breed with them. Our workshop participants considered both contrasting system conditions in these scenarios as unsatisfactory because it becomes less worthwhile for independent private breeders to invest in developing their own parental lines and these conditions may thus act as a barrier to necessary innovation. A first lesson to be drawn is that it is important to maintain an innovative and competitive market, stimulating commercial breeders to continually develop new potato varieties with the aim to contribute to food security in a sustainable manner. Therefore, governments should guarantee that breeders retain full access to genetic material and new fundamental knowledge; have the opportunity to use a diversity of (genetic) breeding techniques; and have the opportunity to adequately protect newly developed (hybrid) potato varieties.

An important potential benefit of hybrid breeding is the rapid development of new potato varieties for different purposes. A purpose that is often mentioned in view of food security and sustainability is a 'potato that is "robust"'. However, in the context of different system conditions, robustness may have different meanings. In the agro-industrial system context, robustness refers to a genetically uniform potato that can be cultivated, with the necessary inputs, in an as large area as possible worldwide. In a more diverse international development context, robustness rather refers to a potato that is optimally adapted to specific and local socioeconomic and agroecological system conditions. In discussions of both the 'Global Duopoly' and 'Sustainable and High-Tech' scenario, our workshop participants voiced concerns about the neglect of soil fertility and (agro) biodiversity as issues that should be taken into account in breeding strategies guided by the aims of food security and sustainability. Thus, a second lesson to be drawn is that it is important for governments to promote a diversified approach, in which careful consideration is given to the combination of potato varieties, cultivation systems, and production chains. It is precisely a diversified approach that offers opportunities for global food security and sustainability in both the short term – by contributing to yield security – and the long term, by ensuring broad genetic diversity.

As true potato seed can reach areas that currently do not have access to high-quality seed potato tubers, hybrid breeding is seen as an opportunity for the Dutch potato sector to expand its export market. The scenarios, however, suggest major worldwide 'shifts in the organisation of potato production chains'. The future of hybrid potato can therefore both strengthen and weaken the position of the Dutch sector at system level. The Diverse Markets scenario opens the possibility of a new and promising business model for the sector, with a shift of focus to the international marketing of know-how. Following from that is a third and final lesson to be drawn. In order to continue to play a significant international role, it is crucial for the Dutch potato sector and the Dutch government to continue to invest in knowledge development relating to (hybrid) breeding, cultivation and also the organisation of potato value chains within different contexts. By developing, on this basis, specific know-how about local production conditions and about breeding locally adapted varieties, the sector might acquire a pivotal position within local potato production chains worldwide, based on collaboration with local partners, including smallholder farmers. In this regard, the sector could learn from the experiences of internationally operating Dutch vegetable breeding companies, as in the project SEVIA for example, a partnership of Wageningen University & Research and two seed companies.

3.7 Conclusions

Hybrid potato breeding may contribute to the productivity, sustainability and diversity of potato production systems, but this will not come about spontaneously. By no means is it a foregone conclusion that the promises of the hybrid potato will actually be fulfilled. The aim of responsible research and innovation is to direct innovation to public values, in the midst of an uncertain world. We have described how scenario construction may help to explore and understand the uncertainties and complexities of innovation in a process of mutual learning, and to identify at system level scenario-transcending strategies for the responsible development of hybrid breeding.

The scenarios show that hybrid potato breeding can play a role in very different futures, with various impacts on food security, short and long-term ecological sustainability, and the economic position of different stakeholders in the potato sector. Clearly, different future development paths are possible, but not every path is equally plausible and self-evident. In this respect, a tension was revealed in the workshop discussions between the plausibility and desirability of the futures discussed. Even though the 'Diversified Markets' scenario was marked as an attractive future by a significant number of participants, the 'Global Duopoly' scenario strongly figured as the most plausible one. This tension was also manifest in the critical responses from societal stakeholders beyond the conventional sector who we consulted afterwards about the outcomes of our scenario building exercise. In their view the scenarios are too much technology-driven, with productivity as a main concern. Instead, a more radical system transformation is needed, supporting nature-inclusive and (bio)diverse forms of agriculture, in order to secure long-term food security and sustainability on a global level.

How hybrid breeding finally will take shape in actual practice is determined by the economic, social, and policy decisions that are adopted by the different parties involved. Companies can choose – within certain margins – how sustainably they wish to operate and which contribution they wish to make as regards world food issues. But these choices are also driven by applicable regulations and by governmental policies regarding knowledge, innovation and sustainability, and by the public pressure that civil-society organisations may exert on companies and governments. This means that companies, governments and civil-society organisations all need to take action in steering hybrid potato breeding in socially desirable directions.

Acknowledgements

This chapter is a result of the research project Responsible Innovation in Dutch Potato Breeding (POTAREI, MVI-14-007), funded by the Dutch Research Council (NWO), which falls under the responsibility of the Dutch Ministry of Education, Culture and Science. Additional funding came from the Solynta Company (Wageningen) and the Kramp Group BV (Varsseveld), the Netherlands. We would like to thank all the interviewees, workshop participants and all others who have provided information and feedback on the topic of this chapter. A requirement for the funding of this type of RRI project by the Dutch Research Council is that the research should involve cooperation between multiple scientific disciplines and a partnership with an innovative company. This project has been a coproduction between agronomists and social scientists from the universities of Wageningen and Groningen and from the Rathenau Instituut in The Hague, in collaboration with the hybrid breeding innovator Solynta.

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Appendix

Three potato future scenarios

More comprehensive and rich versions are available in Edelenbosch and Munnichs (2020).

Global Duopoly

In 2040, potatoes are big business. Major population growth in Africa and Asia and the increasing popularity of potatoes make investing in bulk potato production a profitable enterprise. Two large multinationals dominate the potato sector and maintain tight control over a fully integrated potato production chain, including the production of hybrid potato seed as starting material. The two mega-companies own a repository of potato parental lines from which new hybrid varieties can be developed. Patents are used to block other breeders from accessing the technologies and varieties that have been developed. The two companies have only a limited interest in a greater diversity of varieties, because that makes the cultivation and processing of potatoes more complex. The result is a limited range of high-yielding varieties for the starch industry, the processing industry, and the fresh produce market. For the large-scale cultivation of potatoes, the companies depend on monocultures, which has led to a worldwide reduction in crop diversity and soil fertility. Yield per hectare is the leading factor, contributing to global food security, but at the expense of environmental sustainability.

Sustainable and High-Tech

In 2040, the Netherlands has been hit hard by global warming. A large proportion of Dutch agricultural land has had to make way for nature and recreation as a result of policies aimed at raising the water level of peat meadow areas so as to combat soil subsidence and CO_2 emissions. A switch to the use of true potato seed and mini-tubers made it possible to grow potatoes on a limited acreage and the traditional Dutch seed potato sector has completely disappeared. With the large-scale use of technology and ICT throughout the entire chain and a veritable revolution in hybrid potato breeding, innovation is responding to increasingly strict health, environmental and climate policy requirements. The emphasis in breeding is on disease resistance, higher yields, tolerance to wet conditions, nutrient efficiency and human health. Companies are permitted under breeder's rights legislation to utilise the genetic traits of competitors' hybrid varieties. A significant part of the cost of sustainable production is charged on to the consumer, who pays substantially more for food than in 2020. Poor countries have not been able to keep up with these technological developments and the gap with well-developed countries has grown in recent decades.

Diversified Markets

In 2040 breeders all over the world are using hybrid breeding to develop varieties that are optimally adapted to local tastes and growing conditions. A few years after the EU decided to no longer allow patents on the natural properties of plants, this decision was adopted by governments worldwide. Subsequently, public (CGIAR) institutes have been developing, with support of the FAO, a range of potato parental lines and made them publicly available, enabling local breeders to develop regionally adapted hybrid varieties. Globally, two types of market are developing. On the one hand, a local fresh produce market supplied by small-scale farmers and, on the other, a market for bulk varieties supplied by large-acreage farms to the processing industry. The fresh produce market for potatoes is highly diverse worldwide. In the processing industry, the picture is entirely different: a limited range of varieties suffices for processors because they are assured of a good crop thanks to the robustness of the potatoes involved. Although the demand for Dutch potato seed has fallen sharply, the Netherlands has acquired a new role as an exporter of know-how about hybrid potato production chains.

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Chapter 4. Potato in the Netherlands – a remarkable story

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Abstract

The Netherlands is leading in the global market of seed potatoes. Annually, close to 800,000 tons are exported to a wide range of countries inside and out of the European Union. This success has roots in history. In this chapter, I analyse how this position was obtained and provide some scenarios for the future given the current developments in policies and technologies. I conclude that the leading role in both potato breeding and international trade in seed potatoes is rooted in a history of a combination of science, entrepreneurship and explicit policies and institutional arrangements that have evolved over the past century. Just like agriculture itself, also the breeding practice and seed markets are changing at an increasing pace. After a brief review of relevant developments, I conclude that the Netherlands could maintain, or even expand its leading role, but when business models change, the outcomes are likely to be significantly different for the various operators in the potato seed chains.

Keywords: seed potato, potato breeding, history, breeding methods

4.1 Seed potato in the Netherlands

Potato is a staple food in the Netherlands. Until some 50 years ago, cooked or fried potatoes were on the Dutch family table every day. This dominance of potato reduced from the 1970s onwards when pasta and rice started to find their way to the Dutch dining table. During that same transition of food habits, the consumption of chips and crisps increased significantly. Still, the Dutch consider potato a 'very Dutch food'. A quite different use of potato is for starch and protein, an industry that is concentrated in the country's northeast and that plays an increasing role in the protein market as well.

The country is very well suited for potato production with deep soils, a temperate climate and a fair amount of wind from the sea, which is favourable to limit the spread of insect-transmitted viruses. As the current second largest exporter of agricultural products globally, the Netherlands also considered potato exports early on. Since land is scarce and expensive and potato farmers are very knowledgeable, a major focus has been on the export of more valuable seed potatoes, rather than ware potato, notably since World War II.

Paul C. Struik, Peter R. Gildemacher, Dirk Stemerding and Pim Lindhout (eds.)
Impact of hybrid potato
DOI: 10.3920/978-90-8686-946-6_4, © N.P. Louwaars, 2023

The Netherlands is by far the largest exporter of seed potatoes worldwide. Of the 164,400 ha cropped with potato in the Netherlands in 2022, 26.5% was for seed, 26.57% was for starch and 47% was for ware potato (Akkerwijzer.nl, 2022), which shows the significance of seed tuber production in this country.

Goffart *et al.* (2022) estimate that 43% of the seed potato production area in north-western Europe is located in the Netherlands; 22% in France and 16% each in UK and Germany. Belgium complements the area with 3%. The Netherlands, with limited land surface, is reaching its maximum area of seed potato growing, taking into account the important quality requirements, including rotation. Annually, close to an average of 800,000 tons (2015-2019) was exported to some 86 countries: 55% within the EU and 25% to North Africa as main destinations (https://tinyurl.com/2p8ru9vj). So, the range of importing countries, their diversity of ecologies and thus varietal needs, are significant.

This position has developed over the years. The added value is generated to a large extent by some 2,500 farmers producing these high value products on average. The other part of the value is absorbed by the trading firms. They invest significant amounts in R&D, notably potato breeding. This breeding activity provides a basis for future sales of seed potato tubers in a very competitive market. Farmers all over the world need quite different varieties that suit their growing conditions, consumer preferences (e.g. colour and texture of the flesh) and specific demands of the processing industries. Potatoes for the starch industry have very different characteristics from those for fries and crisps. Currently, 548 varieties are on the Netherlands variety list; 505 being of Dutch origin (41 German and 2 French), to cater for these different demands (NVWA, 2021). Twenty-three varieties are presented by the organic sector as particularly robust for their cultivation method, notably regarding their resistance (or escape) to *Phytophthora* (https://tinyurl.com/5asz54vs).

In this chapter, I analyse how the Netherlands obtained this global position, and what the impact might be of recent technological developments.

4.2 Early history of the potato in Europe

Potato developed into a major food crop in north-western Europe following its introduction from Latin America in the 16th century and the initial appreciation as a novelty food by the European aristocracy. The crop arrived in the Netherlands around the year 1700 where it was quickly accepted by the population and soon became an important component of the daily diet (Van Loon, 2019). An important reason for this rapid adoption was the high yield in both produce and dry matter compared to the cereals and legumes that formed the basis of the European plant-based diet. The potato crop performed particularly well in the cooler parts of Europe, where, apart from day-length, the conditions bear similarities to the native Andean conditions where the crop was domesticated and first cultivated.

When the crop became more widely grown in the late 18th century, diseases started to play an increasingly disturbing role, finally culminating in the ravaging *Phytophthora* outbreak in the 1840s throughout Europe, but best known as 'The Great Famine' in Ireland (Kinealy, 1994;

Ó Gráda, 2006). The poorer population was so dependent on this single source of food that the disease outbreak caused massive hunger, starvation and migration. A major opportunity for potato diseases is that the crop is vegetatively propagated and that many disease agents, whether viral, fungal or bacterial, can infect tubers, survive during storage, and provide a source for inoculum in the next crop. As a consequence, it is the farmer himself who carries the diseases through winter and spread them to other fields. Several diseases are also soil borne, which means that the party is on – for the diseases at least! That diseases could spread so quickly was also because only a narrow genetic diversity of the crop had been introduced into Europe (Bourke, 1964), meaning that genetic resistances that may exist in the centre of origin were not present in Europe. The vegetative propagation method – and the absence of scientific breeding at the time – did not allow for recombination and thus the co-evolution of the crop with its diseases and pests. In the late 18th century already, a solution had been proposed to reduce disease incidence, i.e. to grow the crop from true seeds (Van Loon, 2019, p. 21). Likely because this required much additional labour for land preparation, and since yields were so much lower and variable, this idea never took hold.

Crops have been domesticated from the start of agriculture over 10,000 years ago and farmers have continued to adapt them to their different farming systems. Conscious breeding, however, including crossing plants in order to obtain better varieties was initially limited to horticultural hobbyists, notably working on flowers and fruit trees. Only in the 19th century, applied scientists like Louis de Vilmorin in France got interested and the first crosses of major food crops like wheat were reported (Louwaars and Burgaud, 2016). It was only by the end of that century that the scientific concept of plant breeding took a firm hold with the introduction of advanced line- and family selection methods in cereals by a farmer-cooperative in Sweden (Nilsson, 1898). There are indications that potato crosses have been made as early as 1780 in Germany and 1807 in England, but systematic potato breeding with an important and lasting economic success started in the second half of that century, with Luther Burbank in the USA (Figure 4.1), and Geert Veenhuizen in the Netherlands (Figure 4.2) (Van Loon, 2019).

4.3 Seed potato quality: production and trade

The potato famine clearly showed the importance of plant health, and especially the health of seed potatoes that, through their vegetative propagation nature, can accumulate many disease agents, acquired during subsequent growing seasons. Plant health thus became a primary concern all around Europe. Gradually, scientific and practical data became available about the spread of viruses, nematodes, bacteria and especially *Phytophthora*. As a consequence, the importance became clear to reduce the occurrence and spread of diseases. The major measures in the early 20th century were:

- seed production in open areas with winds coming from the sea to reduce virus-transmitting aphids and other insects;
- a strict crop rotation; and
- controls of subsequent generations of seed potatoes.

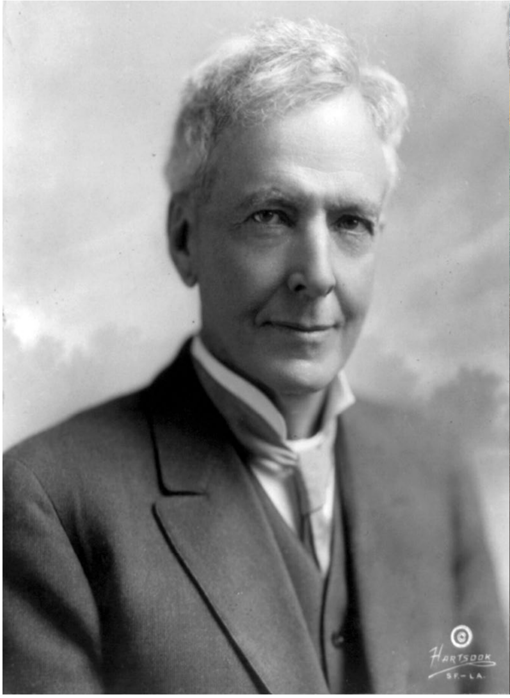

Figure 4.1. Luther Burbank (1849-1926) (From United States Library of Congress. Prints and Photographs division (digital ID cph.3a00184).

Figure 4.2. Geert Veenhuizen (1857-1930).

The Netherlands, and notably the areas of the country close to the sea, became one of the main areas from where healthy seed tubers could be obtained, next to adjacent areas in northern Germany and in Scotland.

The international success of the seed potato sector in the Netherlands is due to policies, institutions, technological developments and entrepreneurship.

4.3.1 Institutional development: quality awareness and controls

The professionalisation of seed production in the 19th century led to a quickly increasing quality awareness among farmers. For seed quality, a seed testing station (RPvZ) was established in Wageningen in 1877 (Van Soest, 1977); for seed potato quality, a formal inspection service was established jointly by farmers and seed producers only in 1932: 'Netherlands General Inspection Service for field crop seeds and seed potatoes (NAK)', bringing several seed inspection operations under one national flag. A major task of 'the NAK' was and is to guide and control seed production and certify the identity and quality of seed potatoes in the trade (Siebenga, 1949). Already in 1924, the first list of recommended varieties was published, confirming varietal identity and comparing the value of different varieties of field crops (De Haan, 1964). These initiatives, currently operating under the Seeds and Planting Materials Law (ZPW) and under supervision of the Ministry of Agriculture, were important to organise and supervise seed production, including for seed potatoes. The NAK-label has become a very important proof for quality for Dutch seed potatoes in the Netherlands and worldwide.

The other important policy area of concern is the need to avoid the spread of crop diseases and pests. A formal phytosanitary office was established in the Netherlands in 1899 (Van Poeteren, 1931), in first instance to provide guarantees for exported trees, but gradually also charged with avoiding the introduction of diseases into the country, notably those originating from the centre of domestication of crops. Such risks had already been identified as an important issue for estate crops in colonial days. Botanical gardens, such as Kew, had established an important role as quarantine station since the early 1800s to make sure that diseased plants of major crops, like cocoa and coffee, were not transported to new production areas in the colonies. (The task of cocoa quarantine station was moved to Reading University in the 1980s; www.icgd.reading.ac.uk/icqc). In the Netherlands, the dedicated Plant Health Service became the official National Plant Protection Office under the Ministry of Agriculture in 1951 when the International Plant Protection Convention (IPPC) was signed (history of the IPPC). Introductions of potato from the Americas had to be quarantined before they could be released to breeders or farmers; a rule that is still in place under EU regulation. This is currently also valid for true seeds even though the number of diseases that can be transmitted through true seeds is significantly lower than through seed tubers.

4.3.2 Technology

Also technology plays an important role, whereby the Foundation for Plant Breeding in Wageningen created new insights and was initially the place where all crosses were made for the breeders to base their selection on. The quick multiplication of healthy stock became possible through rapid multiplication techniques *in vitro*, hydroponics and aeroponics and the subsequent production of mini-tubers from such plantlets. Technology to identify disease agents and test plants and tubers for diseases even before they show visual effects continues to improve the quality guarantees. A range of programmes have been undertaken to share this knowledge with importing countries such that local multiplication can be monitored better. However, institutional shortcomings remain challenging in many countries.

4.3.3 Entrepreneurship

Also entrepreneurship is an important factor for the success of the Netherlands as seed (potato) exporter. Seed production and trade, notably of vegetables from the early 19th century onwards (https://edepot.wur.nl/405592), attracted an increasing number of entrepreneurs towards high-value products like seeds rather than bulk food products. A diversity of producers and traders of seed developed. Entrepreneurial individuals established family-owned companies that dominated the vegetable seed sector. In field crops, where farmer-cooperatives developed to manage markets and processing (e.g. sugar, starch), also breeding/seed cooperatives were established next to family businesses. In recent years, their number, both in cereal and potato seed, has reduced. The entrepreneurial skills opened markets for Dutch seeds in numerous countries in competition mainly with Germany and Scotland. Reliability of supply and quality of both varieties and seed tubers remain the strong selling point.

In conclusion, both its location near the sea, and institutional support systems laid the basis for the excellent position of the Dutch quality label for seed potatoes, embedded in a strong culture of entrepreneurship and scientific advancements.

4.4 Potato breeding in the Netherlands

4.4.1 Early developments

The year 1888 is considered as the start of potato breeding in The Netherlands, when Geert Veenhuizen started to systematically cross and select superior genotypes, leading four years later to the variety 'Eigenheimer'. This variety remained popular for over a century, only bypassed in importance by Bintje, bred some ten years later by De Vries (Van Loon, 2019).

The discovery of Mendel's laws on heredity in 1900 gave a tremendous boost to scientific interest in plant breeding, including in the Netherlands, where an 'Institute for Breeding of Field Crops' (IVL – later IVP) was established already 12 years later. Plant breeding took off in the Netherlands quickly based on the scientific position of the country in the natural sciences at the time with several Nobel laureates in physics and other disciplines. In biology, Hugo de Vries, who coined the terms 'mutation' and 'gene', and one of the scientists re-discovering Mendel's laws was a renowned scientist (De Vries, 1900a,b). The position of the country in the world of breeding was later confirmed by Amsterdam hosting the founding meeting of the International Association of Plant Breeders (ASSINSEL) in 1938. The Netherlands also became the country with the oldest, continually operating system for the protection of plant breeder's rights (first established in the 'Kweekersbesluit' dated 1941) in the world, showing its commitment to supporting practical plant breeding in the private sector. Many other countries, notably the USA, the Soviet Union and developing countries, continued to assign the task of breeding of all or most crops to public universities and research institutes.

4.4.2 Public support to potato breeding research

A policy decision that became very relevant for potato breeding was the establishment of the Foundation for Plant Breeding (SVP), in 1948, that was to do breeding research, supporting practical (private) breeders next to the more academically oriented IVP (Van Loon, 2019). The Foundation, created under the Marshall Plan, fitted in Dutch policies towards food security and evolved very quickly in a clear example of public-private collaboration. The research was initially fully funded by the Government, but private breeders had an important say in the Board of the institute and the actual programming of the research. This proved important to close the gap between science and application, which so often challenges research programming at universities and the application of results in practice. The USA took a different approach to closing that gap, by assigning the tasks of both breeding and agricultural extension to the Land

Grant Universities; in the Soviet Union it was done by placing scientists at the collective farms to push innovation coming from research institutes. In many developing countries, with poorly funded extension systems and research programmes, this link between science and application remains a serious challenge.

Next to closing the gap between farming practice and research, the SVP was also a significant research entity on all aspects of the potato, including disease resistances, and providing the breeders with seeds of promising crosses. During the restructuring of agricultural research in the Netherlands in the 1990s, the (successors of) IVP, the plant research institutes like SVP, and the applied research stations in the country came together in Wageningen University and Research in 1998 forming a substantial critical mass in the research chain from academic to strategic and applied.

New forms of science-support started with programmes for public-private collaboration at the rather fundamental (Centre for Biosystems Genomics) and strategic (Technological Top Institute Green Genetics) levels in the early 2000s, followed by the Topsector approach in 2011 in which breeding research gradually received less attention and which lacked a specific focus on crops like potato. In response, the potato value chain developed a programme in 2017 called Holland Innovative Potato (https://www.hollandinnovativepotato.nl), an extension of which for a next five-year period is currently due.

4.4.3 Breeding as a science and an art

Potato breeding remained largely a numbers game for most of its history. It is a good example of the idea that plant breeding is both a science and an art, showing the importance of the 'breeder's eye' next to scientific measurements. Largely because of that, potato breeding developed a unique organisation of seed potato (trading) companies that employ some scientifically trained breeders, who cooperate with specialised farmers performing a large part of the actual selection work. This innovative organisation, which was dubbed 'farmer-participatory plant breeding' many years later when applied in developing countries (Almekinders and Hardon, 2006; Sperling and Ashby, 1997), produced many new varieties responding to the diversity of farmers' needs, and thus supporting export markets.

The respective roles of the farmer-breeders and the companies are gradually changing with more technology becoming available. Bio-tests to establish susceptibility of clones to diseases have to be performed centrally; the same is true for marker-assisted selection and the increasingly important pre-breeding that is necessary to introduce 'new', desired diversity (often from crop wild relatives) into the breeding populations. These technologies have made breeding more predictable, the level of which is however not comparable to that in crops like maize and tomato, where breeding work is increasingly supported by *in silico* analyses, matching vast amounts of genetic and phenotyping data. The tetraploid nature of the potato crop is partly to blame for that, but also the significant number of complex traits that need to be selected for.

4.4.4 Public investments start to pay off

The old varieties like 'Eigenheimer' (1892) and 'Bintje' (1905) remained immensely important throughout most of the 20th century. This was partly due to the slow pace of breeding caused by apparent complexities of the heritability of the important yield and quality factors for cooking and frying in this tetraploid crop, and the multiple pests and diseases for which breeding has to cater. This is combined with a long time to market of new varieties because of the low multiplication factor, and with rather conservative approaches by the potato-based industries and consumers. The processing industry (chips and crisps) stuck to well-known varieties because each new variety needed adjustment of processing conditions like time and temperature, and its customers required a very constant product. Finally, the widespread availability of crop protection chemicals made replacement of the old, very *Phytophthora* – susceptible, varieties less urgent for farmers.

All this has led for quite some time to a slow turnover of varieties and a significant area planted to varieties that had passed the protection period of new varieties. This availability of old but still somehow acceptable varieties, and the relatively low profit margin for seed tubers compared to (hybrid) seeds, significantly reduce licence income for breeders and subsequently investment opportunities in research.

However, targeted government support for breeding, combined with innovative collaborative arrangements between farmer-breeders, companies and the government created an excellent knowledge infrastructure for the development of varieties for a wide range of farmers' needs in the Netherlands and abroad. This environment also developed the (applied) science of breeding itself. Plant breeding has incorporated different science fields over the last 50 years. Genetics has been the basis of plant breeding since Mendel, but the value of that science can only be tapped when it is combined with a thorough understanding of crop physiology, pathology and in some cases taxonomy, complemented with biochemistry, food sciences and behavioural sciences. The science of plant breeding soon incorporated several other sciences: mathematical statistics, developed in the 1920s (Fisher, 1921), became a major tool for trial management and analysis from the 1930s onwards. The predictive models applied by cereal breeders from the 1960s appeared not very applicable to the vegetatively propagated tetraploid potato though. Developments in tissue culture (Murashige and Skoog, 1962) appeared more interesting for the crop, mainly for disease free multiplication and regeneration as a basis for the next sciences to be incorporated into the toolbox of the breeder: genetic modification (Herrera-Estrella *et al.*, 1983). Transgenesis and Marker Assisted Selection took off in the Netherlands as well, even though the applications of the former moved to other parts of the world due to EU regulations regarding genetically modified organisms (GMOs).

A call by the joint biotechnology sectors towards the Netherlands government in 2021 (https://tinyurl.com/2p9encbd) to support biotechnology in the medical (red), industrial (white) and agricultural (green) fields should be seen in this view that the knowledge infrastructure is crucial for the development of knowledge intensive sectors such as breeding of crops with a significant margin in seed sales.

The knowledge infrastructure for breeding has contributed to the Netherlands having a unique concentration of breeding companies for a wide range of crops. Potato has a significant focus in research investments, which contributed to the position of the Netherlands in the world of potatoes. Nevertheless, it remains remarkable that the innovation capacity of the breeding companies was confronted with a low turnover of cultivars in the potato sector.

4.5 Recent technological developments in breeding

Like in any other crop, advancing effectiveness and efficiency of the plant breeding and seed production operations is top of the wish-list of every potato breeder. Breeding is a powerful tool to reach sustainable improvements in crop production and quality characteristics, but for potato both breeding and the build-up of sufficient stock of seed tubers for the introduction of new varieties are time consuming. From the seedling of a cross between two elite clones to a new variety in farmers' fields currently requires 10-15 years; introduction of traits from a more distant part of the gene pool takes much more time. Some radical developments have recently taken root in the last few years: cisgenesis, gene editing, multiplication through true seed rather than tubers, and breeding at the diploid level.

4.5.1 Omics

The ability to 'read' proteins (electrophoresis) and DNA generated a very interesting new set of tools for plant breeders. The science of genomics was complemented by transcriptomics (RNA-sequences), proteomics (protein sequences) and finally metabolomics (describing metabolic pathways in the cell), which together can trace products through the life processes back to the actual genetic sequences. However, biology is less linear and straightforward as this model tends to look like. There is still a lot to learn in this area.

4.5.2 Cisgenesis

The problem of losing important combinations of genes after crossing a tetraploid crop like potato could be overcome by transgenesis, the introduction of functional genes from another species through genetic modification techniques. The introduction of the first transgenic crops such as FlavrSavr tomato and herbicide or insect resistant maize, cotton and soybean triggered such a heavy regulatory burden, that initial transgenic work on potato was abandoned. Around the year 2000 though, ideas to transfer genes within the genepool of crossable potato species took root. So called cisgenic potatoes (Jacobsen and Schouten, 2007) were created containing different *Solanum* resistance genes against *Phytophthora*, providing promising sustainable resistance management opportunities for the crop (Haverkort *et al.*, 2016). The proven environmental benefits and the reduced ethical opposition compared with transgenesis, created a novel, and much more positive debate in society towards these technologies. However, the legal definition of genetically modified organisms obstructed the further development of this promising technique in practice.

4.5.3 Gene editing

Next was gene editing, initially using technologically complex TALEN (transcription activator-like effector nucleases), ZincFingers, ODM (oligonucleotide-directed mutagenesis) and other methods, but revolutionised by the development of CRISPR (clustered regularly interspaced short palindromic repeats) based technologies in 2012. The Netherlands was very much involved in the integration of fundamental developments into actual crop improvement, but in gene editing this translation was done elsewhere. An important scientific foundation of the CRISPR-Cas gene editing technology was laid in the Netherlands (Brouns *et al.*, 2008; Jansen *et al.*, 2002) but the practical application was developed elsewhere (Jinek *et al.*, 2012) for which Douda and Charpentier received the Nobel Prize 2021. These techniques are very promising for all crops, but particularly also for difficult-to-breed crops like potato.

The debate is ongoing about the regulatory status of the products of these technologies in different jurisdictions and the access to the technology by breeders. The actual impact of the technologies on potato breeding is therefore difficult to predict yet. The policy environment is crucial for a technology to have impact. For example, the expectations of transgenesis in a multitude of crops and applications have not been met mainly because the global policies resulted in the transgenesis technology being used on few globally important crops by the largest seed companies only.

The role of the European Union in this respect is crucial for the future opportunities for the Dutch breeders to use cisgenesis and genome editing for the potato crop that is conventionally so difficult to breed.

4.5.4 Diploid breeding

Breeding at the diploid level makes it possible to precisely recombine traits and efficiently introduce traits in elite materials through repeated backcrossing, which would at the tetraploid level create unmanageable levels of diversity. In addition, the use of molecular biology tools and genomic analysis is more effective at this level (Nakaya and Isobe, 2012). The breeder even has the option to check at which ploidy level the crop may eventually perform best (2×, 4× or possibly even 3×). Secondly, it allows to produce uniform lines that can be used as parents in hybrid seed production. This could significantly reduce the time to market of a new variety. Working with (uniform) seeds also has the advantage that the build-up of a commercial stock of a new variety is potentially much quicker, and also the generation system may be simplified while still guaranteeing varietal identity and seed health.

Hybrid breeding would then allow the breeder to respond much quicker to new demands in the market. The development of a new variety can in principle be done more quickly by making new combinations of inbred lines rather than by starting a new crossing and selection process. Whether this will work as efficiently with potato, with its many important quantitative traits, as with some vegetables, is still to be experienced. Hybrids in other crops have the additional advantage for the breeder of a 'biological protection' against the use of farm-saved seed, which is one of the reasons why investments in breeding of crops like maize, tomato, cabbage and rice have grown tremendously (Ter Steeg *et al.*, 2022). However, given the possibility to multiply potato through tubers, this advantage will be much smaller for crops for which such farm-saved seed cannot be restricted. A distinction may develop though between 'higher end' farmers using true seed, and others, reproducing the genetics through tubers. However, whether the seed product to enter the market for produce farmers will be true seed, young plants, mini-tubers (or seedling tubers) or conventional seed potatoes, breeding will be advancing at a higher pace using these new insights. Even though several breeders have started working at the diploid level, commercial varieties based on such breeding have not reached the major markets yet.

Significant technological developments bear important promises in supporting on the one hand the management and creation of diversity and on the other hand the efficiency and effectiveness of selection of new varieties of crops, including potato.

4.6 Developments in multiplication: from seed potato to potato seeds

The 200-year-old idea of multiplication through true seeds came up again at the International Potato Center (CIP) in Peru in the 1970s (Malagamba and Monares, 1982). The production of healthy seed tubers in developing countries presents a significant bottleneck when areas with sufficient altitude are far away from the crop production areas, and when the institutional and logistical arrangements are weak. Such challenges often even require regular importation of bulky seed tubers. Furthermore, true seed would be a solution for CIP's international research programmes where phytosanitary controls block international exchange of tubers. And finally, true seed could significantly reduce the investment for a farmer in planting materials compared to seed tubers, because of higher multiplication rates and lower storage and transport costs.

However, the true seeds developed in the public sector have not had the expected impact on the targeted farmers in the Global South (Almekinders *et al.*, 2009). This may be due to the lack of uniformity of the plants and the products, no clear genetic added value and lack of efficient seed production and distribution systems.

Starting a potato crop from true seed rather than seed tubers requires quite a different agronomy, such as seed bed preparation, length of the growing season, etc. Growing potato directly from true seed would then become more like horticulture rather than field crop agronomy, where a less refined soil preparation and care for the plants are needed. However, having genetically and physiologically more uniform seed might shift the balance for the seed or ware grower. Alternatively, the benefits of true seed in storage, transport and phytosanitary complexities might be combined with the benefit for the farmer of handling more robust planting materials either by developing specialised 'young plant growers' providing transplants to farmers like in tomato and cabbage, or to grow mini- or first year (seedling) tubers that give the plant a head start in a more conventional potato growing agronomy. These different models are under investigation, and results may differ depending on the farming systems that are targeted.

4.7 Diploid breeding and true seeds: the position of the Netherlands?

What would be the influence of these technological developments on the position of the Netherlands in the world of potatoes? Are the historical developments a guarantee for future dividend?

First, it is likely that diploid breeding is here to stay and that this work will benefit from the gene editing and next level technological developments described above and as long as sufficient business perspectives, combined with ongoing public-private cooperation in research, allow for the necessary investments in R&D. These developments will likely be leading to increased advances in breeding and a higher turnover of varieties, especially when advances can be made without altering the chips/crisps processing standards. It is likely that this development further strengthens the position of the country where the knowledge infrastructure is best.

There are various scenarios for the future of potatoes multiplied through true seed, and their direct or indirect (young plants/mini-tubers/seed potato) use by farmers, and whether there may be a distinction between regions and types of farmers. If the direct use of true seeds would become mainstay, this would be to the detriment of seed potato growers – both the 2,500 potato seed tuber growers in the Netherlands and those in the high-altitude regions in the tropics. For the Dutch seed potato value chains, a shift towards exports of true seed could likely reduce phytosanitary and logistical needs. Using true seeds as starting material for mini-tubers or regular seed potatoes as the basis of ware potato growing, will create a new class of specialised mini-tuber producers in both the Netherlands and the importing countries.

Whether such shift would be a blow for the export earnings of the Netherlands remains to be seen, though. The Dutch vegetable seed sector is thriving and very profitable. Even though much of the seed production does not take place in the country, most of the added value of the exported seeds 'lands' in this country since value is created through both breeding and seed processing and quality controls. Also for that sector, knowledge infrastructure and the institutional excellence in the Netherlands, through the Board for Plant Varieties, the Seed Quality Control and Phytosanitary Services, make the country the place to invest for seed companies. If potato would develop largely or partly towards true seed, export earnings of the Netherlands may not suffer much, but it would mean a significant shift in where the added value will 'land', from currently the seed potato grower to the breeding/seed company. It might also change the roles of the cooperative structure of part of the seed potato companies.

More importantly, if, as stated above, technologies like gene editing, which is relevant both for conventional, diploid and hybrid breeding, will be accepted all over the world but not in Europe, then the Netherlands will lose a significant part of its position in breeding not only seed potato/potato seed, but also for other crops, which in turn will also damage the unique knowledge infrastructure for breeding and seeds in the country.

4.8 Conclusions

The geographical location and the history of the Netherlands determine to a very large extent the unique current position of the country in the area of seed potatoes. Explicit policy decisions (breeder's rights, phytosanitary services, and governance of public research and seed quality controls), and investments in the knowledge infrastructure leading to scientific excellence and good science-application linkages, have created an environment where the seed potato business could thrive and international markets could be developed.

Recent technological developments may create new business models and may challenge existing ones. They may revolutionise the breeding processes, shorten the time-to-market of new varieties, and reduce the required scale of seed production in The Netherlands. The impact on the Dutch seed sector will also depend on government policies towards the latest (and upcoming) breeding methods, and variety registration procedures. Furthermore, the farmers' acceptance of new types of starting material (true seed, mini-tubers, seedling tubers) in the Netherlands and elsewhere will be crucial. Irrespective of the latter choices, the Netherlands could maintain its leading position.

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Chapter 5. Regulatory aspects of use and trade in true potato seeds

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Abstract

Breeding and marketing of hybrid potato varieties which are raised from true seeds are new developments. Current national and international regulations for production, marketing and international movement of genetic material of potatoes are all based on the use of potato tubers. Development of regulations which take into account the specifics of true potato seeds is in its infancy. This chapter aims to provide the background information and ideas for the development of regulations for true potato seeds. The chapter covers variety registration and listing, plant variety protection, seed certification and phytosanitary certification.

Keywords: registration and variety listing, plant variety protection (PVP), value for cultivation and use (VCU), distinctness, uniformity and stability (DUS), phytosanitary certification

5.1 Introduction

The global production, marketing and international movement of true potato seeds (TPS) are new developments. Many countries have rules and regulations for the commercial registration and protection of new varieties and for the certification of seeds, plants or plant parts that are used as starting materials for a new crop. At present, the vast majority of potato starting materials are seed tubers or mini-tubers. There are experiences with TPS, but these are either limited, absent or in development and should finally be established at national levels, worldwide.

This chapter describes the existing regulatory global frameworks for protection, registration and commercialisation of potato varieties, that are commercialised via seed tubers. These regulatory frameworks need to be adjusted for the usage of TPS, whereby experiences with other seed-based crops that are biologically similar to potato may be helpful to set the new rules. Experiences with vegetable crops like tomato, pepper and eggplant that belong to the same nightshade family as potato will be instrumental for setting the new regulations for TPS.

This chapter also provides recommendations for these new regulatory frameworks dedicated to TPS with some emphasis on variations in regional and national detailing of these frameworks that are already manifest.

DOI: 10.3920/978-90-8686-946-6_5, © G. Meijerink, 2023

5.2 Registration and variety listing

Most countries require that any new plant variety is added to the national list of varieties for commercial purposes. This means that new candidate varieties have to go through a process of registration, before they can be marketed without restrictions. Most countries do allow limited trialling of the new variety during the process of registration. This may require a special permit. During the registration process the candidate variety is checked for distinctness, uniformity and stability (DUS). Additional validation for value for cultivation and use (VCU) may be required. Often the registration and listing process parallels the process to obtain plant variety protection (PVP), where DUS criteria are equally crucial. So, the same DUS tests are often used for both processes.

5.3 Testing for distinctness, uniformity and stability

- Distinctness means that the variety is phenotypically or morphologically different in one or more characteristic(s) from any known variety in the species concerned. For TPS this means both seed-based and tuber-based varieties.
- Uniformity means that the vast majority of plants of the variety show identical characteristics in the DUS-test.
- Stability means that the variety characteristics are stable across generations.

DUS are verified by an official executing office (EO) on a sample of the new candidate variety, provided by the applicant, during the so-called DUS-test. This is done by comparing the candidate variety with 'similar' varieties in a comparative DUS-test and preparing a detailed variety description. The EO will use an official protocol (Technical Questionnaire or TQ) to perform the DUS-test and to make the variety description. Both UPOV (the international Union for the Protection of New Varieties of Plants) and CPVO (the EU agency Community Plant Variety Office) have developed a Technical Questionnaire (TQ) for DUS-testing of potatoes (seed potato). This TQ has been developed specifically for clonal, tuber-based potato varieties. The TQ contains instructions how to evaluate and describe the different morphological characteristics of the leaves, flowers, stems, tubers and sprouts of a potato plant. Since sprouts often are a unique characteristic of a potato variety, special tests for sprout evaluation under artificial light conditions are included in the TQ.

The breeder already provides some morphological characteristics of the candidate variety when making the application and providing the sample to be tested. This enables the EO to group similar varieties in the trial and to choose the right varieties to compare with. The breeder may also suggest one or more existing 'similar' varieties to be included in the comparative test.

In the case of seed crops the DUS test is performed in two consecutive years on the same seed sample. For potato (tubers) the applicant has to provide new material for the second year of testing.

Once the registration is completed and the variety is listed, the breeder remains responsible for variety maintenance, so the variety continues to stay within the official variety description as listed.

5.3.1 Adjustment of DUS-testing for usage of TPS varieties

In the case of TPS, neither the UPOV Technical Questionnaire (TQ) for DUS-testing, nor the CPVO TQ can be followed in all detail. UPOV, CPVO as well as official National Examination Offices (EOs) have to develop and implement a specific test protocol to evaluate plants and potato tubers produced from true seeds.

One of the main topics to be resolved is whether the sprout-related characteristics also need to be evaluated for TPS-varieties and if yes, how to do so. It is evident that light sprouts characteristics can only be observed when starting with tubers. Should sprout characteristics be evaluated on the basis of tubers supplied by the breeder, or on tubers harvested by the Executive Office in the first year of the DUS-trial, or can these characteristics be skipped since they are not relevant for TPS varieties?

Other characteristics that may require adjusted evaluation criteria in case of TPS varieties are, among others (Kacheyo *et al.*, 2021):

- plant habit: TPS plants grow from a single stem, while potato plants grown from tubers have multiple stems);
- branch habit: TPS plants grow more above-ground basal branches but no below-ground basal branches;
- frequency of flowers and berry development.

Uniformity of the potato plants raised from true seeds may be lower than that of potato plants raised from seed tubers, although initial experiments with diploid TPS varieties show very similar levels of uniformity (Stockem *et al.*, 2020). This also depends on the breeding method used. Some hybrid TPS varieties may be generated from non-homozygous parents which results in lower uniformity. These are tentatively designated Slightly Inbred Parents Hybrids (SIP-hybrids). When hybrid TPS varieties are generated from completely homozygous parents, such hybrids are more uniform. These are tentatively designated Highly Inbred Parents Hybrids (HIP-hybrids).

A DUS-protocol for TPS has to accommodate both breeding methods (SIP and HIP) and variable uniformity, so two levels of requirements for uniformity of TPS-varieties may be considered.

Selecting suitable reference varieties as comparison for the new candidate TPS-variety is also challenging. The number of TPS-varieties right now is very limited and it may be difficult to obtain true seeds for DUS-testing. Tuber-based potato varieties are not a good alternative as the initial plant and growth habits are very different.

An additional technical challenge in DUS-testing of TPS is the raising of young plants from seeds. Direct sowing of the seeds in the field is not realistic, as young seedlings are very vulnerable for external conditions like the frost in temperate climates with low spring temperatures. So, seedlings need to be raised in a protected environment and then transplanted into the field. Uniformity of seedlings, fragility of seedlings, seedling health, sensitivity of seedlings for aphids (and subsequent virus-infections) and plant quality require equipment, care and skills of the Examination Office.

After transplanting, the fragile seedlings need extra care in order to result in good growth of the potato plants in the field. For example, transplanted seedlings may need to be covered with insect netting to prevent aphid infestations and drip irrigation is needed to secure uniform watering of the plants and enable reliable DUS-observations.

5.3.2 Towards a DUS testing protocol for TPS in NL and EU

Development of an adapted protocol for DUS-testing of candidate TPS varieties is still running, since the development of hybrid TPS-varieties is quite new.

The Dutch Plant Variety Board developed such a specific protocol for use by the official Dutch Examination Office NAK-Tuinbouw.

This protocol was proposed to be taken over by the EU Community Plant Variety Office (CPVO) to be valid for all EU Member States. However, CPVO required further study and testing in order to take a decision, which is expected by 2023.

The evaluation of the NL-protocol with the two systems of SIP- and HIP-hybrids currently done by CPVO is thereafter also expected to be put forward for adaptations of the UPOV protocol. DUS-testing of candidate TPS varieties will need to be done by specialised EOs, in view of the extra care required during seedling production, transplanting and growing. Taking over of DUS-reports from these specialised EOs by other countries is highly recommended, in view of the additional costs of DUS-testing of TPS varieties and to reduce administrative burden by local authorities.

5.4 Testing the value for cultivation and use

The objective of VCU-testing is to assess the agronomic value of the variety under field conditions, in other words: the added value of the variety is evaluated for usage by farmers, processors and consumers in de country of evaluation. The VCU tests are done by official testing institutions at the national level: the Examination Office (EO). VCU tests are a standard part of variety registration for agricultural crops in most countries. For potato the Technical Questionnaire for Examination of the VCU details the traits which are assessed in The Netherlands (Table 5.1). In other countries, testing the VCU may include other traits.

Table 5.1. Traits included in VCU-tests of potato in the Netherlands.[1,2]

Yield and earliness of the crop in the field
Cooking quality of the tubers
Resistance-level for Y^{NTN}-virus
Resistance-level for late blight (caused by *Phytophthora infestans*)
SGA of the tubers

[1] SGA = solanine glycoalkaloid content; VCU = value for cultivation and use.

[2] In other countries, testing the VCU may include other traits.

Testing the VCU of TPS-varieties requires a different approach, compared to testing of tuber-based potato varieties. The different starting materials (true seeds and seedlings versus tubers) result in differences in growth and plant habit. Consequently, the TPS-plants may also react differently to stress and to disease pressure, especially when the plants are young and small. In general, TPS-plants also show some more heterogeneity in comparison to clonal tuber-based potato varieties. So, the aspect of 'uniformity' requires a somewhat lower threshold in VCU-evaluations.

Several alternative routes are explored by executing dedicated experiments initiated by the Plant Variety Board in The Netherlands, in order to define the best way of establishing the VCU of TPS varieties. These involve:

- testing of potato plants directly raised from seeds, versus plants raised from 1st generation tubers of TPS-varieties;
- method of evaluation of plant heterogeneity; per individual plant as is done for tuber-based varieties ('off-types') or per plot (variation within a certain bandwidth);
- evaluation of variety resistances.

An alternative approach of VCU-testing of TPS varieties could be to use 1st generation tubers harvested from plants raised from seeds. The testing process using 1st generation tubers of TPS varieties is technically much easier. And the plant habit of potato plants raised from 1st generation TPS-tubers is comparable to plants from varieties raised from tubers, so the VCU can also be evaluated in comparison with traditional tuber-based varieties.

The first TPS variety, tested for registration purposes in The Netherlands is 'Oliver' developed by Bejo. As this variety showed a higher variation between individual plants than usual, when seed tubers were tested, the VCU tests of such varieties require a larger number of plants per plot and in more replicates in trial fields. More recently bred hybrid TPS varieties show less variation and can be evaluated in similar ways as is used with the traditional seed tubers.

5.5 Variety denomination

Besides testing for VCU, the Examination Office (EO) will also check the proposed name of the new variety. The variety name should not have been used for at least the last ten years for potato or a related species and should not result in confusion with an existing potato variety name. For that purpose the International Union for the Protection of New Varieties of Plants (UPOV) has developed the PLUTO database and a breeder may also consult the 'Variety Finder' database of the EU Community Plant Variety Office (CPVO). These databases may be consulted by the breeder or representative who wants to register a new variety, in order to check whether a proposed variety name may be successfully proposed to the Examination Office.

5.6 Plant variety protection

Breeders can protect the intellectual property of a new variety in order to enable them to obtain a return on their R&D investment. This is designated PVP whereby the breeders get ownership called Plant Variety Rights (PVR), or Plant Breeders' Rights (PBR) which is valid in a country, a group of countries or a region, (e.g. the EU). This is not a mandatory legal requirement, but a right that a breeder may apply for. The International Union for the Protection of New Varieties (UPOV) is the global organisation to initiate and harmonise PVP. Many countries have implemented legislation which enables breeders to apply for PVP of newly bred varieties. Most countries that facilitate granting of PVP have legislation which is compliant with the principles laid out in the UPOV-convention. The most important requirements to obtain PVR are the DUS criteria: distinctness, uniformity and stability. Another important criterion for PVR is 'newness' or 'novelty' of the candidate variety. Newness or novelty entails that the variety has not been marketed in the country or region where PVR is applied for, longer than one year before the date of application or not longer than four years in any other country or area.

When a breeder applies for PVP the DUS-test for PVP can be combined with DUS-testing for registration or variety listing. DUS-testing is discussed in Section 5.2.

If the candidate variety meets the criteria, PVR is granted and the new variety is listed in an official register. The protection period usually is 25 years, but in some cases is extended to 30 years. For potato, the protection period in the EU is 30 years, but the majority of countries use shorter periods of official protection (25, 20, 18 or even 15 years). When the protection period has passed, varieties are considered to be free for commercialisation by third parties.

What rights does a breeder get for a PVR-protected variety? The breeder is granted exclusive rights to produce, process, store, import, export, pack, distribute, offer for sale and sell the protected variety in the country/area where the protection is granted. The protection extends to the products harvested from the protected variety, in case of unauthorised use of the variety. The breeder can grant a licence (and charge a fee) to other operators wishing to perform above activities with the protected variety. In case a breeder wants to protect a variety in other countries/areas, these countries/areas may take over the DUS-report from another country where that variety is listed already. This saves money and time. Countries may have agreements whether they take over each other's DUS reports. The applicant can choose on the application form his preferred country as origin of the earlier DUS report.

5.6.1 Breeders' exemption

Breeders are allowed to use PVR-protected proprietary varieties of other breeders for crossing and selection in their own breeding programme. If the resulting new variety then again meets the DUS-criteria (so is sufficiently different from the original PVR-protected variety, and other varieties of common knowledge), it can again be granted PVR. There is one exception: in case the newly developed variety is a so called 'essentially derived variety'; this scenario is not discussed in this chapter. For further reading on this topic, see: https://tinyurl.com/556s3y9a.

This Breeders' exemption allows for a continuous flow of gradual improvements in plant breeding. The Breeders' exemption is one of the main differences with patent protection, which does not allow accessing the patented material without consent of the patent holder.

5.6.2 Farmers' exemption

According to the Farmers' exemption, farmers are allowed to use (a limited quantity) of the harvested product of a protected variety for their own use. This is called farm saved seed (FSS). For example, farmers are allowed to use some of the wheat seeds harvested from a protected wheat variety for replanting on their farm in the following year. Breeders may set a (reduced) licence fee for use of FSS of protected varieties. The definitions of 'own use', 'limited quantity' and 'reduced licence fee' may differ per country. This also applies to the possibilities for breeders to verify 'own use' under the Farmers' exemption and to collect related licence fees.

In the case of newly developed high value TPS-varieties, PVR-protection of the hybrid varieties is evident in order to enable breeders to obtain a return on their R&D investment. Protection of the TPS variety will also extend to the use of the harvested product: the tubers. In some countries (e.g. the Netherlands, UK), the existing system of reporting the use of FSS of seed potatoes and collecting related licence fees from farmers may also apply for tubers produced from TPS and used for next generations of seed potatoes. But in other countries, especially in developing countries, such licence collection system will either not exist at all or, if existing, will be very difficult to enforce especially for smallholders. Still, it may be useful, also in developing countries, to develop contracts for the larger players in the market of professional potato propagators, to define the business rules in case they produce and market seed potato tubers that originate from TPS-varieties. Licence fees should be in balance with the added value of the TPS-varieties in those markets.

5.7 Certification

Plants or plant parts of agricultural crops that are commercialised may be subject to product certification to assure adequate product quality for growers. Plant reproductive material of potatoes is included in Certification systems of some countries.

The potato plant has different organs, that are used for the cultivation and commercialisation of the crop: tubers are formed on stolons in the soil. Traditionally, the tubers are harvested at the end of the season, stored and distributed over farmers to start a new cropping cultivation. These are designated 'seed tubers'. Tubers that are used for processing or fresh consumption are designated 'ware tubers'. When potato plants flower, they can produce berries that carry seed, designated 'true seeds' or TPS.

When TPS germinate, they produce small plants, designated 'seedlings', that are usually raised in protected environments like nurseries, greenhouse or screenhouses. These seedlings are transplanted into the field to start a potato cultivation.

Potato plants can also be maintained and multiplied in completely artificial and sterile conditions. This '*in vitro* cultivation' is usually done to maintain and vegetatively multiply disease-free plants of important genotypes, like varieties, inbred lines, hybrids or unique genotypes. This *in vitro* cultivation is also done to keep plants in aseptic conditions to prevent contaminations with pathogens.

In vitro plants are often designated 'tissue culture plants' that may be used to transport clean plant propagation material over larger geographies. As stated above, commercial varieties are maintained by a stock of *in vitro* culture plants. Shoots of these plants are used to start a fresh and clean multiplication of starting material for commercial production of seed tubers. The shoots are transferred to greenhouses, where they grow into small plants. By choosing the right conditions, these plants produce 'mini-tubers' of 15-35 mm in diameter that are planted in the field to produce the first generation (G1) of seed tubers.

All these plant materials are used for production, multiplication, transport and usage of potato for commercial purposes. As these are biological materials that are sensitive to storage and handling, the quality of these plant parts may vary considerably. To guarantee good quality to the users (farmers), rules and regulations are in place to assess the quality of these products. This is described in more detail below.

5.7.1 Tubers

Many countries have detailed regulations to control and certify the quality of seed potato tubers planted by growers in their country. Besides aspects such as physical quality of the tubers and trueness to type, these regulations mainly focus on the plant health status of the seed potato tubers which are intended for multiplication. Countries may introduce different classes of tubers (e.g. pre-basic seed, basic seed and certified seed) with different levels of requirements and prescribed maximum number of generations per class.

The quality regulations may also specify the crop rotation requirements for seed potato. For instance, in case of production of seed tubers, a rotation period of four years needs to be taken into account, mainly to prevent building up of soil nematodes which reduce crop yield (Potato fatigue caused by *Globodera* cyst nematodes).

See, for example, the EU Directive on the Marketing of seed potato. Quality control of the health status of potato tubers needs to be strict, since some fungi, bacteria and viruses may easily be passed on to the next generation of crops. For that reason, the continued multiplication of tuber-based seed potato is limited to a maximum number of years. When that maximum number of years is reached the harvested tubers cannot be used as seed potato for a next crop of certified seed potatoes anymore.

An informative document on the different classes of seed potatoes and their requirements can be found in an explanatory document prepared by the UK Government to inform the UK potato growers (APHA, 2020).

In the Netherlands the inspection service NAK applies the schedule as given in Table 5.2. Every year seed crops are automatically downgraded one class. In this way regular use of healthy seed is stimulated. Depending on inspection results, further downgrading or rejection may occur.

Table 5.2. Netherlands potato certification classification schedule.

Class		Generation (max.)
PBTC[1] (minitubers/microplants)		G0
Mother plant (clonal selection)		
Category Prebasic (PB)	PB1	G1
	PB2	G2
	PB3	G3
	PB4	G4
Category Basic	S	G5
	SE	G6
	E	G7
Category Certified	A	G8
	B	G9

[1] PBTC = prebasic tissue culture.

5.7.2 Adjustment for usage of seed tubers produced from TPS

Above requirements are not applicable to TPS itself, but may be applicable to tubers raised from TPS and multiplied again for some generations from these tubers. Since tubers grown from TPS may be used as starting material (or basic seed) for several generations of tuber-multiplied potatoes, it is feasible that these seedling tubers follow the same certification rules and requirements. However, there may be quality differences between tubers raised from seed tubers or raised from TPS. Therefore, additional studies are needed to evaluate the impact of tubers multiplied from hybrid seeds, before deciding whether these can follow the same rules or require some adaptations. In the EU such studies are done as part of the 'Temporary Experiment on seed potato tubers derived from TPS'.

5.7.3 Mini-tubers and tissue culture material

Producers of mini-tubers and tissue culture material need to establish preventive and hygiene protocols upon which they are audited and certified by the responsible inspection service. Producers need to have adequate facilities and equipment to work in a sterile environment. All activities need to be administered and traceable.

Starting material for the production of mini-tubers and tissue culture material needs to come from officially inspected and approved fields/plants. This starting material is thoroughly tested and needs to be free of various fungi, bacteria and viruses. After the 1st multiplication 10% of the produced material is re-tested to verify absence of *Ralstonia solanacearum* (causal agent of bacterial wilt) and of *Clavibacter michiganensis* spp. *sepedonicus* (causal agent of ringrot).

5.7.4 Adjustment for usage of tissue culture materials produced from TPS

In some cases where countries do not (yet) allow import of TPS (seeds), it is possible to get a permit to import tissue culture material. This may be useful in situations where breeding material or parent line material for multiplication purposes is imported. The material has to be produced in a facility which is recognised by the national plant protection office (NPPO) of the exporting country and must meet the certification requirements of the importing country. For example, it may be necessary to test the material to be devoid of the potato spindle tuber viroid (PSTVd). For more detailed guidance on the requirements for the production of tissue culture material of potatoes, I refer to the following international phytosanitary standard: ISPM 33: Pest-free potato (*Solanum* sp.) micro-propagative material and mini-tubers for international trade.

5.7.5 Seedlings and transplants

In order to safeguard production and supply of good quality and healthy seedlings and transplants of TPS varieties, countries may implement a certification system for seedlings and transplants. At present, no regulations exist on the usage of seedlings and transplants, raised from TPS. Therefore, new regulations should be developed for these materials.

Since TPS are very small (one gram contains some 2,500 potato seeds), direct sowing in open field may be a risky operation. Late frost which could damage the fragile seedlings in temperate climates and poor field establishment and difficult weed control in (sub-)tropical climates are the main challenges for direct sowing. Pelleting of the seeds or the use of 1st generation hybrid tubers or mini-tubers may be a solution in some countries/production systems. However, the use of seedlings/transplants which are raised in optimal conditions in protected nurseries can be a feasible alternative. This may be done by professional plant raisers in nurseries, as is done for some vegetable and flower species already. Irrigation (drip irrigation or nebulising) is crucial to avoid that the seedlings dry out in the period after transplanting.

In order to safeguard production and supply of good quality and healthy seedlings/transplants, countries may implement a certification system for transplants. Such a certification system could address the following:

- *Nursery management*. Facilities of specialised Plant Raisers may be accredited to produce TPS certified seedlings/transplants if they meet defined 'good nursery practices'. Requirements for 'good nursery practices' may include aspects such as: nursery isolation, management of critical processes, traceability, record keeping, management of plant health, etc. An example of such an approach is the good seed plant practices (GSPP) protocol, which was developed to address issues with a bacterium in tomato.
- *Seedling and transplant quality*. The certification system for seedlings/transplants of TPS may detail the quality requirements, such as seedling/transplant minimum size and uniformity. Additionally the system will include the specific plant health requirements as relevant for the country concerned. For example the EU requirements in the temporary experiment specifically mention that the seedlings and transplants should be practically free from: *Rhizoctonia solani*, *Phytophthora infestans*, *Alternaria solani*, *Verticilium dahliae*, *Verticillium albo-atrum*, *Pectobacterium* and *Dickeya* species (blackleg), potato leaf roll virus and potato virus A, M, S, X and Y. The certification system will also provide details about the methods of inspection and the authority for official inspections to grant the certification status.

Inspections may be visual as well as backed up by laboratory tests of plant material, where needed.

The EU Council Directive 2008/72/EC provides an example of such a regulation for vegetable propagating material other than seed (EC, 2008).

5.8 True potato seed

5.8.1 Seed quality and certification

Marketing of TPS, being an agricultural commodity, may be regulated in an official certification system. In such a seed certification system, countries may set requirements for TPS, which are comparable to the requirements for other species grown from seeds.

These requirements could include: variety identity, trueness to type and varietal purity, germination percentage, physical/analytical seed purity, moisture content, seed health (free of seed transmissible pathogens like PSTVd) and labelling.

The EU is currently running a study by means of a 7-year experiment (Commission Implementing Decision 2017/547) to evaluate the impact of this new development in potato breeding (EC, 2017). During this experiment, seeds and tubers raised from TPS-varieties can be grown, certified and marketed within the EU in limited quantities. Performance data are being collected in order to evaluate if, where and how the standard EU marketing requirements for seed potatoes may need to be adapted to accommodate marketing of TPS in the EU, while safeguarding the quality for growers, trade and consumers.

During the experimental period, some derogations from the standard requirements for seed potatoes are granted for TPS and for tubers raised from TPS, provided that the variety is listed or has been submitted for listing in one of the EU Member States:

- First generation tubers raised from TPS may be classified as 'basic seed potatoes';
- The minimum requirements for homogeneity and off-types do not apply;
- Marketing of tubers <25 mm is also allowed.

2023 is the final year of the 7-year experiment, so an update of the EU Marketing Directive for potato, to accommodate the marketing of TPS in the EU, is expected in 2024. Above experiment does not include import of TPS into the EU. It only concerns intra-EU-community trade.

5.8.2 Import of TPS and phytosanitary certification

Many countries have not yet opened the possibility to import TPS, nor have defined the import requirements to do so. For example, currently it is not yet possible to import TPS produced in 3rd countries into the EU countries.

How to stimulate countries to initiate phytosanitary regulations for the importation of TPS? The first step is to create an understanding of the relevance of TPS for potato growers and consumers in their country, as well as for the very limited phytosanitary risks of TPS compared to seed potatoes in the form of tubers. This may induce countries to initiate a pest risk analysis (PRA) by the NPPO, to define the relevant pests of concern for the potato species in the country of the PRA and for the pathway TPS and to define the proportionate requirements for those pests in relation to the pathway seeds. The phytosanitary requirements for TPS require specific attention. These cannot just be copied from existing plant health requirements for seed potato tubers. There are over 200 pests known that can be transferred by tubers but less than a dozen pathogens that are transmissible via true seeds (seed transmitted) (Wale *et al*., 2008).

So, the phytosanitary requirements for TPS have to be defined for those pests which are of quarantine nature (absent or present but regulated in the country of production because of major economic risk) and for which TPS has been identified as a pathway with risk of introduction of the pest into the country.

The International Plant Protection Convention (IPPC) has developed and adopted a number of international standards for phytosanitary measures (ISPMs) which give guidance to countries when performing a PRA.

Specifically ISPMs number 2 (Framework for Pest Risk Analysis), number 11 (Pest Risk Analysis for quarantine pests) and 21 (Pest Risk Analysis for regulated non quarantine pests) give guidance on the PRA process.

An example of a list of pests considered in a PRA is presented in Table 5.3. This PRA furthermore concludes 'TPS may become infested by *Cms* and *Rs* through contamination of the seed crop (mechanical transfer from contaminated tools, equipment, surface water, etc.). As far as known, seed infection or transmission of the species via contaminated seeds has not been shown but neither can be excluded. For PSTVd, seed transmission has been shown. The other eight (actually seven, eds) pospiviroid species have many similarities with PSTVd and might also be transmitted via TPS. Natural infection of potato with these species has, however, not been recorded so far'.

Table 5.3. Pests considered in the plant risk analysis for true potato seed in EU.

Clavibacter michiganensis ssp. *sepedonicus* (Cms)
Ralstonia solanacearum (Rs)
Potato spindle tuber viroid (PSTVd)
Chrysanthemum stunt viroid (CSVd)
Citrus exocortis viroid (CEVd)
Columnea latent viroid (CLVd)
Pepper chat fruit viroid (PCFVd)
Tomato apical stunt viroid (TASVd)
Tomato chlorotic dwarf viroid (TCDVd)
Tomato planta macho viroid (TPMVd)

This PRA is prepared and published in 2015 by the European Plant Protection Organisation (EPPO). In case those pests require to be regulated, the PRA recommends that TPS are produced (originate) in areas where those pests are not known to occur or are produced at a production site, where appropriate measures have been taken to prevent infestation and no symptoms of disease caused by those harmful organisms have been observed on the plants at the site of production since the beginning of the last cycle of vegetation. In the case of PSTVd, a laboratory test on a seed sample may be an alternative option. Such a laboratory test can routinely be applied by breeders and seed producers.

Other countries have also done or are in the process of performing a PRA for TPS. For example, the NPPO of the USA (Animal and Plant Health Inspection Service, APHIS) has drafted a PRA in order to define the import requirements in the USA commodity import approval process for TPS originating in the Netherlands and to be imported into the USA. The draft PRA suggests a requirement for PSTVd.

In view of the fragility of TPS seedlings and transplants and in order to protect the plants from extremes in weather conditions and from pests, seed of TPS-varieties is produced in protected environments, such as glasshouses, net-houses or covered tunnels. Additionally, hybrid TPS-production is surrounded by strict prevention, hygiene, inspection and testing protocols. This is the case both for seed production of parent lines by the breeder as well as for the production of hybrid seeds by dedicated seed producers which are based in countries with suitable conditions for TPS production.

In such seed production environments, the scenario of phytosanitary certification on the basis of 'Production site free of…' may be a good option for TPS producers. In order to qualify for this phytosanitary certification option, national authorities may impose strict hygiene and pest management protocols, which need to be approved by the NPPO of both the exporting and the importing country. Such regulation is already in place for the mini-tuber production sites of 'normal' potato varieties. For instance, in the Netherlands, these sites have to meet certain criteria approved and certified by the Dutch Inspection Service for Seed and Seed Tubers of Staple Crops (NAK) and are checked and audited by NAK annually.

A G1 from origin TPS plantlets is more or less the same stage as first generation after mini-tubers in conventional potatoes. From there, further multiplications in the field have the same risks and no quality difference can be expected in the tuber crops based on TPS origin seed or conventional seed potatoes.

The following ISPMs, may be helpful to develop such a 'Production site free' protocol for TPS:
- ISPM 10: Requirements for the establishment of pest places of production and pest free production sites.
- ISPM 14: The use of integrated measures in a systems approach for pest risk management.
- ISPM 33: Pest free potato (*Solanum* sp.) micro-propagative material and mini-tubers for international trade.
- ISPM 38: International movement of seeds.

A practical example of a functioning prevention and hygiene protocol is the Good Seed and Plants System (GSPP) aimed at preventing seed transmitted bacteria of *Clavibacter michiganensis* subsp. *michiganensis* (Cmm) in tomato seeds and seedlings/transplants.

5.9 Derogation for imports of small quantities of TPS

In many countries it is possible to obtain a temporary derogation for importation of seeds which are destined for official testing, scientific or educational purposes, trials, varietal selections, or breeding. For the EU this derogation is regulated in Regulation EU 2019/829 (EC, 2019a). The derogation has to be requested from the NPPO in the EU Member State of importation. For a permanent regulation to import TPS into the EU, it is necessary that the NPPO of the country of production makes an official request, with a supporting technical dossier, to the European Commission. If the Commission would consider such a request it will ask the European Food Safety Authority (EFSA) to make an assessment. EFSA will then do a risk assessment including question and answer exchanges with the requesting country. EFSA will make a recommendation including risk management options to the EU Standing Committee on Plant, Animal, Food and Feed (SCOPAFF), who will take a final decision and if positive will set the conditions for import into the EU.

This is not an easy route and in view of current developments in other solanaceous crops (e.g. tomato) not very likely to succeed. The phytosanitary requirements for intra-EU movement of TPS can be found in Annex VII (item 21) of the Commission Implementing Regulation (EU) 2019/2072 (EC, 2019b).

5.10 Regulatory institutions

The following global regulatory frameworks are relevant for marketing and international movement of plant material, including TPS.

The International Union for the Protection of New Varieties of Plants (UPOV). UPOV is an intergovernmental organisation. The UPOV Convention is the global framework for the development of national regulations for the protection of new plant varieties/cultivars (Plant Variety Rights). Variety and cultivar (= short for cultivated variety) have the same meaning in plant breeding. For the sake of clarity only the term variety is used in this text. Currently 78 states/organisations from all continents are UPOV member and 19 states or countries and one organisation are in the process of becoming a member.

This means that those countries do have or are developing national legislation which is in compliance with the UPOV Convention. The UPOV member countries are following a harmonised process and technical protocol to evaluate whether candidate new varieties meet the requirements for national listing and/or granting of Plant Variety Rights. As a result of this harmonised way of working, UPOV Member countries can also more easily take over reports from each other, without redoing al the testing of candidate varieties. This facilitates the introduction of new varieties in multiple countries.

The International Seed Testing Association (ISTA). ISTA produces internationally agreed rules for seed sampling and testing. Currently seed testing laboratories in more than 80 countries are accredited by ISTA. Accredited laboratories follow the agreed ISTA rules (for example for germination testing), are audited by ISTA and participate in proficiency testing to proof their continued qualification for accreditation. ISTA accredited laboratories may issue so-called Orange International Certificates, which are used to independently demonstrate compliance with agreed seed quality levels.

The International Plant Protection Convention (IPPC). IPPC is an intergovernmental treaty signed by over 180 countries, aiming to protecting the world's plant resources from the spread and introduction of pests, and promoting safe trade. The Convention introduced ISPMs, which serve as global standard setting guidelines for IPPC member countries. The ISPMs cover subjects such as pest risk analysis, pest list, phytosanitary certification, etc.

5.11 Conclusions

This chapter describes the regulatory aspects of use and trade in TPS. TPS varieties may be commercialised via true seeds or via tubers. This requires two different systems for legislation of TPS varieties in general. The current systems for hybrid vegetables seeds could be used as example to legislate true seeds of TPS-varieties, while the current systems for potato may be applicable to commercialise tubers of TPS varieties. So, regulatory ingredients are available but have to be attenuated to TPS.

Acknowledgements

Rian Stekelenburg is acknowledged for critical reading and useful suggestions for improvements.

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Chapter 6. Potential impact of hybrid true potato seed in Sub-Saharan Africa

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Abstract

Potato farming underpins the livelihoods of millions of smallholder producers in Sub-Saharan Africa, but productivity remains well below its potential. Poor access to and consequent limited use of quality seed is an important factor contributing to low productivity. So far, attempts to develop potato seed systems mirroring the European model have not been successful or only partially. The innovation of hybrid true potato seed (HTPS) has created the opportunity to transform the seed potato sector in Sub-Saharan Africa taking a new, radically different approach. The land requirement for an HTPS-based seed system is lower as fewer generations are needed. Also, it will no longer be necessary to maintain and rapidly multiply plantlets from tissue culture. Availability of early generation seed (EGS) can quickly increase as quality seed can now be produced centrally in large quantities. Subsequently, EGS can be distributed easily to local specialised multipliers circumventing the logistical constrains of transport and storage of the vegetative system. Local multiplication means that seed tubers are grown close to the smallholder's farm; this generates trust between seed supplier and client, which is important in the absence of a functional certification system. It is expected that smallholder potato producers will prefer seed tubers rather than HTPS or seedlings. Of course, HTPS varieties must match the needs of smallholders. Current product portfolios of international breeding companies are not tailored to Sub-Saharan Africa market demands. Short dormancy, late blight resistance and earliness are very important traits in Sub-Saharan Africa, while being (much) less important on the global seed potato market. HTPS (diploid) varieties can be improved faster making breeding for Sub-Saharan African demands feasible. Moreover, seed potato costs are expected to be lower in an HTPS system. Despite these obvious advantages, HTPS will not be an instant success. A last-mile retail system, bringing seed potatoes close to smallholder farms is adamant, and varieties tailored to specific smallholder needs must still be developed and must be affordable. Finally, training of smallholders on good agricultural practices, seed degeneration and the added value of quality seed will take time and resources. This chapter analyses current practices and constraints along the seed value chain and whether HTPS can address these challenges. In this way, it assesses the potential of HTPS to catalyse a transformation of the seed potato sector for the benefit of smallholder producers in Sub-Saharan Africa.

Keywords: hybrid true potato seed, Sub-Saharan Africa, early generation seed, seed potato systems, seed value chain analysis

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Impact of hybrid potato

DOI: 10.3920/978-90-8686-946-6_6,

6.1 Introduction

Potato is a food and cash crop that sustains the livelihoods of millions of smallholder producers in Sub-Saharan Africa. In Kenya alone, 800,000 households produce and market surplus potatoes (Kaguongo *et al.*, 2015). Potato can be harvested in 3-4 months and is easily marketable. The market continues to grow because of changing diets and population growth. The crop can only be grown in areas where there are cool night temperatures (Struik, 2007) providing farmers in suitable agro-ecological zones with natural exclusivity. It also prevents markets from being overflown and results in relatively stable remunerative prices.

Potato productivity in Sub-Saharan Africa remains well below its potential. It seems to increase only at a modest pace even though there are strong market incentives resulting from growing home consumption and processing (Figure 6.1). The persistently low productivity can partly be attributed to the use of poor-quality seed potatoes, and associated degeneration due to seed-borne diseases, such as virus diseases and bacterial wilt, in combination with sub-optimal crop husbandry including poor late blight management (Thomas-Sharma *et al.*, 2016). Additionally, potato is mainly a rainfed crop making drought an important factor depressing yields, in comparison to situations where water supply can be managed.

Seed potato systems in Sub-Saharan Africa function differently in comparison to European systems, which is often used as a benchmark. In Europe, most seed tubers used by farmers are grown by formal, reliable and independently controlled specialised producers. Farm-saved seed is only used sporadically. Seed potato trade companies have extensive product portfolios with

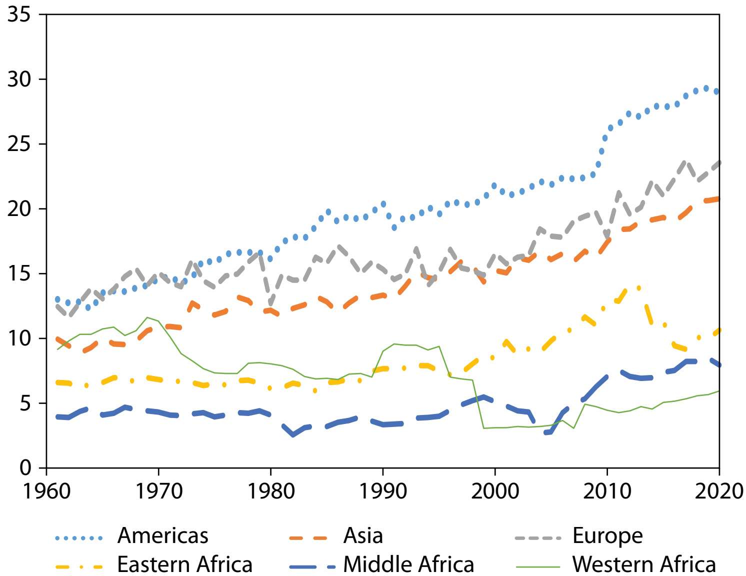

Figure 6.1. Average potato yield (t/ha) in Eastern, Middle and Western Africa, compared to those in the Americas, Asia and Europe (1960-2020) (FAOSTAT, May 2022).

varieties for seed potato users to choose from. There is a private seed potato sector, characterised by competition and the role of public bodies is limited to quality assurance and regulation. In Sub-Saharan Africa, potato producers typically use home-saved seed potatoes selected from their last crop as default option and only occasionally replace their seed stock. The choice of varieties is limited to a few varieties maintained by the public sector, and few varieties from the international private sector. The private seed potato sector is under-developed, and in many countries for parts of the seed potato production chain the public sector is acting as producer.

For decades, efforts have been made to improve seed potato systems to assure better access to seed and to increase the quality of seed potatoes for Sub-Saharan African smallholder producers. Most efforts have been made by development organisations. However, it appears that these efforts have not (yet) resulted in a substantial rise in potato productivity contributing to increasing land-use efficiency, rural household incomes, and food security. Ter Steeg *et al.* (2022a) distinguish two existing models for the development of formal potato seed systems in low-tech markets. The first system is based on imported elite material of private commercial varieties, multiplied locally or directly marketed. The second system is based on rapid multiplication of private varieties, or multiplication by local seed potato producers of varieties largely originating from public breeding efforts. The authors indicate that hybrid true potato seed (HTPS) could become the basis of a third, alternative system.

The innovation of HTPS has created the opportunity to transform the seed potato sector in Sub-Saharan Africa taking a new, radically different approach. This chapter explores whether the HTPS technology could transform the seed potato sector in Sub-Saharan Africa improving availability and use of quality potato starting material and breaking the deadlock of stagnant productivity levels. The chapter first dissects the seed potato value chain in Sub-Saharan Africa analysing its current underperformance. Subsequently, it explores if HTPS technology could remove these challenges limiting development of seed potato systems. Finally, it outlines recommendations when seeking to transform the seed potato systems in Sub-Saharan Africa through the deployment of HTPS technology.

6.2 Production systems in Sub-Saharan Africa

Discussing 'potato production systems in Sub-Saharan Africa' is a gross simplification considering enormous existing diversity. Each country is home to unique production systems shaped by the agroecological and socioeconomic context, regulatory environment and level of seed sector development, with different seed potato value chains operating in parallel as well as being intertwined. Describing the specificities of individual countries goes far beyond the purpose of this chapter but it may be helpful to distinguish between three potato production areas to inform readers (Table 6.1). The first production area encompasses the East and Central African highlands (above 1,500 m a.s.l.) including Ethiopia, Kenya, Uganda, Rwanda, Burundi, DR Congo and Tanzania. In these countries, potato production is characterised by the bi-modal rainfall pattern, resulting in two main growing seasons. At the highest altitudes, where evapotranspiration is low, the period between the two seasons is less dry allowing for year-round production. There is also production in valley bottoms drained during the dry season, complemented by limited production

Table 6.1. Potato production zones in Sub-Saharan Africa.

	East and Central Africa	Southern African and West-Africa	Sahelian zone
Altitude in m a.s.l.	Highlands above 1,500	Mid-altitude 1,200-1,500	Sea level
No. of seasons	2-3	1-2	1
Water source	Rainfed	Rainfed / irrigation	Irrigated
Dominant seed source	Self-supply	Self-supply	Import
	National formal seed system	National formal system	
		Import	
Type of potato producers	Smallholders	Smallholders and medium scale producers	Medium scale producers with some capital

using basic sprinklers or furrow irrigation. It is relatively easy for potato producers to recycle small tubers from their last harvest as seed for the next season. The year-round potato production means that pest and disease pressures are high. Potato production is done by smallholder producers and medium-scale farmers, while large-scale (mechanised) potato production is very rare.

Southern and Western Africa represents the second production zone, where the potato areas are located at mid-altitude (1,200-1,500 m a.sl.) where cool night temperatures occur, making potato production possible. Depending on the country, there are two rainfed seasons (Malawi, Northern Mozambique, Cameroon), or a single rainfed and an irrigated season (Nigeria, Southern Mozambique, Zimbabwe, Zambia, Angola). Potato farmers largely rely on self-supply of seed. Producers that only grow potatoes for a single season per year are more likely to buy seed from specialised multipliers or imported seed potatoes. Storing home saved seed for 7-8 months to bridge between the seasons, is (very) challenging under ambient temperatures occurring at mid-altitude. Some Southern African production areas are routinely served with South African seed potatoes. Potato production is mostly done by smallholders in Malawi, Nigeria, and Northern Mozambique. Medium-scale farms are more prominent in Southern Mozambique, Zimbabwe, Zambia and Angola.

The third production zone is the Sahelian region. During the dry season in countries like Guinea, Mali, Burkina Faso, Niger, but also Sudan, night temperatures drop and reach levels which allow for potato production. Production is irrigated, and seed potatoes are imported, as the high ambient temperatures and the long storage period between seasons make seed recycling virtually impossible; it would require cold storage. As production is based on imported seed potatoes and a water source is required, potato production in the Sahelian zone is done by better-off medium scale farmers with access to required capital.

6.3 Seed potato value chain analysis

The African potato seed system will be analysed in more detail using the Seed Value Sector Analysis model (Audet-Bélanger *et al.*, 2013). For each seed value chain component, Sub-Saharan

African characteristics are described and constraints for potato seed sector functioning are identified. Examples of past interventions and their results are discussed. Finally, the ability of HTPS technology to remove these constraints is evaluated. Table 6.2 summarises the text below and provides an overview of this step-by-step analysis of the Sub-Saharan African potato seed sector value chain and opportunities offered by HTPS.

Table 6.2. Potato seed value chain analysis (based on studies conducted by KIT Royal Tropical Institute for the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) in Cameroon, Mali, Nigeria, Kenya and Uganda and authors' personal observations).

	Characteristics	Constraints	Opportunities HTPS
Breeding	• Public mandate mainly • Mostly done by CIP • Desired traits not prioritised: – Short dormancy – Short growing season – Drought tolerance – Heat tolerance – Late-blight resistance – Bacterial wilt resistance – Virus resistance – Multi-purpose, little market segregation	• Under-funded • No private sector breeding focusing on SSA needs • Breeding for short dormancy reduces storability • Late-blight resistance associated with longer growing season (Collins *et al.*, 1999) • No reliable bacterial wilt resistance for potato • Virus resistance not prioritised by private sector	• Focused breeding for African desired traits • Specific traits can be bred into existing varieties using conventional breeding techniques.
Variety selection and registration	• Variety selection by NARS • Variety selection by Dutch private sector	• Long registration procedures in each individual country • Hesitance to register many varieties to cater for the diversity of demands of farmers and consumers	• Rapid multiplication, allowing for faster registration process and immediate release after registration
Early generation seed production	• Breeder seed, pre-basic seed often public • Basic seed private multipliers • EGS poorly available • Poor link between supply and demand for EGS	• Disease pressure, resulting in low quality • Lack of multiplication capacity • Fixed prices • Poor availability and timing of public EGS production	• Use of true seed as EGS – Reducing production to 1 season – Under fully controlled conditions – On very limited space • Bulk production in a single or few locations possible • EGS timing and distribution simple

Table 6.2. Continued.

	Characteristics	Constraints	Opportunities HTPS
Seed potato multiplication	• Seed potato multiplication by a limited number of medium-scale multipliers	• International private companies not able to find large-scale local partners • Large scale multipliers often lacking because of poor access to highland • Seed potato multiplication less economic than ware potato production • Cash flow constraints and risks for medium scale multipliers • Storage is a major cost and risk. • Non-sale is also a major risk.	• Seedling production possible on much smaller areas, saving land compared to conventional multiplication • Decentralised multipliers easily supplied with TPS • Possibly self-nursery (rather than seed plot, like rice)
Seed potato marketing and dissemination	• Limited marketing necessary. Demand is higher than the supply. Marketing largely done on reputation. • Often no adapted retail packaging • Few varieties on offer • Lack of pre-ordering systems	• Country-wide retailing difficult, but this is more theoretical as demand is higher than supply. • International trade is complex because of transport, sprouting and dormancy.	• For HTPS: Risk of non-sales lower, as less perishable • Wider marketing HTPS possible because light • In case of seedlings more staggered production is possible.
Seed potato use	• Farmers recycle seed from their own farm. • Farmers only occasionally buy certified seed.	• Farmer agricultural practices are sub-optimal, thus not making the best use of high-quality seed. • Farmer own seed quality management is sub-optimal.	• In case of TPS use, additional farmer training is a pre-requisite. • In case of tuber use, no difference with current system. Promotion of good quality seed use required.

Table 6.2. Continued.

	Characteristics	Constraints	Opportunities HTPS
Seed policy and regulation	• Regulation based on vegetative multiplication. • Phytosanitary rules for imports focus on quarantine disease risk management.		• Seedlings require a form of quality assurance. • Quality assurance for tubers exists, but may require some adaptation. • HTPS requires to be accepted under same conditions as hybrid vegetable seed for import and certification (truthful labelling).

6.4 Breeding and variety selection

6.4.1 Current practices, constraints, and opportunities

Specific potato breeding efforts for Sub-Saharan Africa are highly limited. The most important actor is the International Potato Center (CIP), which collaborates with the national agricultural research organisations (NARS) in African countries. The main breeding programme of CIP is located in Latin America and does not focus exclusively on African demands; it does have an eye for these demands. NARS receive at request candidate varieties for local variety selection. The international private potato breeding enterprises are not breeding specifically for Sub-Saharan African demand, which is understandable as the market for seed potatoes remains very small. They offer best-bet varieties from their portfolios in selected African countries.

The lack of focus on specific Sub-Saharan African traits has contributed to current narrow variety portfolios, which do not respond very well to producer and market demands. Producers and traders alike appreciate multi-purpose varieties, which are suitable for home consumption and production of French fries through single frying. Contrary to the global potato market, the bulk of French fries' production in the region is still done through hand-cutting and single frying in smaller restaurants and hotels. The market for frozen or vacuum packed pre-fried French fries is in its infancy. Furthermore, popular traits in Sub-Saharan Africa are a very short dormancy period, late-blight resistance, virus resistance, bacterial wilt resistance, earliness and heat and drought tolerance. Kaguongo *et al.* (2008) found these traits to be sought after by producers in Kenya and Uganda.

Short dormancy compromises storability making breeders reluctant to focus on it. However, in all bi-modal production areas in Sub-Saharan Africa, short dormancy enables producers to almost immediately replant their farm-saved seed. Losses during the storage period can reach up to 50%. Thanks to the short or non-existent dormancy period, farmers do not have to store their seed tubers and can avoid the risk of high losses. In Kenya, during the early 2000s the landrace Nyayo was more popular than other formally released varieties because of a dormancy period of

3 weeks. Similarly, the most popular Kenyan variety of today, Shangi, is also appreciated for its very short dormancy period, and has been registered formally only after having emerged as a landrace.

Late blight and virus resistance have been the focus of the CIP but have not been prioritised by international commercial breeders. The European market has focused on full chemical control and zero disease tolerance rather than integrated disease management, which better matches the needs of African farmers. Virus resistance slows down seed degeneration and hence, reduces the need to renew seed, which is not aligned with interest of commercial breeding companies. Varieties with stable bacterial wilt resistance have not been developed until today. The first late-blight resistant varieties developed by international potato breeding companies are entering the market now.

In the East African highlands as well as the West and Southern African mid-altitude production zones, a medium level of late-blight resistance is the minimum requirement for smallholder potato producers. Most potato production in these areas is rainfed, while late-blight control by farmers is mediocre. Consequently, there is high late-blight pressure in the potato production areas during the rainy season. Smallholder farmers rely on hand-operated knapsack sprayers, which result in sub-optimal crop cover. Moreover, they tend to have access to a limited selection of fungicides of variable quality. In summary, management of the disease is difficult when growing susceptible varieties. Problems are exacerbated by the lack of regular dry spells during the main rainy season allowing the fungicide to dry on the crop. A high level of varietal resistance significantly reduces the risk of high crop losses, and farmers can get away with fewer and imperfect crop protection measures.

In most countries, smallholder potato producers seek for super early maturing varieties for a variety of reasons. Generally, potato production is practised on prime land, in prime agro-ecologies, where land pressure is high. Rapid returns on investments are crucial for cash-short smallholders farming small plots. In bi-modal rainfall areas, or irrigated areas, farmers want to clear their land quickly to move to the next crop in their rotation scheme. In other areas, such as Nigeria, farmers need early varieties to escape the peak of late-blight disease pressure.

Considering the rainfed nature of smallholder potato production in Sub-Saharan Africa, drought tolerance is of major importance. Rainfall patterns are becoming less reliable due to climate change. Also, increased tolerance of potato plants to higher soil temperatures would expand the area where potatoes can be grown commercially to more tropical conditions and lower elevations. Currently, potato growing area is constrained by the requirement of moderate average daily temperatures (below 18 °C), but better still 15 °C) to trigger tuberisation, enhance tuber bulking and increase dry matter content (Struik, 2007).

6.4.2 Opportunities hybrid true potato seed

The major benefit of HTPS varieties is that they are diploid hybrids, making targeted breeding for the specific traits appreciated by Sub-Saharan African producers and consumers possible and more affordable (Ter Steeg *et al.*, 2022a). Breeding of tetraploid potato varieties is based on making best-bet crossings from pre-breeding lines and requires assessment of field performance of the entire progeny. Breeders 'hope' to 'discover' individual plants that outperform established cultivars: effectively, it remains a game of chance and can take decades to find varieties. In contrast, the diploid genome of HTPS varieties allows for targeted inclusion of desired traits ('trait-stacking') from wild potato species or existing cultivars through conventional breeding techniques. This can be done as rapidly as within 2 years (Lindhout *et al.*, 2011; Su *et al.*, 2019), once a broad collection of parent lines is available allowing for gradual improvement of (diploid) varieties. With diploid varieties, a potato breeding programme could be launched, which takes into consideration the demands of African farmers and consumers, which currently receive little attention in commercial breeding (Beumer and Stemerding, 2021). Still, hybrid breeding is still a highly expensive undertaking, and companies tend to prefer markets with more secure returns on investments. A dedicated potato breeding programme for the low-tech Sub-Saharan African market will require public-private collaboration (Ter Steeg and Lindhout, 2022; Ter Steeg *et al.*, 2022a).

6.5 Early generation seed production

6.5.1 Current practices, constraints and opportunities

The potato early generation seed (EGS) production chain is, without exception, underperforming in Sub-Saharan African countries. The few existing commercial seed potato multipliers are almost without exception struggling to obtain a reliable supply of quality starting material. The ordering and distribution system of potato EGS is functioning poorly across countries; provided there even is a 'system'. In East Africa, the public research institutes play a pivotal role in EGS production. They maintain breeder seed as *in vitro* plantlets and run limited rapid multiplication operations to produce mini-tubers. Public institutes are not profit-driven and do not respond directly to market incentives. Consequently, production volumes of mini-tubers are often too low, and production timing tends to be suboptimal.

In Kenya, Ethiopia, Rwanda, Burundi, Malawi, Tanzania and Uganda, public and private mini-tuber producers have emerged with assistance of development actors assuring a broader base of mini-tuber sources (Schulte-Geldermann *et al.*, 2022). The private mini-tuber producers tend to remain dependent on the NARS for their supply of rooted plantlets. Still, it is difficult for private actors to enter the market and compete with inefficient public actors as mini-tubers are often sold at artificially cheap prices using subsidies. Involvement of private producers at different stages of EGS production could assure that multipliers further down the chain do not rely fully on the public ability to produce and distribute EGS. In Kenya and Rwanda, the seed potato system has advanced, and there are private operators maintaining and rapidly multiplying *in vitro* plantlets and producing mini-tubers for (semi-)private multipliers. Such examples of privately run for-profit *in vitro* laboratories producing potatoes plantlets remain scarce (Harahagazwe *et al.*, 2018).

Importation of mini-tubers or other EGS materials from Europe for multiplication is the 'go-to alternative' of private enterprises. It reduces the required investment and hence, risk for breeding companies. However, phytosanitary regulations in most East African countries have made this cumbersome. There has been a strong push over the last decade to simplify import regulations for both advanced breeding materials and potato EGS. In West-Africa, countries like Cameroon, Mali and Burkina Faso rely entirely on imported European seed potatoes. Nigeria has the largest area under potato cultivation of the African continent with more than 300,000 hectares in production annually (Gildemacher and Belt, 2019; Ugonna *et al.*, 2013) but a rapid multiplication system is non-existent, and the few seed potato multipliers rely fully on haphazard import of certified seed from Europe as starter material (Gildemacher and Belt, 2019). In some countries, for example Burundi, prices of the first generations of seed potatoes are fixed by the public seed regulatory body, which has a distorting effect. Fixed, low prices of pre-basic seed make it attractive for seed multipliers to buy pre-basic seed in larger quantities and reduce the number of multiplication cycles they do themselves. As a result, the limited amount of high-quality seed available flushes out early and loses its value. Advocacy by the seed multipliers to abandon the fixed prices have proven idle until today, as the governments resort to price fixing to keep seed potatoes affordable for smallholders.

Seed-borne diseases such as bacterial wilt and viruses pose a significant challenge for EGS production. In many Sub-Saharan African countries, bacterial wilt is endemic and multiplying EGS without attracting any infection is an uphill battle and risky business. It has proven very difficult to keep viruses at acceptable levels during the first field generations. EGS is usually grown in the middle of potato production zones, and isolation of EGS fields is difficult. Isolation of EGS fields is required by law in Nyanza, Zimbabwe since 1956, but these rules are hard to enforce (Svubure *et al.*, 2016).

Alternative rapid multiplication techniques to make the EGS production more efficient are currently being tested. Sand hydroponics, aeroponics and apical cuttings have been applied with varying levels of success. These technologies definitely hold potential to improve the EGS value chain (Schulte-Geldermann *et al.*, 2022). However, required investment for an aeroponic facilities is high and returns cannot be obtained in the absence of a functioning multiplication system.

6.5.2 Opportunities hybrid true potato seed

With HTPS, EGS can be produced from true potato seed rather than potato seed tubers. This changes, and significantly simplifies the EGS production system. EGS can be produced and processed, as is done for tomato hybrids, at few locations in the world and is easily shipped to clients by air mail or courier. Seed of parent lines can be produced under fully controlled and secure conditions, and the F1 seed for global distribution in a single field generation. For HTPS, local maintenance and rapid multiplication of *in vitro* materials are not required, nor is a system in which mini-tubers are produced from *in vitro* plantlets. Effectively, the effort of setting up a new or improving the dysfunctional EGS chain can be avoided completely. Additional advantages are the virtual absence of seed-borne diseases in HTPS, absence of seed dormancy, low perishability, and last but surely not least, the ease of logistics. Considering that it is invariably difficult to produce potato EGS for profit in Sub-Sahara Africa, HTPS offers a strong potential alternative. A country like Nigeria, with no *in vitro* laboratory producing potatoes, can invest in developing a multiplication system based on HTPS, rather than building a full potato EGS system based on *in vitro* multiplication.

6.6 Seed potato multiplication

6.6.1 Current practices, constraints and opportunities

It remains a major challenge for seed multipliers to obtain a sufficient supply of EGS in terms of quantity and quality. In most cases, their enterprise depends on the performance of a single source of mini-tubers, or if there are multiple sources of mini-tubers, these depend on a single source of *in vitro* plantlets. High disease pressure makes it impossible for seed producers to multiply many generations, especially due to viruses and bacterial wilt.

A challenge blocking the development of a commercial seed multiplication system is that in most areas where potatoes are grown, large landholdings are relatively scarce. Larger areas facilitate crop rotation and a minimum of four seasons is recommended for seed potato production. This recommendation is a requirement for most certification schemes and makes it less attractive for farmers to grow seed. Potato is the main cash crop in highland areas. In the absence of high price premiums, farmers will prefer to grow ware potatoes (almost) every season instead of seed potatoes every four seasons. In addition, the time gap between seed potato production and seed potato marketing is hard for smallholders, as they are cash-strapped, and run into cash-flow problems if they cannot immediately sell their produce after harvest.

As a result, commercial seed potato multiplication is practised mostly on medium-scale farms of 5 ha and larger. Large-scale seed potato producing farms are uncommon, as large farms in general are hard to find in the high-altitude and mid-altitude areas. International seed potato companies struggle to enter the market because there are no large local farms to partner with. The companies seek large and reliable local partners to multiply seed tubers and bring their varieties to the local market in an affordable way. In Kenya, there are a few larger farms in the highlands, which are collaborating with Dutch potato trade companies HZPC and Agrico to do multiplication at a larger scale. Similarly, HZPC has co-invested in the development of the seed potato multiplication value chain in Ethiopia. In Burundi, the number of medium-scale seed potato producers has grown exponentially in the past years supported by a ready market and development projects.

Table 6.3. Classic rapid multiplication generations compared to HTPS multiplication system.

Classic rapid multiplication		HTPS	
Method	**Generation**	**Method**	**Generation**
In vitro germplasm maintenance	0	Simple dry storage true seed of parental lines	0
In vitro rapid multiplication	1	F1 hybrid seed production	1
Mini-tuber production	1	Seedling production	2
Field multiplication	2, 3, 4, 5, 6, 7, 8	Field production seed tubers	2

6.6.2 Opportunities for hybrid true potato seed

HTPS will change the *modus operandi* of seed multipliers. Currently, they buy mini-tubers, pre-basic or basic seed, which they multiply one or more seasons. When adopting HTPS, it will no longer be necessary to multiply seed tubers for several seasons, as multiplication is done during the true seed phase. The role of seed multipliers would likely be to transform HTPS into familiar starting material. Effectively, the seed potato chain can be reduced to a true seed-based multiplication phase, and a true seed to planting material conversion step (Table 6.3). The future role of seed multipliers in this chain will depend on the choice of seed users: will they continue to use seed tubers, convert to seedlings, raise their own seedlings or adopt direct seeding of HTPS? It should be noted that this choice will not only depend on the farmer, but also on the innovation itself and whether direct sowing becomes feasible, for example, through the use of coating.

For the Sahel production system, HTPS will offer business opportunities for local multipliers. Currently, local multiplication is complex with cold storage being a necessity during the hot season. With HTPS, the opportunity emerges to produce seedlings locally offering an alternative for seed tubers imports from Europe. In countries with year-round temperate conditions in the potato producing areas, seed multiplication based on HTPS has major transformative potential. Multipliers are no longer dependent on a supply of sprouted seed tubers and can germinate true seed according to demand. Moreover, multipliers with access to irrigation can plant seedlings for the production of seed tubers year-round. In Nigeria, in the absence of an existing seed potato multiplication system, HTPS could be a breakthrough technology.

The success of the HTPS technology will depend to a large extent on the development of a cost-effective and efficient multiplication system, offering quality seed potatoes at an attractive price. HTPS must be marketed at an affordable price: competitive with existing sources of EGS and compatible with the purchasing power of potato growers buying seed tubers from the multiplier. Local seed multipliers need to learn to use and economically optimise the production of seedlings and seed tubers from HTPS.

6.7 Seed potato marketing

6.7.1 Current practices, constraints, and opportunities

In West-Africa, seed potato marketing is based on import of seed potatoes, both for the mid-altitude as well as for the Sahel production systems. Farmer organisations play an important role in accumulating orders of farmers into block-orders to potato trade companies from France and the Netherlands. In East and Central Africa, seed potatoes are mostly sold directly by seed potato multipliers at the farm gate. Demand is so high that certified seed producers do not need to put in much effort to sell their produce: clients come to them. Considering the fragile nature of seed tubers and need for good storage conditions, this system serves both the producer and client. However, it does make certified seed potatoes difficult to access for those producers with no ability to travel. Last-mile access to quality seed potatoes is better when seed producers are spread throughout potato production areas. In the absence of effective certification systems, the reputation of a seed supplier shapes purchasing decisions of ware producers. Proximity of seed multipliers to ware potato producers is important because farmers may prefer to buy from their neighbours as they can visit their potato fields and storage facilities themselves. A relation of trust between client and supplier offers a local substitute for a certification system.

6.7.2 Opportunities for hybrid true potato seed

The low volume and limited perishability of HTPS allow for a simple distribution system facilitating decentralisation of seed multiplication. HTPS can be marketed to multipliers through existing marketing channels such as seed shops selling staple crop and vegetable seed. It should be noted that potato farmers, multipliers but especially ware producers, may not be connected to these channels at the moment. Last-mile distribution reaching ware potato growers will likely still be arranged via direct marketing from seed multiplier to seed user because of the importance of a trusting relationship. Alternatively, a mail or courier system can be used. Marketing of potato seedlings, raised from HTPS, is a possible new way to commercialise potato planting material. Seedling producers for vegetable crops are emerging in Kenya and Ethiopia. It remains to be seen whether ware potato producers deem seedlings an attractive alternative for seed tubers. In Sahel countries, seedlings may well become popular with the only alternative being expensive imported seed tubers. In other countries where seed multipliers can opt for production and marketing of seed tubers, the competitiveness of marketing seedlings as planting material to ware potato producers is doubtful. Ware producers may be reluctant to change as production from seedlings is much more cumbersome than planting sprouted seed tubers.

6.8 Seed potato use

6.8.1 Current practices, constraints, and opportunities

Currently, only a small proportion of potato seed tubers planted are sourced from specialised multipliers, who produce seed potatoes for a profit. For the greatest part, seed and ware potato production systems overlap: most seed tubers planted in Sub-Saharan Africa are smaller tubers harvested from ware potato fields which are graded, stored, and then re-planted. Farmers usually select and save their own seed. If they (have to) sell most of their harvest or suffer losses during storage, they source seed tubers from neighbours or on the local market, where in potato areas small tubers are sold as planting material. In Eastern Uganda, traders who collect potatoes, sort potatoes based on size and sell the 'less marketable' small tubers as seed on local markets at the start of the next season. In Nigeria, these small potatoes represent the only source of seed available on the market.

The rate at which potato producers renew their seed differs. In countries, where bacterial wilt is highly endemic, such as Rwanda and Burundi, farmers are more inclined to renew their seed regularly. A study by Gildemacher *et al.* (2009) showed that in Kenya 41% and in Uganda 26% of farmers indicated to renew their seed regularly, on average farmers did so once every 6-7 seasons, which is very low. Ever since, the supply of quality seed potatoes, either certified or quality-declared, is growing, thanks to public-private efforts to build for-profit seed potato systems. More recent research by Mumia *et al.* (2018) showed that in Kenya nowadays over 80% of farmers regularly replace their seed stock, with an average frequency of once per four seasons. In the experience of the authors, increased volumes of quality seed potatoes find a willing market. The major issues are quality guarantees, timely distribution, and affordability. There is sufficient demand from ware producers, but the seed system fails to deliver at the right time, at the right place and at the right price.

Seed potato recycling ('using farm-saved seed') by ware potato producers is not necessarily a bad practice. In many situations, ware potato farmers have little choice, as quality seed potatoes are simply not available in the reasonable vicinity of their farms. Furthermore, it may be the least risky decision considering the low availability of quality seed, high price of certified seed and unknown quality of purchased seed. Depending on the level of seed degeneration and associated yield loss, recycling seed potatoes for a number of seasons can be an economically sound farming practice. The lack of a reliable seed quality assurance system also poses a serious risk. There may be no or little guarantees regarding quality of certified seed tubers sourced from an anonymous formal system. Two technologies are being promoted to improve the quality of recycled seed: small seed plots to assure one season of multiplication by the ware potato farmer under controlled conditions (Demo *et al.*, 2015) and positive selection (Gildemacher *et al.*, 2012).

Not all ware potato producers are aware of the major impact of seed quality on the production potential. A large component of the loss of yield potential results from accumulating virus infections. Virus infections are only visible to the trained eye. In Kenya, ware potato producers and public extension officers alike deemed heterogeneity of potato plant appearances as a normal feature of the potato crop. They were unaware that differences in appearance were caused by virus infection. Similarly, in Nigeria, farmers explained how they selected seed potatoes from light-coloured plants in the belief that it was a special variety. However, the authors expect the light-coloured plants were virus infected. Demonstration projects can raise awareness, while simultaneously increasing demand for quality seed. The authors witnessed the positive impact of demonstrations with quality seed potatoes on the seed potato market in Burundi.

6.8.2 Opportunities for hybrid true potato seed

It is highly likely that most ware potato producers will prefer seed tubers over tedious true seed or fragile seedlings. Contrary to vegetable farmers, potato producers are not used to working with seeds and raising seedlings. Tubers are robust and have a short growing season. Transplants, either produced by specialised young plant raisers or farmers themselves, could provide an alternative. However, transplants are fragile and initially require more care including irrigation, as they are susceptible to drought. Hence, most smallholders in the East and Central African highlands as well as the West- and Southern African mid-altitude areas may continue to use tubers as starting material. Adoption of seedlings is more likely in the Sahelian zone, where seed tubers are hard to store during the hot period between the potato growing season, and the single source of quality seed is importation. Potatoes are grown during the dry Harmattan season using some form of irrigation. Hence, it makes the transition to seedlings easy and practically possible for all potato producers.

Potential benefits of HTPS for smallholders are threefold: improved access, improved quality, and reduced cost of quality potato seed. The cost reduction is expected as a result of the simplification of the seed potato chain from up to eight generations of multiplication to only two generations, the F1 hybrid true seed and the production of seed tubers from this true seed (Table 6.3). This will improve the seed health, as there is no seed-borne disease build-up possible over generations. It will reduce costs, as multipliers require fewer generations, which reduces storage losses, it reduces the required effort per kg of seed tubers, and the risk and working capital required. Transport costs will also be significantly reduced. Finally, it will be possible to decentralise the seed tuber production much easier, which can bring the seed tubers closer to the ware potato producers, making access to quality seed potatoes easier.

6.9 Seed policy and regulation

6.9.1 Current practices, constraints, and opportunities

When considering the enabling environment of the seed potato sector, there are four main topics: import regulation, variety registration and release, plant variety protection (PVP) and quality assurance (Ter Steeg *et al.*, 2022b). Import regulations are focused on the management of phytosanitary risks. Usually, a distinction is made between importation of research versus commercial material. Research material can be imported more easily, commercial material only when a variety is registered in the national variety catalogue. A certificate of disease testing from the exporting country is required, and additional post-entry quarantine or testing measures are sometimes required. These measures make seed potato export from Europe cumbersome and expensive.

Variety registration in many Sub-Saharan African countries is a (relatively) long process as NARS and national regulatory bodies require the assessment of variety performance for several seasons. Candidate varieties must pass a distinctness uniformity stability (DUS) test to get registered as a new variety. Some countries accept European DUS test reports, but most require local DUS testing. Next value for cultivation and use (VCU) tests are demanded for registration in national variety catalogues. Traditionally, much emphasis has been placed on genotype by environment interaction and yield, while less emphasis has been placed on meeting diverse market demands of producers, processors, and consumers. In the last decade, engagement of the international private sector has contributed to a gradual shift and appreciation of a diverse variety portfolio, allowing producers to choose and catering for different market demands.

Shorter variety registration process or complete abandonment of national variety trials are widely voiced desires in the international private sector. Burundi shows that speeding up procedures is feasible, as its variety testing and registration process have successfully been shortened to one year (or two seasons), through a collaborative effort of seed sector actors. Implementation of harmonised variety release protocols and variety catalogues of the Common Market for Eastern and Southern Africa (COMESA), the Economic Community of West African States (ECOWAS) and the Southern African Development Community (SADC), could further reduce regulatory barriers making more varieties available to farmers.

Variety registration is linked to PVP. In many countries in the region, PVP is either not regulated or implementation of regulations remains a challenge. PVP is of particular importance to international potato breeding companies because they want to protect their varieties. Contrary to single-use products like hybrid maize or vegetable seed, potato varieties can be multiplied vegetatively by farmers. Therefore, companies are careful when exporting tubers or other planting material to countries with a weak enabling environment.

Potato seed certification schemes offer quality assurance of seed potatoes. Certification procedures usually entail field inspections, tuber sampling and laboratory testing to ensure the quality of seed. Subsequently, seed potatoes are labelled as being of 'certified' quality. Seed potato certification is logistically cumbersome. Functional and trustworthy certification systems are still rare in the region. Only in a few countries, such as Zimbabwe and Burundi, the certification system is operational, and certificates offer a reasonable quality guarantee. Seed potatoes are inspected, tested in a laboratory, and labelled within a reasonable time. Kenya, Uganda, Rwanda and Ethiopia continue their efforts to improve the performance of the certification system. Considering the impact of the seed-borne disease bacterial wilt, a seed inspection system has to involve field inspections during the growing season, in combination with tuber sampling and laboratory testing, which requires decentralised inspectors and facilities (Gildemacher *et al.*, 2017) to assure timely delivery of the certificate. In some cases, testing labs are not operational making certification impossible. In other cases, the staffing might be insufficient to do field inspections.

6.9.2 Opportunities for hybrid true potato seed

Importation of HTPS poses a much lower phytosanitary risk as the seeds are not produced in soil. There are only six seed-borne viruses, which can be avoided when producing hybrid seeds under sterile conditions (Lindhout *et al.*, 2018). Hence, HTPS can likely be legally categorised and treated as vegetable seed rather than potato seed tubers. Vegetable seed is simply tested in the country of origin with additional checks via random sampling and quality testing, rather than requiring a full post-entry quarantine system. Initially, countries may require similar tests and procedures for HTPS and seed tubers because they apply the same policies to all potato starting material. However, it should be feasible to push for a more liberalised import procedure similar to the one applicable for vegetable seed.

HTPS variety registration is a matter of national and regional policy. On the one hand, it can be argued that 'diploid' HTPS varieties are somewhat comparable to conventional 'tetraploid' potato varieties. Hence, they can be subjected to the same variety registration requirements and tetraploid local checks can be used during VCU testing. On the other hand, diploid HTPS varieties can be grown from true seed and seedlings instead of seed tubers, and the type of starting material will impact the growth cycle and yield. It might be necessary to define distinct testing protocols and requirements for true seed, seedlings, and seed tubers. An important element is that variety registration takes into consideration the diversity of demands of the potato industry and also considers desired traits such as earliness, pest and disease resistances and processing qualities.

The quality assurance system for HTPS may be simplified and again, comparable to the system used for vegetable seed. In most countries, hybrid vegetable seed is commercialised using 'truthful labelling', rather than deployment of a full seed certification system. Truthful labelling requires the seed supplier to state the seed quality on the packaging and makes the supplier liable if seed does not meet the indicated quality standards. Hence, there is no need for independent field inspections and laboratory testing. Whenever seed tubers are grown from HTPS by specialised multipliers, seed certification would still be necessary. The quality assurance system process would then be comparable to vegetatively propagated seed potatoes. However, HTPS might be a good match for new decentralised systems like quality declared seed, which offer localised and cheaper alternatives for full certification.

6.10 Discussion

Seed potato systems in Sub-Saharan Africa differ from those in Europe. Farmers tend to save their own seed rather than sourcing seed potatoes from specialised multipliers on a regular basis. This decision to recycle seed makes sense considering the high price, low availability and uncertain quality of seed potatoes sold on the market. So far, the impact of attempts to develop formal seed potato systems and increase farmer adoption of quality seed have been limited. Nonetheless, improving the performance of potato seed systems remains and should remain a key priority as low-quality seed remains the single most important depressant of potato yields. Enhanced use of high-quality potato seed has tremendous potential to improve farm productivity and raise smallholder incomes.

There are several reasons for the limited success of previous potato seed sector interventions, which focus on imported seed tubers or rapid multiplication. The import model is difficult to launch in the absence of larger local farms, which can serve as partners of international potato seed companies. These companies seek to partner with one or few larger local multipliers to make their seed available on the local market. These partners are hard to find in areas suitable for potatoes, as these areas have a high population density, and sub-divided landholdings. Also, current variety portfolios of international commercial potato traders are not tailored to specific sub-Saharan African market demand, which makes that it is difficult to reach the mainstream market. Especially, short dormancy and late blight resistance are desired but underrepresented in private portfolios. Finally, several regulatory challenges exist blocking the importation of seed tubers because of phytosanitary risks and/or political reasons.

Launching the second model based on rapid multiplication also turns out to be difficult. It has been a struggle to establish functioning tissue-culture labs. It has proven even harder to establish for-profit labs making these operations commercially viable. The market for potato EGS is relatively limited, which does not make it an easily rendering investment. Kenya and Rwanda are exceptions having a more advanced system with private operators maintaining and rapidly multiplying *in vitro* plantlets and producing mini-tubers. In Kenya, a small but fully commercial EGS production chain exists, which operates in parallel to the public system. In other Sub-Saharan African countries, potato EGS production relies on inefficient production by public services.

HTPS technology could be the driver of potato sector development in Sub-Saharan Africa as it addresses some fundamental challenges of the conventional vegetative multiplication system. The land requirement for an HTPS based seed potato system is reduced, as fewer generations are needed. The constraint of EGS availability can be solved, as EGS can be produced centrally, in large quantities, with very high quality. HTPS can be distributed and stored easily, making a single highly localised multiplication into seed tubers possible. The quality of these locally produced seed tubers will be higher, and the costs are expected to be lower compared to the convention vegetative multiplication. Finally, breeding for specific demands is possible with diploid HTPS, offering a long-term perspective of varieties adapted to African smallholder potato farmer needs.

Despite these obvious advantages, HTPS will not be an instant success. The impact of HTPS in Sub-Saharan Africa will depend on a match with smallholder farmer needs and economics, which are based on principle of prudence and risk minimisation. It is likely that smallholder potato producers will prefer seed tubers over HTPS or seedlings. Seed tubers are much more robust in comparison to HTPS or seedlings. In the Sahelian zone, where irrigation of potato fields is already common, ware producers may be more likely to accept buying seedlings or producing seedlings themselves. Therefore, the main potato transformation would have to take place upstream in the value chain where specialised multipliers will play a crucial role converting HTPS and seedlings into familiar seed tubers. Furthermore, adoption will require HTPS varieties to match local preferences such as short dormancy, late-blight resistance and earliness. These varieties still need to be developed and made available at an affordable price.

HTPS has the potential to radically transform seed potato systems in sub-Saharan Africa and contribute to smallholder income and food security. Past interventions in the seed potato sector in Sub-Saharan Africa demonstrate that one cannot expect a new technology to be a self-multiplying success. In order to realise the potential impact of HTPS in sub-Saharan Africa, specific efforts are needed. Firstly, public-private partnerships are needed to breed varieties tailored to local demand and focusing in particular on smallholder farmers in the tropical lowlands. The current market is too small and risky to make tailored breeding commercially interesting for the private sector. Secondly, ware potato producers need training on the seed degeneration and the added value of quality seed, combined with good agricultural practices. Finally, a last-mile retailing system with quality assurance will present another challenge. Seed potatoes should be produced close to farms to reduce logistical challenges minimising effort and costs to purchase and transport the seed.

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Chapter 7. How could hybrid true potato seed foster development in potato sectors in East Africa?

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Abstract

Hybrid true potato seed (HTPS) holds the promise to foster development in potato sectors in East-Africa. Compared to a conventional production system based on clonal propagation of tetraploid varieties, clear advantages of HTPS are easier transport and storage of starting material, high multiplication rates, increased availability of disease-free planting material and faster and more targeted breeding. Despite these advantages, an informed assessment of how HTPS can be implemented into East African seed and farming systems, and of what the enabling conditions are for such implementation is still necessary. Our aim is to understand if and how HTPS could foster development of potato sectors in East Africa and what are the major opportunities and bottlenecks. We describe the context of potato production in East Africa, and we summarise the key lessons from past experiences with the implementation of (non-hybrid) true potato seed. This informs our analysis of the requirements for an effective and inclusive introduction. Major requirements are a solid understanding of: (1) the criteria farmers use to assess the innovation; (2) local farm realties; and (3) the seed system in which farmers operate. The implementation of HTPS requires adaptations in agronomic management and in seed system configurations, but these adaptations need to fit into the agro-ecological and socio-economic context. This can be achieved through an iterative research cycle linking farmers, researchers, breeders and other stakeholders. To facilitate institutional embedding of the innovation, interactive, multi-stakeholder processes are required to develop shared views on the acceptability, sustainability and societal desirability of HTPS. We conclude by drawing a research agenda with urgent questions that need empirical research prior to and during the introduction of HTPS in East Africa.

Keywords: seed system, SWOT analysis, participatory research, technology characteristics, research agenda

DOI: 10.3920/978-90-8686-946-6_7, © H. den Braber *et al.*, 2023

7.1 Introduction

The potential of hybrid true potato seed (HTPS) to foster development of potato sectors throughout Africa has been recognised by companies, researchers, NGOs and governments. East Africa is commonly mentioned as the first region were HTPS may have an impact (De Vries *et al.*, 2016; NFP, 2021; Stemerding *et al.*, 2020). In this region, potato is a vital source of food and cash for smallholder farmers (Gildemacher *et al.*, 2009b; Devaux *et al.*, 2014). The area under potato cultivation quadrupled in the last few decades and consumer demand increased steadily, but yields stagnated at levels around 8-10 tons/ha, far below potential yields (Gildemacher, 2012).

7.1.1 The promises of hybrid true potato seed

HTPS has the potential to foster development of the potato sector in East Africa, for four major reasons. First, hybrid breeding strongly accelerates the introduction of favourable traits (Jansky *et al.*, 2016; Lindhout *et al.*, 2011). This enables faster development of new varieties attuned to regional needs, for instance in terms of disease resistance (Lindhout *et al.*, 2018).

Second, HTPS has the potential to circumvent seed degeneration through providing clean starting material, since HTPS does not transmit any economically important pathogens (Lindhout *et al.*, 2011). Seed degeneration is caused by the build-up of pests and pathogens in the starting material due to successive cycles of vegetative propagation, and results in reduced potato yield or quality (Thomas-Sharma *et al.*, 2016). Currently, the majority of potato farmers in East Africa rely on farm-saved seed tubers as starting material, hence transmitting seed-borne pests and diseases from one crop cycle to the next (Gildemacher *et al.*, 2009a).

Third, compared to bulky, perishable seed tubers, HTPS can be stored and transported more easily, and in far greater numbers because propagation by means of true (i.e. botanical) seeds from the berries of the potatoes becomes possible. Especially in places with poor infrastructure, in landlocked areas or in remote rural places, HTPS could eliminate logistical challenges of the transport and storage of potato starting material.

Fourth, propagation by means of true seeds results in much higher multiplication rates compared to seed tubers. Conventional clonal propagation by means of seed tubers results in multiplication rates of ten, but with vegetative propagation, multiplication rates of a thousand and higher are possible. Using HTPS, sufficient planting material for a new variety can be obtained within one or two seasons, while it can take up to up to eight seasons in the conventional propagation system. This decreases the potential for disease build-up during multiplication rounds and reduces the costs, time and area requirements of multiplication (Van Dijk *et al.*, 2021a).

These four advantages of HTPS could result in considerable improvements in terms of access to high quality, disease free starting material for farmers.

7.1.2 Aim

Despite these promises, there is an informed assessment needed on how HTPS can be implemented into East African seed and farming systems, and what the enabling conditions are for such implementation. While HTPS is a possibly disruptive technology (Beumer and Edelenbosch, 2019; Stemerding *et al.*, 2020), it is unknown how it performs under farmers' field conditions in East Africa, how it fits in the agro-ecological, economic and institutional context and what the impacts could be in various sustainability domains. In this chapter, our general aim is to understand if and how HTPS could foster development of the potato sector in East Africa and what are the major opportunities and bottlenecks.

7.1.3 Outline

The specific steps to reach the abovementioned aim are discussed in separate sections:
- describe the context of potato production in East Africa;
- summarise the key lessons from past experiences with TPS;
- understand the requirements for an effective and inclusive introduction;
- analyse strengths, weaknesses, opportunities and threats of HTPS;
- develop a research agenda.

7.2 Potato production in East Africa

This section characterises the context of potato production in East Africa in terms of current seed systems, cropping systems and common diseases, with special attention to relevant issues for the introduction of HTPS.

7.2.1 Seed systems

Potato seed systems in East Africa are mostly informal, which implies that selection, production and diffusion of seed tubers occurs mostly through informal networks (Gildemacher *et al.*, 2009a). Diffusion of new potato varieties in informal seed systems happens via friends, relatives and neighbours and through purchasing at local markets. By contrast, formal seed systems are characterised by the involvement of public or private actors who have controlled procedures for seed production, multiplication and release (Louwaars and De Boef, 2012). In East Africa, only a small proportion of the seed tubers used comes from the formal sector, as seed tubers are often not available or simply too expensive for smallholder farmers. In some countries in the region, commercial certified seed schemes are in development, e.g. in Kenya (Kwambai *et al.*, 2022), where small and large seed growers produce and sell certified seed to ware growers who are commercially oriented. This is especially possible in countries with a market for high quality table or processing potatoes. But it also requires a cost-effective production system of early generation seed.

A recent study on informal seed potato systems in Ethiopia found that farmers who received a new potato variety dispersed seed potatoes to more than six other farmers on average. The informal networks in which the seed potatoes were shared were differentiated by gender, wealth and religion: new variety seed potatoes tended to flow from rich to poor farmers, men were more likely to disperse to other men, and dispersion happened more often between people of the same religion (Tadesse *et al.*, 2017a). A main advantage of the informal seed system for potato farmers is that planting material can often be obtained without spending cash. In addition, the above example shows that diffusion of new varieties via informal networks can be an effective strategy, if new varieties are distributed strategically to a diverse group of source farmers. A major disadvantage of the informal seed system is that the planting material circulating in it is almost never free of pest and pathogens. Since potato crop growth, development and yields are highly determined by the quality and health status of the seed tuber, seed degeneration is a major problem (Haverkort and Struik, 2015). For instance, in Kenya and Uganda, respectively 59% and 75% of the potato growers rely entirely on farm-saved seed tubers as starting material, hence transmitting seed-borne diseases from one crop cycle to the next. Buying seed tubers is often not economically viable and the supply of good quality seed tubers is highly insufficient. In addition, 97% of seed tubers sold on Kenyan local markets were found to contain at least one important potato virus (Gildemacher *et al.*, 2009a). Hence, the lack of clean planting material and high disease pressure are two major, interlinked causes of poor yields in East Africa (Gildemacher *et al.*, 2009b; Schulte-Gelderman, 2013). A survey among potato scientists in developing countries reported that: 'the need for improved seed production methods was expressed as an important or very important need by all of our survey respondents' (Fuglie, 2007, p. 359). In this regard, the advantages of HTPS in terms of disease-free seeds, easy transport and storage and high multiplication rates are clear, but what type of seed system configuration is needed to accommodate HTPS remains a major knowledge gap.

7.2.2 Cropping systems

Potato cropping systems in East Africa are dominated by smallholder farmers, who grow potatoes as a major food and cash crop. Due to a bimodal rainfall distribution, potatoes can be grown twice per year throughout most of the East African highlands. In general, land pressure in potato growing areas in East Africa is high and farm sizes are usually between 1 and 2 hectares (Gildemacher *et al.*, 2009b). As a result, rotations are often very short. In Kenya and Uganda, the majority of farmers allocate more than 25% of their farm area to potato (Gildemacher *et al.*, 2009b; Muthoni *et al.*, 2013). In Rwanda, and in some Kenyan districts farmers dedicate on average almost half of their farm area to potato (Muhinyuza *et al.*, 2012; Muthoni *et al.*, 2013). Short crop rotations, in combination with the use of contaminated seed tubers, result in high disease pressure and low yields. In turn, the poor yields result in relatively low profitability of potato farming, and farmers using risk-averse strategies (Figure 7.1) (Gildemacher *et al.*, 2009b; Janssens *et al.*, 2013). In general, potato is grown as a monocrop. Other main crops grown by potato farmers are maize and beans in Kenya, Uganda and Rwanda, whereas grain crops such as barley, wheat and teff are important in Ethiopia (Gildemacher *et al.*, 2009b). Cabbage is widely grown in Kenyan potato areas: depending on the district, 30-60% of potato growers grow cabbage (Muthoni *et al.*, 2013). In Rwanda, vegetables were ranked as fourth important cash crop by potato farmers (Muhinyuza *et al.*, 2012). In East Africa, the production of cabbage and vegetables such as tomato and onion often relies on seedling raising in nurseries, followed by transplanting into the field (De Putter *et al.*, 2007; Gogo *et al.,* 2012; KALRO, 2016). The importance of cabbage and other vegetables in potato growing areas suggests that many potato farmers are used to produce seedlings from seeds, and that transplanting is a commonly known practice. This could provide an entry point for the introduction of HTPS, since the use of HTPS may also require farmers to raise seedlings and transplant these seedlings to the field. However, what shapes farmers preferences for a certain starting material – which could be seeds, seedlings or seed tubers – remains an open question.

7.2.3 Common diseases

Late blight and bacterial wilt are commonly mentioned as the most important potato diseases in the region (Schulte-Gelderman, 2013). Bacterial wilt, caused by *Ralstonia solanacearum*, is a soil- and seed-borne disease, which can cause yield losses of up to 30-75% (Lemaga *et al.*, 2005). A nation-wide survey in Uganda reported an overall bacterial wilt prevalence of 80%, while disease incidence was on average around 2% (Abdurahman *et al.*, 2019). Similar prevalence, but slightly lower incidence were reported for the major potato growing areas in Kenya (Gildemacher *et al.*, 2009a). The disease has a wide host range, can survive in the soil for several seasons and spreads via latently infected planting material (Abdurahman *et al.*, 2019). Hence, short rotations and lack of clean planting material are major causes of the high bacterial wilt incidence. Late blight, caused by the oomycete *Phytophthora infestans*, causes major yield losses throughout Sub-Saharan Africa. Similar to bacterial wilt, the disease can be soil borne and can also spread via latently infected planting material. A main difference between the two diseases is that late blight is also air-borne, enabling the disease to disperse over long distances and to infect whenever the conditions are conducive (Nowicki *et al.*, 2012). Contrary to wilt, chemical control of late blight is common in the region, and late blight is the main reason for the use of fungicides on potato in Kenya, Uganda and Ethiopia, which has important ecological and economic consequences (Gildemacher *et al.*, 2009b). A case-study in Ethiopia showed that seed and ware potato farmers had limited knowledge about causal agents, spreading mechanisms and effective disease management options of bacterial wilt

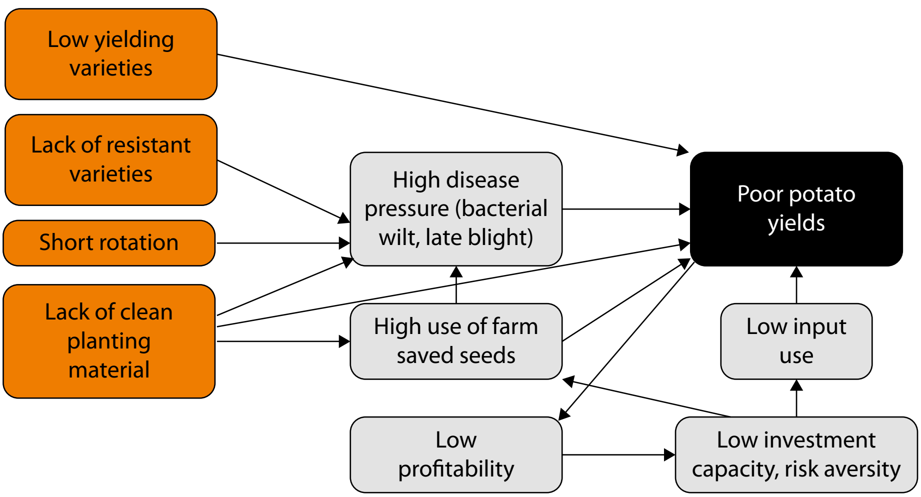

Figure 7.1. Diagram showing some of the main causes of low potato yields in East Africa.

and late blight. Effective disease control requires integrated management options and collective action at community-level (Damtew *et al.*, 2020; Tafesse *et al.*, 2018). The increased availability and use of clean planting material is an important aspect of such an integrated approach, alongside various other phytosanitary and cultural practices, such as rogueing diseased plants, implementing crop rotations and decontamination of farm tools (Tafesse *et al.*, 2018, 2020). As HTPS could increase the availability of clean planting material, it could provide an essential building-block of such integrated approaches to alleviate disease pressure. With regards to breeding for late blight resistance, hybrid potato breeding provides an unprecedented opportunity. Recently, hybrid potato breeding has been applied to stack multiple late blight resistance genes into an existing variety in just 3 years (Su *et al.* 2019).

7.3 Key lessons from experiences with true potato seed

Past experiences with true potato seeds (TPS) provide valuable insights to understand if and how HTPS could foster development in potato sectors. The International Potato Center (known under its Spanish acronym CIP) conducted extensive research on TPS technologies from 1977 to 2000. The advantages of TPS in terms of logistics and pathogen-free starting material made TPS a promising pro-poor technology (Almekinders *et al.*, 2010). In contrast to HTPS, the varieties used in CIP's TPS programme were not diploid, inbred hybrids, but non-inbred tetraploid varieties which produced a relatively heterogenous crop. However, in terms of the implementation in potato production systems, TPS and HTPS are not hugely different. Similar to TPS, HTPS requires new agronomic practices, it requires new seed system configurations, it may change the role of existing stakeholders and it may draw in new stakeholders.

7.3.1 Experiences with true potato seed: where and how

As a result of CIP's research, TPS was adopted by farmers in a wide variety of regions and agro-ecologies, such as China, Vietnam, Nicaragua and Egypt (Almekinders *et al.*, 1996). Converting potato from a vegetatively propagated crop to a sexually propagated crop added new options for propagation and for obtaining planting material (Table 7.1). For instance, ware potato farmers in Sri Lanka sowed TPS in seedbeds and propagated their own planting material. In most cases, seedling tuber production from TPS was done by specialised actors. In Bangladesh, cooperatives and large-scale farmers specialised in the production of seedling tubers from TPS, whereas in China, government seed farmers and specialised nurseries were involved in the propagation from TPS. In Egypt and India, TPS provided cheaper or better planting material than the national seed tuber systems (Almekinders *et al.*, 1996). In Vietnam, on-farm research on the agronomic practices for TPS was conducted in close collaboration between farmers, extension agents and researchers. In this case, farmers grew and transplanted TPS seedlings using methods very similar to rice cultivation (Hoang *et al.*, 1988). In the Vietnamese cropping system, potatoes are grown in a relative short winter period between two rice crops. At first, TPS varieties were too late-maturing to fit in this short growing season, but later varieties fitted better. In addition, yields from TPS seedling tubers were higher than yields from locally available seed tubers. This led to a relatively high use of TPS in Vietnam: in the late nineties, TPS-derived seedling tubers were used on 10% of the total potato area. After a flooding disaster in Peru, the fast multiplication opportunities

TPS offered were used to rapidly restore potato production. In Nicaragua, TPS thrived for a while, mainly because the TPS varieties had a higher resistance to late blight than other locally available varieties, even though the TPS variety was not uniform in terms of tuber colour (Almekinders *et al.*, 2010). However, in this particular case, the lack of institutional embedding prevented the widespread use and scaling of TPS (Swart and Stemerding, 2019). In 2009, TPS, or TPS-derived planting material, was used by farmers in China, India, Nepal, Bangladesh, Vietnam, Peru, Nicaragua and Venezuela (Almekinders *et al.*, 2010).

7.3.2 Key lessons

Contrary to the high rising expectations, TPS did not revolutionise potato production in smallholder farming systems. However, it remained a technology that was used in a wide variety of 'niches'. On-farm research in Indonesia, India, Egypt and Peru showed that although TPS-derived starting material was cheaper compared to the use of seed tubers, the crop value produced was also lower, due to lower yields and a larger proportion of small tubers (Almekinders *et al.*, 2010). Furthermore, farmers using TPS-derived planting material were facing problems with late maturity, lack of uniformity of the produce and unreliable germination (Almekinders *et al.*, 1996). Manrique (1994) concluded that for TPS to be successfully used by farmers, the main prerequisites were the availability of high yielding, uniform, stress tolerant varieties, adequate water supply and growing medium, good plant protection options and experience with vegetable production, as most vegetables need transplanting as well. Despite the abovementioned challenges, farmers successfully used TPS in a wide variety of agro-ecological and socio-economic conditions. The common characteristic of those 'niches' where TPS was adopted by farmers were a limited seed

Table 7.1. Examples of countries where farmers experimented with true potato seed, and different modes of utilisation.

Country	Mode of utilisation	Source
China	Government seed farms and nursery farmers used TPS to grow seedlings. Seedlings were transplanted in field at high density to produce seedling tubers, which were sold to ware farmers.	Bofu *et al.*, 1987
Vietnam	CIP provided farmers with TPS. Farmers sowed TPS in raised beds. Seedlings were transplanted in the field bare-rooted (e.g. rice) to produce seedling tubers. Seedling tubers used by farmers to grow a ware crop.	Hoang *et al.*, 1988; Malagamba and Monares, 1988
Bangladesh	TPS was used by cooperatives and large-scale farmers to produce seedling tubers for commercialisation.	Almekinders *et al.*, 2010
Peru	CIP provided ware potato farmers with mini-tubers derived from TPS. Vegetable farmers were provided with seedlings derived from TPS.	
Nicaragua	TPS were distributed to specialised farmers, who had the expertise and conditions to grow seedling tubers.	
Sri Lanka and Rwanda	TPS were provided to farmers. Farmers produced seedling tubers from TPS, either through transplanting, or by direct sowing in nursery beds.	Almekinders *et al.*, 1996; Malagamba and Monares, 1988

tuber supply from formal seed systems and high disease pressure (Almekinders *et al.*, 1996). The Vietnamese case showed that familiarity with seedling nursing and transplanting, a good fit in the cropping system, high yields and participatory research on new agronomic practices were important factors contributing to the relative success of TPS in the country.

How do these experiences with TPS around the world relate to HTPS in the context of East Africa? First, the key characteristics of the 'niches' where TPS was adopted are clearly present in East Africa: as explained in Section 7.2, the current seed systems in East Africa fail to provide a steady supply of affordable, clean planting material and disease pressure is high. Second, in terms of the breeding opportunities, HTPS is better placed to remove some of the main disadvantages of TPS, such as low yields, issues with uniformity and unreliable germination. In this regard, progress has been remarkably fast. The proof of principle of hybrid potato breeding was reported in 2011 by Lindhout *et al.*, 2011. Already in 2016, experimental hybrids based on the inbred lines developed by Lindhout *et al.* yielded up to 29 tons/ha in field trials in the Democratic Republic Congo (De Vries *et al.*, 2016). The high yield potential was further confirmed in field trials with a seedling-based crop in 2018, under well-managed conditions in the Netherlands. The best performing experimental hybrids yielded over 100 ton/ha in a flat-bed system in sandy soils, and 45 tons/ha in a ridge-system on clayey soils (Van Dijk *et al.*, 2022). Third, in terms of agronomy and seed systems, the experiences with TPS in developing countries show that potato production systems based on sexually propagated potatoes are feasible in a wide variety of agro-ecologies and under diverse socio-economic circumstances. In addition, various seed system configurations have worked in different places.

7.4 Requirements for an effective and inclusive introduction

This section first addresses crucial technology characteristics that HTPS should fulfil. Some important factors and stakeholders for an enabling environment for the introduction of HTPS are described. Clearly, seed systems providing reliable access to high quality hybrid potato planting material are another requirement for the introduction of HTPS. Participatory testing of new hybrid varieties and agronomic practices is crucial to investigate how the innovation can best be adapted to fit into the agro-ecological and socio-economic context. The need for sustainable business models, both for breeding companies and for farmers is discussed. Finally, we argue that a framework for Responsible Innovation, building on the dimensions of reflexivity, inclusion, responsiveness and anticipation, could provide guidance for the introduction of HTPS.

7.4.1 Hybrid true potato seed: technology characteristics

Many 'innovations' aiming to deliver benefits to smallholder farmers have limited success, and interventions aiming to improve farmers' access to improved varieties of vegetatively propagated crops are no exception (Almekinders *et al.*, 2019). Case-studies show that a main reason for the meagre successes of interventions is that farmers' demand for improved seeds was often based on simplistic assumptions, leading to an overestimation of demand. In addition, limited efforts were made to understand the seed and farming systems in which farmers operate, and hence the motivations for farmers to use or not use improved seeds were often not well understood

(Almekinders *et al.*, 2019). Currently, the majority of farmers in East Africa are not used to paying for their potato starting material (Gildemacher *et al.*, 2009a) and the adoption of any new variety or technology involves risks, investments and experimentation (Verkaart *et al.*, 2019). In this regard, Sumberg (2005) highlights four technology characteristics of a successful innovation in the context of agriculture in Sub-Saharan Africa. Firstly, hybrid potato varieties should address an important demand or constraint, or they should deliver a clear benefit to potential users. Clearly, these benefits could be improved yields, disease resistance or financial gains (Verkaart *et al.*, 2019). However, case-studies show that motivations to use or not use new varieties are more diverse and can also include low risks, taste and colour preferences or maintaining diversity as a risk spreading strategy (Almekinders *et al.*, 2019). Second, the degree to which a variety can tolerate less than optimal management and/or growing conditions while still yielding positive results, should be acceptable. For instance, Ethiopian potato farmers perceived that improved varieties required more management, and this was a main reason for choosing local varieties. In addition, farmers regarded crop management intensity as a more important variety characteristic than yield and disease resistance (Abebe *et al.*, 2013). Thirdly, the innovation should be socially and culturally acceptable. As an example, Peruvian smallholder potato farmers preferred native potato varieties over varieties provided by the formal seed system, because the improved variety seed lots were grown at low altitudes, using synthetic fertiliser and chemical pest and disease control. These management practices were not in line with farmer's personal values and with the culturally determined 'quality cues' that farmers were looking for when selecting seed lots and varieties (Urrea-Hernandez *et al.*, 2016). Fourth, the innovation should be compatible with other farm and non-farm activities that are common among potential users. The importance of crop management intensity as a variety selection criterion, as shown by Abebe *et al.* (2013), points in this direction. The abovementioned technology characteristics show that simplistic assumptions about farmer demand for improved potato seed should be avoided, and that a solid understanding is required of local farm realities and the seed systems in which farmers operate (Almekinders *et al.*, 2019).

7.4.2 An enabling environment

Enabling environments are shaped by knowledge and evidence, politics and governance and by capacity and resources (Gillespie *et al.*, 2013). In terms of knowledge and evidence main actors are (local) knowledge institutes, extension services and NGOs (Figure 7.2). For instance, access to knowledge and participation in demonstration and training activities was an important factor explaining the adoption of improved practices and varieties among potato farmers in Ethiopia (Tadesse *et al.*, 2017b). It is therefore important that farmers, extension services and local knowledge institutes are equal partners in the generation of the knowledge and evidence (see below). With regards to capacity and resources, access to credit and the availability of land and labour were other important factors explaining adoption of improved potato varieties (Abebe *et al.*, 2013; Tadesse *et al.*, 2017b). Connecting farmers with micro-credit services has been suggested as a way to enable cash-constrained farmers to obtain seeds of improved varieties (Tadesse *et al.*, 2017b), but the benefits of HTPS must be very clear before farmers will venture into that. Another important contextual factor that is currently unknown, is the marketability of the hybrid varieties. In terms of politics and governance, an important hurdle for the introduction of HTPS is variety registration (Section 7.4.3).

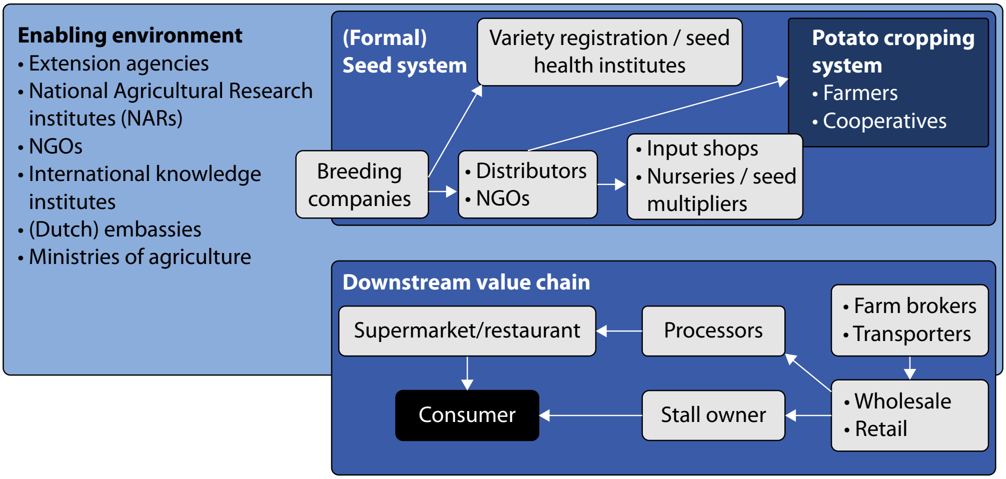

Figure 7.2. Stakeholders in the potato sector in East Africa and actors who may play a role in shaping an enabling environment for the introduction of HTPS in East Africa (Danial *et al.*, 2016; Janssens *et al.*, 2013; NFP, 2021).

7.4.3 Variety registration

Currently, several breeding companies are working on the development of hybrid potato varieties, such as Solynta, HZPC, Bejo Zaden and Aardevo (NFP, 2021). To commercialise and distribute hybrid varieties, breeding companies need to register their varieties at official variety registration institutes, which are usually hosted by the ministries of agriculture. For instance, in Kenya, candidate varieties need to be tested in 'value of commercial use' trials, which are sometimes referred to as 'national performance trials'. These trials take place over at least two growing seasons in multiple locations. They are meant to assess the agronomic potential of the candidate varieties and to test against locally available varieties. Commonly, registering new vegetable varieties, grown from seeds, requires different procedures than registering seed potatoes. Since hybrid potato has characteristics of both, it is often not clear what procedures have to be followed, or existing procedures have to be adapted, which complicates and delays the registration (NFP, 2021). In this regard, HTPS varieties need to comply with regulations set-up for seed-tuber propagated varieties, often requiring an extra step of seed-tuber production from HTPS transplants.

7.4.4 Functional seed systems supporting hybrid true potato seed

For the introduction of HTPS, an accessible and reliable seed system is pivotal to provide farmers with the desired starting material, which could be clean seeds, seedlings or seedling tubers (Lindhout *et al.*, 2018). Any intervention involving seeds or starting material should build on a solid understanding of existing seed systems (Almekinders *et al.*, 2019). Relevant stakeholders in formal and informal seed systems should be identified through stakeholder mapping, interviews and focus group discussions. This also informs understanding regarding how seed systems and their actors will be affected by the introduction of HTPS.

To find functional seed system configurations that can support HTPS, it is crucial to understand which type of planting material is required by farmers, which type of logistics is most effective to get planting material to farmers and which actors are needed for that (Table 7.2). Farmers may use the seeds to grow seedlings in a raised seedbed or small nursery, after which the seedlings can be transplanted at high densities in the nursery or in the field to obtain seedling tubers, or the seedlings can be transplanted at lower densities in the open field to obtain a ware crop. Alternatively, specialised nurseries may use the seeds to raise seedlings or seedling tubers, which can be distributed to farmers. Nurseries could be managed by local entrepreneurs or cooperatives – also called decentralised multipliers (Almekinders *et al.*, 2019) –, or the multiplication could be done more centrally by larger public or private organisations (Table 7.2). Most seed system interventions in vegetative crops assumed a system with decentralised multipliers, but the empirical evidence for this assumption is scant (Almekinders *et al.*, 2019). A major bottleneck for the introduction of HTPS is the intermediate infrastructure needed to get planting material to farmers (NFP, 2021). Nurseries and seed tuber multipliers are not yet familiar with HTPS, and capacity building needs to happen to solve this.

Table 7.2. The top part summarises the main advantages of using seeds, seedlings and seedling tubers. Possible seed system configurations are shown in the bottom part.

	HTPS (Botanical seed)	**Seedling**	**Seedling tubers**
Advantages	• Free of diseases	• Versatile, can be used for ware crop or for obtaining seed tubers	• Short crop cycle to obtain a ware crop
	• Easy to transport and store		• Farmers are used to seed potatoes
Disadvantages	• Sowing tiny seeds requires skill and patience	• Cannot be stored for long	• Can transmit diseases
		• Requires regular water and intensive care	• Bulky
		• Transplant shocks	• Require specific storage conditions
Possible seed system configurations			
Farmers only	Farmers use HTPS to grow their own starting material, and produce a ware crop from that starting material; ware potato farmers are involved in all stages.		
Decentralised multipliers	Local entrepreneurs or cooperatives use HTPS to produce starting material, either seedlings or seedling tubers. Specialised nurseries may be employed. Starting material is then sold to farmers who use it to grow a ware crop.		
Centralised multipliers	Larger public or private organisations use HTPS to produce seedlings or seedling tubers, using specialised nurseries and dedicated seedling tuber producers. Seedling tubers are then distributed to ware crop farmers.		

7.4.5 Adapted agronomic management

HTPS provides multiple cultivation pathways for potato production through direct field sowing, field transplanting of nursery raised seedlings and the use of seedling tubers (Van Dijk *et al.*, 2021a). In contrast to tuber-based cultivation systems, where various aspects of the system, including agronomy, have been rigorously studied, limited information is available for most of the aspects of the above-mentioned cultivation pathways. The implementation of HTPS requires major changes in agronomic management practices, most notably in terms of growing the starting material, and the starting material itself. Growing the desired starting material, which could be seedlings or seedling tubers, starts with the sowing of true seeds, followed by seedling nursing, and in most cases, seedling transplanting into the field. Currently, most studies on the agronomy of hybrid potato have been conducted on nursery-raised seedlings which were transplanted to the field, mostly in the Netherlands, and to a limited extent in East Africa. The effect of transplanting date, plant density and some aspects of transplant crop management through additional hilling on yields and tuber size distribution have been explored (Van Dijk *et al.*, 2021a,b, 2022). When using seedlings as starting material, adaptations in plant density are most likely needed, because under Dutch conditions, increased plant densities result in higher yields, but they also affect the tuber size distribution. Optimal plant density for total yield is between 50 and 100 plant/m^2 but this depends on the soil type and cultivation system (Van Dijk *et al.*, 2022). Furthermore, seedlings have a slower initial growth than seed tubers, and therefore, a seedling-based usually crop has a longer crop cycle. However, the length of the crop cycle also depends on the genotype (Van Dijk *et al.*, 2021b). It is paramount to align these findings to current cropping systems in East Africa and bridge various knowledge gaps in the agronomy of HTPS based cropping systems. For instance, it is important to assess whether a seedling crop with a longer growing cycle could fit in East African cropping calendars. Finetuning agronomic management practices and adapting them to fit a local context will require participatory testing and evaluation.

7.4.6 Participatory trials and evaluation

Involving farmers and other stakeholders in innovation design and evaluation enhances the likelihood that an innovation yields options that fit in farmers' realities (Descheemaeker *et al.*, 2019). Research on the feasibility of HTPS at farm level is urgently needed and requires agronomic insights and information on household-level constraints and opportunities. Farm-level management decisions concerning rotations, soil fertility management and the allocation of land, labour and capital influence the performance of a new technology. Moreover, between farming households, there is a large diversity in terms of resource endowment, farm management and farmers' aspirations and attitudes, which implies that the feasibility of hybrid potato will differ among different types of households (Descheemaeker *et al.*, 2019; Ronner *et al.*, 2019). It is more useful to tailor the innovation and the adaptation of the system towards the needs and capabilities of different household types, rather than offering a fixed technology package (Giller *et al.*, 2011). A recent workshop with several European and African research institutes, governments, companies and NGOs called for a forward-looking view, concluding that:

> Given the many uncertainties associated with HTPS-technology, innovation can only take place in a responsible manner if it is accompanied by sufficient pre-implementation research in collaboration with African stakeholders to better understand the potential merits and robustness of the technology, its socio-economic consequences and the way in which the technology should be introduced (Swart and Stemerding, 2019).

Hence, for an inclusive, effective and responsible introduction of HTPS in East Africa, an iterative research cycle linking farmers, researchers, breeders and other stakeholders is needed. On-farm trials should involve nurseries and potato growers to test, evaluate and adapt agronomic practices, to find out what type of logistics are most suitable, and to select the best performing varieties (Figure 7.3). This participatory testing of different varieties, planting materials (seed, seedlings, seed tubers) and agronomic practices will yield information on desired crop traits and will inform the design of sustainable seed systems and farming systems that could accommodate hybrid potato varieties. Breeders can use this information to improve the variety selection criteria and to develop varieties attuned to regional needs. Vice versa, new varieties can be tested immediately in the on-farm evaluations. Furthermore, ex-ante analyses are needed to gain insight in the potential consequences of HTPS for a diversity of potato farmers, and for various actors in the potato sector.

7.4.7 Business models

Profitability for all actors involved in the potato chain (Figure 7.2), from breeding companies to distributors, multipliers and the downstream value chain is regarded as a key requirement for

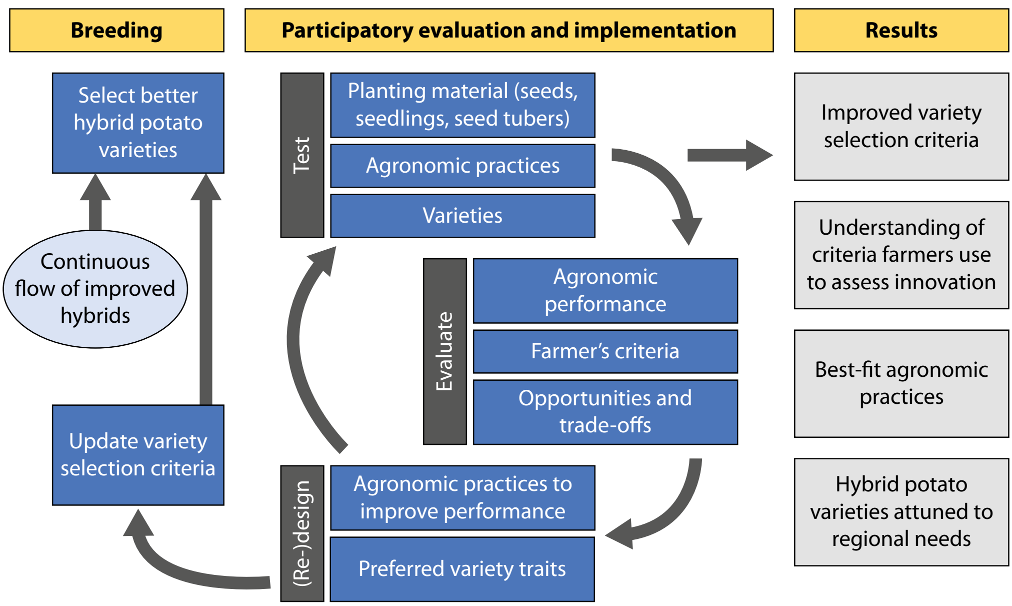

Figure 7.3. Iterative research cycle linking farmers, researchers, breeders and other stakeholders for a participatory implementation of HTPS.

sustainable introduction and continued use of HTPS (Lindhout *et al.*, 2018). This poses major challenges because currently, commercialisation of HTPS is in its infancy. HTPS may have added value in developing countries, but investments to further develop the technology are considerable, and the initial market, consisting of resource poor smallholders may not be profitable enough (Beumer and Stemerding, 2021; NFP, 2021). How much the hybrid seeds or planting material will cost is yet unclear. Future research should investigate the financial feasibility of using HTPS, for ware growers, seed multipliers and other actors in the chain. Financial feasibility for farmers and seed multipliers will to a large extent depend on how much added value hybrid potatoes have in comparison with farm-saved seeds and on how fast the clean hybrid material will degenerate. Business models along the value chain remain an important area for further research.

7.4.8 Responsible innovation

The introduction of HTPS comes with many uncertainties in multiple dimensions and at various levels (Swart and Stemerding, 2019), and it could have major consequences for the seed and farming systems where it will be introduced (Stemerding *et al.*, 2020). Who will benefit from the innovation, and who may not be interested or able to adopt it? What are the suitability criteria that guide such decision making by various stakeholders? Potato sometimes serves as a 'hunger breaking crop' due to its short growing cycle (Haverkort and Struik, 2015), but this function may be impaired by the longer growth period of HTPS grown from seeds or seedlings compared to starting from seed tubers. Ideas about desired future cultivation systems and preferred pathways of getting there may differ among stakeholders, from breeders to seed growers, farmers and policy makers. A framework for Responsible Innovation, building on the dimensions of reflexivity, inclusion, responsiveness and anticipation (Stilgoe *et al.*, 2013) may guide further research and implementation of HTPS in East Africa. This involves interactive, multi-stakeholder processes to develop shared views on the acceptability, sustainability and societal desirability of HTPS. Inherent in this 'responsible innovation approach' is that the potential impact of an innovation should be assessed prior to introducing the technology. In that way, potential negative impacts can be mitigated in time, and the positive impacts can be fostered. Inclusivity should be safeguarded by engaging with a diversity of rural households in the co-design process (Figure 7.3). Participatory processes can encourage all stakeholders involved to be reflexive on their activities, beliefs and assumptions regarding how HTPS should be deployed. Finally, responsiveness can be fostered through the feedback loops in the iterative research cycle (Figure 7.3).

7.5 Strengths, weaknesses, opportunities and threats analysis

Building on the above sections, we summarise the main strengths, weaknesses, opportunities and threats with respect to the introduction of hybrid true potato seed in East Africa (Figure 7.4). As strengths and weaknesses, we regard the attributes of the HTPS itself, which are internal to the innovation. Opportunities and threats are context-dependent and shaped by the external environment of the potato sector in East Africa.

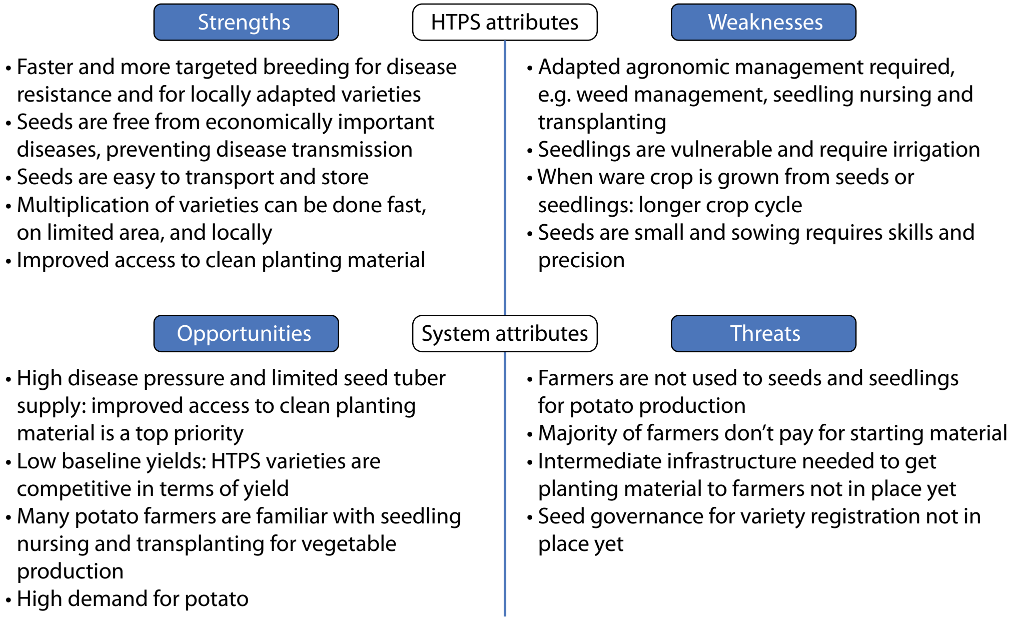

Figure 7.4. SWOT analysis of hybrid true potato seed (HTPS) in East Africa.

7.6 Research agenda

We conclude with urgent research questions that need empirical research prior and during the introduction of HTPS in East Africa. Building on the overview presented in this chapter, we identified four main 'research themes'. First, it is critical to understand which criteria and motivations are important to farmers when they judge the new options that HTPS brings along. This implies that understanding of local farm realities in terms of constrains, priorities and opportunities is required. The wide diversity of farmers and farming systems in terms of resource endowments, cultures, agro-ecology, socio-economy in East Africa makes this a challenging task. A second major area of research is if and how HTPS can be embedded into seed systems, and what the consequences of HTPS introduction will be for various actors in the seed systems. Third, insights from the abovementioned research areas should drive on-station and on-farm research to assess the performance of HTPS. Finally, some pertinent questions remain in the broader context of the introduction of HTPS in East Africa.

Farmers' criteria to judge performance of hybrid true potato seed:

- What are the criteria farmers apply when making decisions regarding HTPS? Do these criteria change under different socio-economic, cultural and agro-ecological conditions, and if so, how?
- Important criteria could be: investments and management intensity needed, length of growing season, marketability of produce, labour, risk, yield, susceptibility to major diseases (late blight, several viruses, bacterial wilt), prone-ness to weed infestation.
- What type of planting material is preferred by farmers, and what are motivations for these preferences? Planting material could be seeds, seedlings or seedling tubers.

Embedding in seed systems:

- What type of seed system configuration and intermediate infrastructure is best suited to deliver the preferred type(s) of hybrid planting material to farmers, and which actors are needed for that?
- Possible options are a 'farmers only system', decentralised multipliers or centralised multipliers (Table 7.2).
- Will hybrid potato varieties percolate into informal seed systems, and how?
- What are the consequences of HTPS introduction for actors in the seed systems?

Performance at field level:

- What are the best-fit agronomic practices to grow ware potatoes from HTPS derived planting material?
- What are the yields from HTPS derived planting material, under farmers' management and farmers' fields conditions?
- How does HTPS-derived planting material compare with the status quo (farm-saved seeds) in terms of farmers' criteria?
- How fast will seed tubers derived from HTPS degenerate?

Broader context:

- Are HTPS varieties acceptable to consumers and to actors in the downstream value chain, in terms of taste, colour, cooking quality or other culturally defined preferences? Who will benefit from HTPS? Will HTPS be mainly interesting for the relatively rich farmers who can invest, or will it also be interesting for farmers with less resources? Which other actors in the value chain and seed systems may benefit? For instance, nurseries, seed multipliers, or downstream value chain actors.
- What are business models for companies delivering seeds to a market of resource-poor smallholders?

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Chapter 8. Introducing improved vegetable varieties in a development context: lessons for the introduction of hybrid true potato seed

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Abstract

Hybrid true potato seed (HTPS) technology has potential to strengthen the smallholder potato sector in Sub-Saharan Africa. For its successful introduction, stakeholders will need to realise promises of the innovation and overcome barriers to adoption. Both promises and barriers can be analysed looking at the seed, farm, and market system. Efforts of two pairs of Dutch vegetable seed companies, East-West Seed and Rijk Zwaan introducing improved tomato varieties in Tanzania, and De Groot & Slot and Bejo introducing true-seed shallots in Indonesia, offer lessons learned when developing a strategy for HTPS in Sub-Saharan Africa. The SEVIA project in Tanzania (2013-2020) demonstrated that main barriers to adoption of tomato varieties were posed by the seed and farm system. The investment in seed of improved crop varieties was worthwhile, only if tomato farmers improved their full-field production practices, and prior nursery care. There were no barriers regarding the market system, but there were also no incentives for adoption: tomato is mostly a commodity in Tanzania and there is no diversified market. The 'True Seed Shallot demonstration project' in Indonesia (2018-2020) sought to introduce true shallot seed (TSS) varieties requiring a transformation of the seed, farm, and market system. The companies decided to promote TSS outside traditional shallot production areas where the potential positive impact of their innovation was larger. Vegetable farmers, familiar with seedlings while unfamiliar with shallots, were trained in shallot production from seed. Adoption of HTPS will, like improved shallot and tomato varieties, require transformations of the seed, farm, and market systems. The two cases show that investments in seed system development are essential. Widespread outreach efforts are needed to demonstrate the promise of an innovation. Moreover, capacity building is then required to enable farmers to realise the potential of an improved variety themselves. Without additional skills, adoption of an innovation is often not economical. In summary, farmers need to be familiarised with the technology and recognise its profitability. Subsequently,

Paul C. Struik, Peter R. Gildemacher, Dirk Stemerding and Pim Lindhout (eds.)
Impact of hybrid potato

DOI: 10.3920/978-90-8686-946-6_8, © E.M.S. ter Steeg and P. Gildemacher, 2023

HTPS technology can be mainstreamed in the seed, farm, and market system minimising disruption and maximising innovation.

Keywords: farm system, market system, seed system, innovation

8.1 Introduction

'Dutch' vegetable seed companies have extensive experience working in developing countries introducing and marketing improved varieties. The aim of this chapter is to draw lessons from these experiences that may predict and overcome challenges of introducing hybrid true potato seed (HTPS) varieties in Sub-Saharan Africa. The structure of the chapter is based on a distinction between the seed, farm, and market system. Firstly, the concept of 'system transformation' is introduced, after which the three different systems are defined and linked to the introduction of improved crop varieties. Subsequently, two case studies regarding tomato in Tanzania and shallot in Indonesia will be analysed looking at the promise of these innovations, barriers to adoption and interventions implemented to overcome these barriers. The case studies are based on two interviews with Flip van Koesveld of Wageningen Plant Research and Rob Bekker of De Groot & Slot. A comparative analysis follows in which lessons learned from the two case studies are applied to the case of HTPS in East Africa. HTPS represents a technological breakthrough in potato breeding (Lindhout *et al.*, 2011; Zhang *et al.*, 2021). Still, the real-world adoption of the HTPS technology may be hampered by systemic obstacles comparable to those faced by seed companies in the past with other crops. The chapter analyses the benefits of adoption of the improved varieties and tries to pre-empt the barriers to adoption that will have to be overcome for successful adoption. Insights from the two cases are used to discuss the probable benefits and help predict barriers for adoption of HTPS.

8.2 System transformation

A distinction can be made between the adoption of a new variety and adoption of a new technology. With the introduction of a new variety, seed companies seek to convince farmers of the added benefit offered by their product. They may organise demonstrations or give away free seed samples to show farmers how the variety performs in a field like his or her own field. Introduction of a new variety can be challenging. Research and experience have shown that even though benefits of an improved variety are demonstrated, farmers may still refrain from adoption (Almekinders *et al.*, 2019; Hoogendoorn *et al.*, 2018; Kilwinger *et al.*, 2022). Contextual factors always need to be considered providing insight into a farmer's livelihood and constraints. Moreover, habits, culture, and traditions are also strong forces, which may pose a barrier to change or prevent adoption of an innovation (Almekinders *et al.*, 2019).

Introduction of a new (breeding) technology is (much) more challenging. Successful introduction of a technology-based innovation hardly ever goes automatically: a system transformation is required to accommodate the innovation. Smits (2002) distinguishes between software, hardware and 'org-ware' required for successful introduction of an innovation, to emphasise that a technology cannot stand on its own but needs to be accompanied by changes in knowledge of and organisation between actors. Vegetable seed companies have been involved in capacity building programmes for many years to build their own market. East-West Seed (EWS) was one of the first to focus on training enabling farmers to realise the potential of quality seed and improved varieties. Without additional skills and knowledge, they could not benefit from a technology and, hence, would not adopt it. Similarly, the introduction of HTPS goes beyond the decision of a farmer whether to adopt a new variety. The success of the introduction of HTPS will depend on the entire systemic context in which the technology is introduced.

A new system will compete with the established system, which holds the simple but crucial advantage of predictability. Farmers know the risks and returns from their own experience. Farming practices have developed based on experiences of farmers themselves and those of their neighbours. Farmers, and in particular smallholders, are cautious in making changes to their practices, and rightly so, as change equals risk (Pannell and Zilberman, 2020). They are typically cash-short and need to prioritise in their investments keeping risks low. In terms of returns, new varieties can have a positive impact in terms of yields, marketability, or ease of production. However, quite often there are also negative impacts or (perceived) higher risks associated with variety adoption. There is an inevitable learning period during which farmers must gather new knowledge and gain skills (Kuehne *et al.*, 2017). The length of this learning period will depend on the learnability of the technology itself as well as the capacity of the targeted population to learn. Due to this period, benefits of adoption will not materialise immediately.

We distinguish between three systems of which transformation may be required for the adoption of a new variety: the seed, farm, and market system. These systems are interlinked. The seed system focuses on the starting material used by a farmer, the farm system focuses on the livelihood structure of the farmer and the market system focuses on sales realised by the farmer. The type of variety grown can determine whether farmers sell their produce to a supermarket or an intermediary or on a local market. Prices offered by exporters, supermarkets or local markets can determine how much a farmer is able to invest in seed and inputs. Moreover, when a farmer invests in expensive seeds and inputs, a farmer will seek to earn a return on this investment either selling more kilos or obtaining a better price per kilo sold. Besides money, improved quantity and/or quality of the harvested crops will require the application of cultivation techniques representing an investment in terms of time and effort.

8.3 Seed system

Seed systems represent the set of activities affecting access and use of seeds including breeding, multiplication, seed management and distribution (Tripp, 1997). Some authors refer to seed systems as the set of market and non-market institutions governing these activities (Lipper *et al.*, 2010). The availability, quantity, quality, and price of seed are key factors which influence the choice made by farmers (Louwaars *et al.*, 2013). Physiological quality (germination/sprouting and vigour), sanitary quality (no seed-borne diseases or pests), analytical quality (high number of good seeds in a unit) and genetic quality (improved variety and varietal purity) can be hard to manage for seed producers and to verify for users (Almekinders and Louwaars, 1999). While it is relatively easy to produce and select seeds for some crops, the chances of disease transmission or degeneration are high for others (Almekinders and Louwaars, 1999). In addition to improved seed quality and availability of quality seed, there is the question of seed diversity, which enhances farmer choice and enables farmers to choose a preferred type of variety or seed (Nabuuma *et al.*, 2020).

Traditionally, a distinction is made between informal and formal seed systems (Louwaars and De Boef, 2012; Louwaars *et al.*, 2013). In informal seed systems, farmers select, produce, and distribute seeds themselves. These seed systems have also been referred to as farmer-managed, traditional, and local seed systems. Farmers use their own saved seed, exchange seed with neighbours or trade seed on local markets. There is no specialised chain with fixed standards for seed quality. Quality is managed through social structures based on reputation rather than regulation. In formal seed systems, seed reaches farmers through a specialised, regulated chain. Improved plant varieties are generated by professional plant breeders and seed production is done by professional seed producers. Seed is sold via market channels and farmers have access through purchases. Seed quality is managed through government regulation, official certification schemes and company standards. Also, branded packaging of seed companies provides reassurance. In Sub-Saharan Africa, it is estimated that around 80% of seed used is produced by the informal system (Louwaars *et al.*, 2013; World Bank, 2007). For potato, this number is much higher and can reach around 95-98% (Gildemacher *et al.*, 2009a).

Louwaars *et al.* (2013) distinguish between four types of seed systems: the farm-saved, locally sourced, nationally sourced, and globally sourced seed system. A generic overview of the four systems and their characteristics is provided below in Table 8.1 based on Louwaars *et al.* (2013). In these systems, there is an increasing distance between the farmer and the seed producer. Also, there is an increasing level of formalisation and standardisation.

Table 8.1 illustrates that switching immediately from a local to a hybrid variety represents a major shift. The system, variety type, seed producers and marketing mechanism are all different. Moreover, the cost of seed will be higher posing a financial barrier and cultivation practices

Table 8.1. Overview of four generic types of seed system.

	Informal		Formal	
Seed system	**Farm-saved**	**Locally sourced**	**Nationally sourced**	**Globally sourced**
Variety type	Local variety	Local variety; improved OPVs[1]	Improved varieties; OPVs and hybrids	Improved varieties; mostly hybrids
Seed and seed producers	Local seed produced by farmers	Local seed produced by both specialised farmers and farmers	Certified seed produced by professional seed producers	Certified seed produced by professional seed producers
Seed marketing mechanism	Farm-saved, exchange and trading	Local markets, seed producers and companies	Agro-dealers, local markets, and seed companies	Agro-dealers, seed companies and input suppliers

[1] OPV = open-pollinated variety.

may differ posing a barrier related to knowledge, skills and inputs. A shift to expensive seeds, in particular hybrid seeds, may even trigger a transition from the use of seed by the farmers to the use of seedlings produced by specialised 'seedling producers' or 'young plant raisers' (Van de Broek *et al.*, 2015). Seedling producers represent further specialisation in the chain raising productivity along with upfront investment costs.

8.4 Farm system

The farm system has been defined as a 'decision-making unit comprising the farm household, cropping and livestock systems that transforms land, capital and labour into useful products that can be consumed or sold (Figure 8.1; Fresco and Westphal, 1988).' The farm household provides labour, capital, land, and other inputs to produce crops and livestock. Farm systems are shaped by ecological and socioeconomic conditions. Ecological conditions encompass the natural environment, while socio-economic conditions are determined by the financial, human, and technological resources available to a farm household. The farm household allocates its resources to different cropping and livestock systems to maximise output. In a development context, farm systems tend to consist of more than one cropping and/or livestock system. One household may manage a home garden to grow vegetables for consumption, which is irrigated manually, a rain-fed field for the cultivation of commercial staple crops and may use communal grasslands for grazing of their livestock. Rotation schemes are an important component of the cropping system.

Fresco and Westphal (1988) distinguish between subsistence- and market-oriented farm systems (Table 8.2). Subsistence systems primarily focus on the production for the farm household and social circle. The level of externally purchased inputs is low as market sales are also low and irregular. Market-oriented systems focus primarily on the production of goods for regular sales. Purchasing external inputs is common as well as purchasing goods for household consumption, although the household will likely produce most of its staples (and perhaps also other food) itself. Farm systems can be interpreted along the spectrum of subsistence to market with increased use of external inputs and land-use intensity. Besides subsistence and market orientation, there are also 'off-farm employment systems.' In these systems, the farming is done by few household

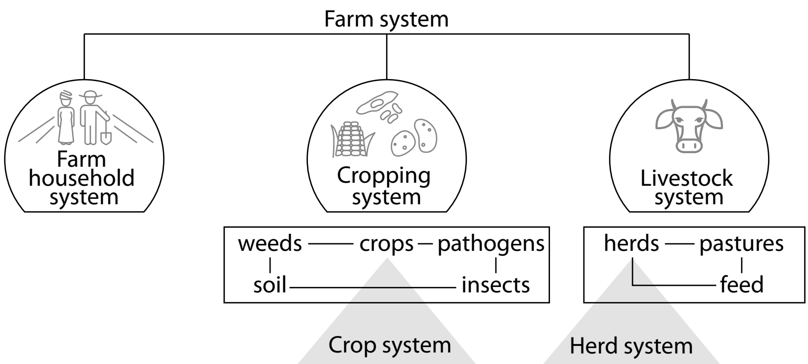

Figure 8.1. Agriculture as a hierarchy (adapted from Fresco and Westphal, 1988).

members as an additional source of income and food supplies. Most household members have a job elsewhere doing agricultural or non-agricultural work.

Some improved varieties can be integrated in existing farm systems, while others will require changes. Adoption may require changes in allocation of financial or human resources to a crop system looking at the costs of inputs or labour. If farmers adopt a high-yielding variety, they should also add fertiliser to maintain soil quality. Alternatively, a variety may require a change in the crop rotation scheme. A resistant variety may enable farmers to grow a crop slightly earlier or later in the season. An example could be an improved variety, which is resistant to a fungal disease during heavy rains or with a shorter growth cycle reducing the risk of contamination. However, a change in one crop system does not stand on its own as it impacts the entire cropping system. If the land needs to be available for another crop or labour is unavailable; a farmer is unable to tweak timing.

8.5 Market system

A market system is a network of sellers, intermediaries, traders, buyers and other actors that come together to trade in a given product or service, in our case either seed or ware. It can be regulated or not. The market system through which produced crops reach the consumer, dictates standards for variety traits and product quality. These standards have an impact on cultivation techniques and post-harvest practices applied. Also, the market system sets the price of products, which determines the potential return on investments in inputs and production practices. Farmers participate in different markets systems for different crops. Sometimes, they are part of two systems for the same crop selling different quality levels for different prices. Farmers make individual choices tailored to their household situation, weighing their resources, risks, and potential benefits of different market options. They can switch between market systems if they can meet quantity and quality standards. It should be stressed that market access itself continues to be a key challenge for many smallholders.

De Steenhuijsen Piters *et al.* (2021) distinguish between four types of consumers in a development context: rural consumers, low-income urban consumers, middle-income urban consumers and high-income urban or foreign consumers. Rural consumers can produce their own food and/or purchase food on local informal markets. Urban consumers do not produce their own food and will buy their food on informal or formal markets. In developing countries, the high-end formal market channels only represent a fraction of the total market. In informal market systems, standards tend to be unregulated, and agreements are based on social networks and kinship

Table 8.2. Overview of two generic types of farm systems.

System orientation	Subsistence	Market
Primary focus of farm system	Household consumption	Household income through market sales
Use of external inputs	Low level of external inputs	High level of external inputs
Land-use intensity	Low	High

relations. In formal market systems, standards are more regulated, and agreements are made between registered businesses working with contracts. The systems in Table 8.3 are based on the work of De Steenhuijsen Piters *et al.* (2021). They show an increasing distance between producer and consumer, which results in standardisation and higher quality requirements. Quality in subsistence farming is linked to household needs whereas quality on export markets is defined by international standards.

Benefitting from adopting a new variety might be possible without making any changes in the market systems the farmer is navigating. A more disease-resistant variety may simply enable the farmer to reduce the risk of crop losses and increase productivity and hence, marketable surplus. Moreover, a more disease-resistant variety can enable a farmer to plant slightly earlier or later avoiding the main harvest period. The varieties can deal with less or more rain and associated pressure of diseases and pest. As a result, farmers avoid the price drop during the main season and can sell for a higher price. For other variety benefits, a shift in the market systems may be required. In developing countries, most farmers do not participate in a market system where quality premiums apply for traits such as longer shelf-life or better taste. In local spot market systems, price differentiation for different quality grades or different varieties is often not very pronounced or inexistent. In both informal and formal market systems it is challenging to introduce a new variety with different traits than consumers are used to (taste or skin colour) or a change in packaging, collection, wholesale, or retail practices.

8.6 Application to case studies

Changes often represent barriers for adoption of the innovation. The successful introduction of a new crop variety entails that a farmer decides to change his or her practices because promises outweigh barriers. A prerequisite for technology success, or adoption is that the promises of the technology will materialise for a farmer. We consider the magnitude of the systemic changes required as an important indicator of the chances of successful technology introduction. We analyse these for the seed, farm and market systems separately pinpointing promises and barriers. In the two case studies below, we look at promises of an innovation and weigh these against the system changes required for adoption. The goal is to extract lessons for the introduction of HTPS in a development context in a structured manner looking at the three systems.

Table 8.3. Overview of three generic types of market systems.

	No market	Informal market	Formal market
Market system	Home consumption	Local markets	Local and export markets
Consumer type	Rural consumer	Low and middle-income urban and rural consumer	High-income urban or foreign consumer
Type of crop	Local crops	Local and global crops	Global crops
Quality level	Low quality or 'quality matching household need'	Low and medium quality including rejects from formal market	High quality meeting national or foreign standards

8.6.1 Seeing is believing: tomato in Tanzania

EWS, Rijk Zwaan and Wageningen University & Research joined forces to introduce improved tomato varieties as part of the Seeds of Expertise for the Vegetable sector of Africa project: SEVIA (Mwashayenyi, 2022). EWS and Rijk Zwaan are both Dutch family-owned vegetable breeding companies. Rijk Zwaan focuses on hybrid varieties for more temperate conditions. EWS has both hybrids and open-pollinated varieties (OPVs) in its portfolio suited for tropical climates. The goal of SEVIA was to stimulate adoption of improved vegetable varieties including tomato and to build farmer capacity to unlock the potential of these varieties. Tomato was the key focus being the main commercial crop for most vegetable farmers. The partners could build on their shared expertise and experience in tomato breeding, cultivation, and extension. The SEVIA project started in 2013 and ended in 2020.

8.6.2 Starting point

Tomato producers often use farm saved-seed, purchase seed on local markets or acquire seed at a seed shop or agro-dealer. Farm-saved seed is often harvested from bad fruits, which cannot be sold on the market. Farmers do not realise that the quality of the tomato fruits is an indicator of the genetic, physiological, and physical quality of the seed. They should save seeds from their best rather than their worst plants and fruits. Seed sold on local markets generally has a better quality, because it is clean and produced professionally. The price of a package is based on the number of grams or the number of seeds. The quality of seed sold on markets, locally sourced, or in seed shops, nationally sourced, is still uncertain (Guijt and Reuver, 2019). Farmers are at risk of buying counterfeit seed or seed, which has been repacked or stored under bad conditions. Either way, poor quality seed results in low germination and low plant vigour. Moreover, uncertain seed quality disincentivises farmers to invest in cultivation.

Tomato is an important part of the farm system as it is a key source of income. However, tomato production is also a tricky business. On average, tomato farmers face major losses once every five years (Guijt and Reuver, 2019). These losses are often caused by production conditions such as diseases, pests, excessive rain, or droughts. Disease such as late blight or bacterial wilt can have a devastating impact. Currently, most farmers mitigate risks by planting a smaller plot of tomatoes and/or minimising their production costs with a low-input strategy (Guijt and Reuver, 2019). Very few farmers invest in a greenhouse, which allows for better control of agronomic conditions, resulting in lower crop losses. Greenhouses are more commonly used for sweet pepper than for tomato production.

Moreover, many farmers lack the knowledge, skills, and technologies required to improve their tomato production. Plants, which are left to lie on the ground will never be as productive as vine or bush plants, which are supported by trellises to grow tall. These plants are vulnerable to diseases and pests as they are close to the soil and their leaves stay wet. Also, farmers often do not know which crop protection and fertiliser to apply and how to do so while protecting the plant's health and their own. Farmers tend to use standard fertiliser throughout the season, which might not match the soil or needs of the crop at certain growth stages. Similarly, standard mixes for crop protection are applied without considering the specific disease threat.

Most Tanzanian farmers grow tomatoes during the same period, as they depend on the rains to water their field. Tomato cultivation takes place during both rainy seasons: the long rainy season runs from March until May and the short rainy season from October until December (Guijt and Reuver, 2019). Viruses, fungi, and bacteria all pose a major threat (Everaarts *et al.*, 2011). Off-season production is challenging because it requires reliable access to water. Consequently, the market is flooded with tomatoes during harvest time. Farmers must all sell at the same time because once the fruits have ripened, there is only a limited timeslot to get them to the market.

During transportation, tomatoes are easily damaged because of the soft skin. Traders anticipate losses during transportation and at the market (Sibomana *et al.*, 2016). Hence, they want to buy in bulk at a low price. Most tomatoes are sold on fresh markets in rural and (semi-)urban areas. On these markets representing over ninety percent of sales, there is no price premium for quality. The high-end tomato market where premiums are paid, including supermarkets, restaurants, and hotels, is estimated to represent about one percent (Guijt and Reuver, 2019).

8.6.3 Promise of innovation

The innovation brought to Tanzania by EWS and Rijk Zwaan was high-quality seed of improved OP and hybrid tomato varieties. Seed is produced through a specialised chain in accordance with the company standards, which are stricter than national standards. In terms of physiological quality, germination rates are close to a hundred percent. The varieties were tailored to local conditions and harboured many disease resistances raising the yield potential in comparison to common popular varieties. In general, varieties of EWS are more suitable for small-scale farmers growing tomatoes in the open field (Figure 8.2). Varieties of Rijk Zwaan tend to be a better match for large-scale farmers or high-tech growers using greenhouses.

Figure 8.2. Farmer showing his trellised tomato plants in Tanzania.

The formal brand and delivery method serve to communicate these traits to farmers and ensure them of seed quality. In informal seed systems, a degree of uncertainty always remains regarding quality. When developing a distribution network, seed companies need to build trust in the system in general and in their brand in particular. Rijk Zwaan does this by selling seed directly to customers or working with a selected partner. In this way, it can exercise strict control. EWS builds relationships with agro-dealers and seed shops providing training to those retailing its seed. In this way, it tries to ensure quality control along the chain. In Tanzania, EWS developed its sales channels via an existing brand, Mkulima Seed, which it acquired.

Improved tomato varieties serve to massively increase marketable yield. Everaarts *et al.* (2011) report tomato yields of 0.5-0.7 kg/m^2. Provided that farmers apply good agricultural practices, yields can increase by a factor 3 to 5 (East-West International BV *et al.*, 2020). Tomato yields of 2.5-7 kg/m^2 in the field and 25 kg/m^2 in greenhouses were reported. The varieties are less affected by pests and diseases and, hence, the risk of losses is lower. Moreover, some varieties also have a shorter growing period reducing the risk of contamination. Even when farmers invest less time and money in crop protection, resistant varieties might perform better than traditional ones.

8.6.4 Barriers to adoption

Still, it can be challenging for farmers to switch from farm-saved or locally sourced to globally sourced seed of EWS and Rijk Zwaan. The price of seed of improved varieties is high when compared to seed bought via informal channels. Farmers who save their own seed are not used to paying for seeds at all. A higher seed price increases the upfront cash investment required of producers. Also, it increases the risk of losses when something goes wrong during the season or during marketing of produced fruits. First, farmers need to have cash available and second, they need to be able to cope with these risks. Moreover, the increase in price might entail a switch of paying per gram of seed to paying per individual seed.

The high germination rates of quality seed are realised when farmers apply the recommended seedling raising practices. Raising strong seedlings requires farmers to invest in sterile planting media, trays, and a nursery infrastructure, which adds further costs. When a farmer plants good seed in bad soil, the investment is likely wasted. Alternatively, farmers can buy seedlings from a specialist farmer, a seedling producer. In this way, they avoid all risks associated with the nursery stage. The farmer has now switched from paying a price per gram of seed, to paying per seed, to paying per seedling. Again, the upfront investment increases as seedlings are significantly more expensive than seeds.

Realisation of the genetic potential of improved varieties requires the application of good agricultural practices. Without additional care, an improved variety might still outperform a local variety, but a farmer is unlikely to earn high returns on the investment. Some good agricultural practices can be applied without additional costs. One example is correct spacing of plants. The right plant density maximises the number of plants but makes sure each plant still has sufficient room to grow. Another example is a raised plant bed, which improves drainage and protects the plants from 'wet feet' during heavy rains. Raised beds require additional effort, but no additional costs. Similarly, careful monitoring of pests and diseases takes skills and time, but it enables farmers to reduce pesticide and fungicide use optimising benefits from disease resistance. Other practices do entail additional expenses. The high costs of an irrigation pump, tunnels or a greenhouse are obvious. However, trellises also require farmers to buy or collect sticks increasing production costs. Sticks have a market value and could otherwise be used as firewood.

If farmers want to get a better price for their tomatoes, they need to avoid the main harvesting period and tweak their timing. However, most farmers have a tight rotation schedule, which might not leave room for change. On the market, there are barely any rewards for improved fruit quality. Over 90% of tomatoes produced in Tanzania are sold on local urban or rural fresh markets (Guijt and Reuver, 2019). On these markets, there is a fixed price per kilo. Price premiums are only paid on the high-end market, which represents around one percent of the market (Guijt and Reuver, 2019). Usually, farmers are dependent on traders or 'brokers' who come to pick up their harvest at the farm (Everaarts *et al.*, 2011). Improved quality and uniformity of fruits may help farmers build a stronger relationship with a trader or a broker. During peak-production season, when the market is overflown, a reputation for quality fruits with the desired ripeness, colour, thickness of skin and absence of damage or blemishes is an advantage as traders are looking for robust fruit with a good shelf-life.

8.6.5 Strategies applied to overcome barriers

The general objective of the SEVIA project was to provide farmers with access to improved varieties as well as the knowledge, skills and technologies required to maximise the benefits gained from adopting these improved varieties (Mwashayenyi, 2022). SEVIA was a 7-year and 9.5-million-euro operation, which gives an indication of the time and resources required to initiate a transition. The project supported the development of applied research and training centres, implementation of variety trials, organisation of farmer field demonstrations, and capacity building of professionals. Basically, the project partners developed an outreach programme to build their own market creating demand for improved tomato varieties.

A local team of agronomists and station workers was trained by Wageningen Plant Research. Improved varieties were tested first on SEVIA's demonstration farm (Mwashayenyi, 2022). In this way, local trainers could gain experience with the new varieties and techniques. Demonstrations were organised throughout the country and a snow-ball effect was initiated building on farmer-to-farmer dynamics in communities. To offer farmers the option of buying seedlings rather than seed, ten lead farmers received nursery management training and support, including access to credit, to specialise as seedling producer. Other farmers were trained to produce strong seedlings themselves at their farm. They preferred doing their own seedling production to avoid high production costs. Besides good agricultural practices, planning of and calculations for production were important modules in the farmer trainings. Farmers were also encouraged to shift the timing of their production tapping into better market prices.

In 2020, at the end of the project, training had been provided to more than 48,000 farmers and 1,400 sector professionals (East-West International BV *et al.*, 2020). The impact of SEVIA on tomato production is visible in the targeted project areas. Previously, use of improved varieties by Tanzanian tomato farmers was very limited. Nowadays, the use of improved OPVs and hybrids has become more common. Out of ten trained lead farmers, four ended up setting up a seedling nursery business and now sell young plants to their peers. Prior to SEVIA, no seedling nurseries existed. Nowadays, trellises can be spotted in farmer fields in the targeted areas. Impact on farmer livelihoods is difficult to measure. Still, growing seed sales reported by EWS and Rijk Zwaan can give an indication of adoption and hint at lasting change.

8.6.6 Conclusions

The SEVIA project theme was seeing is believing. The goal was to show farmers how to unlock the potential of improved varieties. This approach seems to have worked for some farmers who are shifting to hybrid varieties and adopting new agricultural practices. It seems likely that adoption and system transformation are driven by a large, established market for tomatoes. Farmers are motivated to adopt and invest in innovations to tap into this market making them willing to change. In the absence of premiums for quality, farmers will focus on quantity, which may be unsustainable in the future. The tomato market will not expand forever: farmers need to be able to compete on other quality factors and diversify their production moving into other crops.

However, obstacles to the adoption of improved tomato varieties certainly remain for small-scale farmers. These are related to knowledge gaps and financial resources. Capacity building is needed to teach farmers about good agricultural practices. Basic skills and technologies are required to unlock the full potential of improved varieties. Also, farmers need to be able to invest in seeds, inputs, and equipment. They will move step-by-step selecting varieties and feasible agricultural practices, which match their livelihood. During SEVIA, farmers received training regarding the full package, but in the end, they will decide for themselves what is feasible and affordable.

8.7 Reinventing rather than transforming: shallots in Indonesia

De Groot & Slot is the global market leader in onion and shallot seed. It works closely together with the Dutch vegetable breeding company Bejo, which covers a wider variety of crops and has a strong global presence. In 1995, De Groot & Slot was the first to apply the generative seed multiplication and breeding system of common onion to shallots. The innovation of hybrid true shallot seed (TSS) was first introduced in Europe, after which the companies shifted their attention to Indonesia. The shift from shallot bulbs to (hybrid) TSS requires a transformation of the seed, farm, and market system. In the past years, De Groot & Slot and Bejo have experimented with different strategies and undertaken several projects to introduce their innovation in a development context.

8.7.1 Starting point

Traditionally, shallots are multiplied vegetatively, offering farmers a relatively simply way to grow their own seed. Small shallot bulbs attached to the main bulb are harvested, stored for about eight weeks to overcome bulb dormancy, and used as seed for the next planting season. The shallot seed system is largely informal, based on this process of recycling one's own material and exchanging or trading of seeds with neighbours to get access to new varieties. The system fails to supply sufficient quantity and quality of shallot seed: each growing season, shallot farmers face shortages.

Quantities of seed available are too low due to high losses. Storage losses reach 40%, especially during the rainy season when disease pressure peaks. Anticipating these losses, some farmers save a large share of their harvested crop as seed. Other farmers in urgent need of cash are unable to do this and need to sell their harvest. The quality of seed bulbs is another major challenge. Quality of vegetatively multiplied bulbs deteriorates over seasons due to a build-up of pests and diseases that survive in the bulbs (so-called degeneration). Viruses are a particularly big problem in vegetatively propagated shallots, resulting in small plants and low yields. Exchange of seed between farmers can result in the transmission of diseases. Moreover, international seed bulb exchange creates a risk of cross-border transmission.

In response to persistent shortages of shallot seed bulbs, Indonesia imports these from neighbouring countries such as the Philippines, Vietnam, and Thailand. These countries have a different rainy season and can export seed bulbs to Indonesia shortly after their harvest right on time for planting. As a result, imported seed bulbs are cheaper and often better than local ones, as the storage time is much shorter. In this case, cheaper should be interpreted as 'less expensive' as international transport is costly. Seed bulbs can account for up to 50% of shallot production costs. Also, the imported shallots mostly benefit Indonesian farmers located close to ports, while farmers in remote areas continue to struggle to access seed.

Many Indonesian farmers grow shallots (Figure 8.3): it is the second largest horticultural crop after hot pepper. Shallots are grown during the dry season running from March to October. During

Figure 8.3. Shallot farmers working in the field in Indonesia.

the dry season there are two growing periods. Both seasons require reliable access to water for irrigation. At the end of the dry season, rivers and wells tend to run dry. During the rainy season, few farmers grow shallots because of high disease pressure. Shallots are mostly grown in very heavy soils at sea level. The weight of the soil makes shallots grow slowly increasing their shelf life.

Local demand for shallots is enormous. On average Indonesians consume 4.5 kilo of shallots per capita per year. The French consume 550 grams of shallots per year, and the Dutch merely 85 grams. In 2013, Indonesia introduced an import ban on shallots to stimulate domestic production. The price of shallots rose from 90 eurocents to almost 3 euros per kilo. Financial and physical access of farmers to shallot seed for cultivation and consumers to shallots for consumption was reduced.

8.7.2 Promise of innovation

The promise of TSS compared to seed bulbs is that high quantities of high-quality seed can be produced faster, cheaper, and easier. A single shallot plant produces only six to ten bulbs, whereas it can also set up to 200-600 true seeds under optimal conditions. The high multiplication rate of TSS means associated costs of seed production can be reduced. Contrary to bulbs, true shallot seed is generally free of pests and diseases. All logistical issues of bulbs related to storage or transportation are removed as true seeds are easily stored and shipped. The innovation of true shallot seed results in a constant and reliable supply of quality seed, which can be planted whenever the barrier of dormancy is removed.

The hybrid variety 'Maserati' can outyield local varieties by over 30%. This increase in yield is explained by the clean nature of the starting material and improved genetics of the hybrid variety. As the true shallot seed is free of pests and diseases, the plants have a good start and turn out healthier. Strong genetics improve the chances of the plant surviving under pressure from pests and disease. In the hot and humid Indonesian climate, farmers still need to spray, and there is no cost reduction. Still, farmers see the added value of the hybrid: De Groot & Slot and Bejo also sell true shallot seed of an OP variety, but this one is much less popular amongst farmers.

In industrial agricultural systems, (hybrid) true shallot seed offers another benefit. The uniformity of true shallot seed supports mechanisation. Bulb shallots still require manual labour during planting and harvesting, which is costly. By contrast, seed shallot production can be partially mechanised. This benefit is less relevant in a development context where the cost of manual labour is low, farmer fields are small, and mechanisation of agricultural production is limited.

The taste and colour of seed and bulb shallots are similar. However, the quality of seed shallots is either similar to, or higher than the quality of bulb shallots. Shallots grown from seed tend to be more uniform and larger than bulb shallots, which are usually small due to viruses. Bulb shallots are usually the size of a large garlic clove. Consumers prefer larger shallots because they need to peel less. Also, the shelf life of seed shallots tends to be longer than of bulb shallots. A shallot can be stored when it ripens without being contaminated by diseases or pests. Use of clean starting material and production in clean soil are the most effective ways to mitigate the risk of contamination.

8.7.3 Barriers to adoption

Currently, shallot farmers do not buy their plant material from agro-dealers or in seed shops. In fact, formal market channels to sell shallot seed bulbs are non-existent. Farmers are used to saving their own bulbs, exchanging bulbs with neighbours, or buying bulbs through the informal market. In this system, the reputation of farmers and geographic areas play an important role. One of the few means available to verify quality was for farmers to undertake field visits, visually check the state of the shallot plants and decide from whom they would buy bulbs.

The shift from using shallot bulbs to true seed also represents a major hurdle. It is cumbersome for shallot farmers to switch from using bulbs to using true seed as planting material. Shallot farmers are used to robust bulbs, which are planted directly in the field. The true seeds are planted in a nursery and after 6-8 weeks, the seedlings are transplanted to the field. Alternatively, true seed can be sown directly in the field, but the plants will take longer to mature. Shallot farmers have no or very little experience with germinating seeds, raising seedlings, and transplanting seedlings.

Moreover, shallots grown from true seed thrive in other soils than shallots grown from seed bulbs. Traditional production areas are characterised by heavy clay soil and heavy rainfall. By contrast, true seed shallots flourish in lighter soil, as they struggle to establish their root system and emerge and need moderate rains. Also, there are doubts regarding the performance of new varieties under high soil-borne disease pressure which characterises the traditional production areas. Even though hybrid shallots are grown from clean seed, many resistances are needed to grow under these conditions. For many years, local varieties have been selected by farmers, which can cope with high disease pressure.

Finally, the use of true seed impacts the plant growth cycle. One of the first questions of farmers about a new variety is: how much time will it take me to grow the crop? In Indonesia, farmers have strict rotation schemes as they have three growing seasons per year. Plants grown from directly sown shallot seeds take 3-4 weeks longer to mature clashing with a farmer's planning. Seedlings are produced in a nursery and the growing period in the field remains the same. Therefore, the introduction of TSS via seedlings is possible while direct sowing is likely not an option.

Few barriers to adoption seem to exist related to the market system. In terms of varieties, the shallots grown from true shallot seed should be at least equally popular. A study conducted in 2012 by Van den Brink and Basuki stated that consumers prefer traditional varieties with a deep red colour over improved varieties with a lighter skin colour (Van den Brink and Basuki, 2012). However, the main hybrid variety of De Groot & Slot and Bejo called Maserati also has a deep red colour.

8.7.4 Strategies applied to overcome barriers

De Groot & Slot and Bejo applied two different strategies to introduce TSS. First, they sought to launch a bulb-based system producing bulbs from true seed. The aim was to minimise change for the shallot farmer supplying seed bulbs to market and not true seed. They invested in a farm in

Thailand to grow bulbs for the Indonesian export market. Production of shallot bulbs from true seed would be done internally on farm, and subsequent rounds of multiplication would be done by outgrowers. The harvest could be shipped to Indonesia directly after the rainy season. In 2013, after several years of testing to optimise the production, the companies and their outgrowers were ready to export. However, around this time, the Indonesian government decided to implement an import ban on shallots. Previously, 30% of Thai shallots were shipped to Indonesia.

While Thai market prices crashed, Indonesian market prices peaked. The companies decided to move their operations to Indonesia. They figured that scarcity and high market prices could fuel technology adoption. Also, they decided to go for a radically different strategy: there would be no investments in vegetative multiplication. Moreover, the focus would not be on traditional shallot areas and traditional shallot farmers. In 2017, the company identified the most suitable cultivation areas for shallots grown from (hybrid) true seed together with Wageningen University & Research. In these areas, vegetable farmers were targeted to include shallot production into their rotation schemes. The fields with lighter soils were suited for seedlings and farmers already had experience working with seedlings growing other horticulture crops.

In 2018, a project funded by the Dutch Enterprise Agency (RVO) was implemented to establish a training centre, organise demonstrations for farmers and supply free seed samples. De Groot & Slot and Bejo invested in capacity building of farmers in shallot cultivation using a farmer-to-farmer training model. De Groot & Slot says: 'they shifted from investments in hardware to investments in software.' The vegetables farmers were unfamiliar with shallot cultivation. They are now training these farmers to cultivate shallots from true seed. Farmers will be able to tap into the massive domestic market and simultaneously, seed companies expand their customer base. In the coming years, Bejo and De Groot & Slot expect a snowballing effect to commence as other farmers learn about the potential of true shallot seed. High prices provide a strong incentive to grow shallots and adopt innovations to increase productivity.

The new strategy of De Groot & Slot and Bejo has yielded considerable success. The companies have now been promoting (hybrid) true shallot seed in Indonesia for 5 years. Currently, about three to five percent of area under shallot production is planted with true seed. Worldwide, De Groot & Slot and Bejo have a market share of 50% in long-day shallots and hence, they are not satisfied. In the coming years, the two companies aim to increase their market share in Indonesia. De Groot & Slot and Bejo stress that it took twenty years to realise the 50% market share in Europe. The five-year timeline in Indonesia is still relatively short.

8.7.5 Conclusions

The transformation of the shallot seed, farm and market system turned into a reinvention of these systems. Initially, De Groot & Slot and Bejo sought to minimise change for traditional shallot farmers. The companies then decided to take a radically different approach targeting new areas and farmers. A research project preceded the design of its market strategy identifying the most suitable areas, which turned out to not to be the traditional shallot areas. De Groot & Slot and Bejo have focused on capacity building and aim for a snowball effect. As farmer communities in new areas become more familiar with shallot cultivation, they expect their market share to grow. The large domestic demand for shallots is a strong force for adoption. Nowadays, their market share of the Indonesian market is estimated to be around five percent, which is considerable, but insufficient for global market leaders in allium crops.

The key remaining barriers to adoption are financial ability, knowledge, and skills. First and foremost, many farmers still cannot grow shallots because of the high upfront investment costs: the costs of seed bulbs are simply too high. True seed can somewhat reduce and stabilise the price of starting material enabling more farmers to grow shallots in remote shallot areas. However, many farmers still cannot afford to adopt innovations. Second, farmers need to be familiarised with good agricultural practices. Increases in national shallot production are based on expansion of the cultivation area rather than yield gains. The hybrid variety Maserati has major potential, but farmers need knowledge and skills to realise this potential. As long as yields are low, the return on the investment of farmers in seed also remains low.

8.8 Disruption or integration: hybrid true potato seed in East Africa

HTPS technology has the potential to become a disruptive innovation. The potential impact of HTPS on the potato sector in developing countries is high (De Vries *et al.*, 2016). HTPS offers an alternative for the current potato seed system based on tetraploid varieties, which are cumbersome to improve genetically using conventional breeding methods, and which are multiplied slowly through vegetative seed potato production systems (Jansky *et al.*, 2016; Lindhout *et al.*, 2018). Still, HTPS introduction will require either integration of HTPS in existing potato seed, farm and market systems or transformation of these systems, which may prove challenging. The first commercial hybrid potato varieties are becoming available now being introduced on the market by Bejo (tetraploid TPS) and Solynta (diploid hybrid TPS). The first commercial varieties of Aardevo and HZPC are expected in 2025. It raises the question how the innovation can effectively be introduced in a development context.

8.8.1 Starting point

Potato farmers in the Netherlands can produce 42 tons per hectare, whilst average yields in East Africa are around seven to twelve tons per hectare (FAOSTAT, 2020). Potato productivity has only improved marginally over the last decades, and the growing demand is met by area increase, rather than productivity increase (Gildemacher *et al.*, 2009b). This has resulted in a situation where the maximum areas under cultivation which can be considered sustainable in terms of soil health management have been surpassed. Further growth of production will have to be realised through productivity increase in the traditional highland production areas.

Traditionally, potatoes have been multiplied vegetatively. Farmers use seed tubers as starting material for potato production; some tubers are saved and used to grow new plants. In East Africa, more than 90% of the seed tubers is provided via the informal seed system (Gildemacher *et al.*, 2009a; Schulte-Geldermann *et al.*, 2022). The most common source of seed tubers is self-supply, selecting and storing small tubers from the previous harvest. Farmers also exchange or trade seed tubers within their social network. Only a tiny proportion, 2-5% of seed tubers, is sourced via the formal system from specialised farmers adhering to a quality control system (Ferrari *et al.*, 2018; Gildemacher *et al.*, 2009a). High-quality potato seed tubers tend to be expensive or unavailable. A major financial barrier exists to buy certified seed as costs would account for up to 60% of total production costs (Schulte-Geldermann *et al.*, 2022).

The low quality of potato seed has been identified as a key constraint contributing to low productivity. Quality of seed tubers decreases every cycle of vegetative multiplication due the accumulation of soil- and seed-borne diseases and pests and contributes greatly to the perpetually low yields of smallholder potato farmers in East Africa (Schulte-Geldermann *et al.*, 2022). From this amount, around 20% of the tubers are saved by farmers as seed for next season further lowering their marketable surplus.

Losses during storage period can reach up to 30% (Gikundi *et al.*, 2022). In Kenya, the popular variety 'Shangi' already sprouts two weeks after harvest to avoid a storage period (Gikundi *et al.*, 2022). Managing tuber dormancy is a major element in the potato production, as the moment of sprouting needs to match the desired moment of planting. This complicates considerably the seed potato system for professional seed producers, seed users and breeders alike.

In East Africa, potatoes are almost exclusively grown by smallholder producers, as landholdings in the highlands suitable for potato production are highly fragmented (Devaux *et al.*, 2021). Amongst farmers, there is a lack of awareness regarding good agricultural practices, disease and pest control and soil fertility. Potato farm systems in East Africa are generally 'low input,' in comparison to industrialised systems. In East Africa, it is mostly grown under rain-fed conditions and the majority of smallholder producers uses sub-optimal crop protection and soil fertility management.

Potato is an important food and cash crop in East Africa. The market can be divided into two segments for ware versus processing potatoes. Ware potatoes are bought by consumers, whereas processing potatoes are used to produce crisps or French fries. In developed markets, these are strictly separated, while in developing countries, they tend to largely overlap. Market prices are subject to large fluctuations. Farmers do not grow potatoes during the off-season because of a lack of irrigation facilities. During the harvesting period, prices drop as market is overflown. Before the start of the new season, supply runs low, and prices go up. Meanwhile, demand for potatoes continues to grow because of population growth and changing diets, which can be linked to urbanisation.

8.8.2 Promise of innovation

An immediate benefit of HTPS technology is the possibility to grow potatoes from true seed rather than seed tubers. So far, little progress has been made in developing effective vegetative seed systems that serve smallholder producers in developing countries with affordable high-quality seed tubers (Schulte-Geldermann *et al.*, 2022; Tadesse *et al.*, 2020). The benefits are comparable to the benefits of (hybrid) true shallot seed moving from a vegetative to a generative seed system. A transition from the vegetative to the generative seed system allows for much faster multiplication, reducing the number of multiplication generations from up to eight to a maximum of two (Ter Steeg *et al.*, 2022). Less land is required for seed multiplication, risks of crop losses and quality deterioration are reduced. HTPS can be stored for a long period of time in a (dry) cupboard instead of a high-tech storage facility. Also, true seed is transported in an envelope rather than containers, cars, sacks, or crates. In summary, the availability and affordability of starting material for potatoes can radically increase.

HTPS is free from almost all diseases and pests, contrary to the vegetatively multiplied shallot bulbs and seed potato tubers, which tend to be contaminated by seed-borne diseases (Kreuze *et al.*, 2020). The seed- and soil-borne disease bacterial wilt is endemic in East Africa. Use of clean seed is essential for its containment and flush-out over time. However, production of clean seed is sheer impossible when multiplying seed tubers vegetatively in an environment in which disease-free land can hardly be found. HTPS can break the cycle of seed- and soil-borne re-infection. Potato viruses are another major yield reducing factor and accumulate in seed stock over generations of re-use. In East Africa, many potato plants in farmer fields look different. Heterogeneity is caused by high virus disease incidences. Regular renewal of the seed stock with virus-free material from HTPS will mitigate this problem.

Improved varieties with stronger genetics can now be developed for potatoes. Hybrid breeding could not be applied in traditional tetraploid potato varieties due to their genetic complexity (Jansky *et al.*, 2016; Lindhout *et al.*, 2011). A shift to the diploid potato made it possible to add desirable new traits to existing varieties reliably and effectively (Su *et al.*, 2020). In both the tomato and shallot case, the added value in terms of stable and uniform yields were major drivers for adoption amongst farmers. Moreover, like tomato, potato is a vulnerable crop and fields can be wiped out by certain diseases. Resistance to late blight, to viruses such as PVY, PVX, PLRV, and to nematodes such as PCN will play an important role in variety selection. Moreover, resistance to abiotic stresses such as drought will only continue to become more important in the future.

Varieties can also be tailored to specific market demand. In East Africa, processors often resort to buying 'multi-purpose' table potatoes because local processing varieties are unavailable (Placide *et al.*, 2022). New hybrid varieties can fill this gap. Processors are looking for a specific tuber shape, a smooth skin, shallow eyes, low sugar levels and a high dry matter concentration. However, specialised production will only be viable if processors are willing to pay a tangible price premium to producers. Otherwise, farmers prefer the consumption spot market, which is generally a more convenient and reliable offset channel.

8.8.3 Barriers to adoption

Many of the barriers to adoption resemble those identified for the improved varieties of shallots and tomatoes. The main barrier is similar to the one faced for true shallot seed seeking to change the type of starting material. Potato and shallot farmers are used to robust vegetative starting material. True seed requires more care. Ideally, it is planted in a nursery to raise seedlings, which are transplanted to the field 4-6 weeks after sowing (Kacheyo *et al.*, 2020, 2023). The vast majority of potato and shallot farmers has no experience germinating seeds, raising seedlings, and transplanting seedlings. Especially during the first few weeks, seedlings need to be nurtured. Apart from low early vigour, seedlings are sensitive to weed infestation, wind erosion, earthing up and damping off.

Also similarly, no large-scale formal seed systems for potato currently exists and farmers may not be reached easily. A limited number of seed potato multipliers exists, who buy pre-basic seed tubers which they multiply several generations before selling to producers. Sales of seed tubers rather than true seed or seedlings would minimise the change for traditional potato farmers. However, this would increase the upfront investment of farmers and the tomato case showed how farmers prefer to raise their own seedlings to reduce costs. Furthermore, this would either require existing multipliers to learn how to deal with seedlings. Alternatively, it would require young plant raisers to learn how to deal with potato plants. Therefore, integration of HTPS into existing systems requires potato seed multipliers to learn horticultural skills or young plant raisers to familiarise themselves with a new crop.

It might be hard to introduce HTPS in traditional potato farm systems. In traditional areas, soils tend to be heavy and cropping systems are rain-fed (Mazengia *et al.*, 2015). Potato farmers have limited or no access to other water sources, while irrigation is generally necessary for root establishment of HTPS seedlings. Direct sowing of HTPS might be an option in the future, for example thanks to seed coatings, but this would mean that the full-field growing period is weeks longer (Van Dijk *et al.*, 2023). It is highly unlikely that farmers then shift from seed tubers to HTPS, as land is a very scarce resource in the East African highlands. It might be the case that reinvention of the potato system elsewhere working with vegetable farmers is easier.

Hybrid potatoes will compete with familiar, local varieties. National potato markets in East Africa are dominated by a limited number of popular varieties. In Kenya, the Shangi variety dominates the market with a share of over 80% and in Rwanda, the Kinigi variety holds a similar position (Gikundi *et al.*, 2022, Irungu *et al.*, 2022; Muhinyuza *et al.*, 2012). Farmer, trader, and consumer preferences are strong and when it comes to table varieties, consumers prefer large tubers with a familiar skin and flesh colour (Muhinyuza *et al.*, 2012). The most popular varieties are multi-purpose varieties, which can be used for boiling, but also reasonably well for frying. Personal experience of the first author indicates that cultivation from HTPS via seedlings can result in a higher number of smaller tubers in comparison to potatoes grown from seed tubers. Farmers or specialised multipliers may have to include one round of vegetative multiplication in the seed system to assure the desired tuber size is harvested (Figure 8.4).

8.8.4 Proposed strategy to overcome barriers

When considering seed system barriers for the adoption of HTPS, the main barrier is the cumbersome raising of seedlings. Either farmers need to learn how to raise seedlings, or specialisation of the chain is required working with intermediaries. The tomato case shows that the SEVIA project focused both on the training of farmers to grow seedlings in an on-farm nursery,

Figure 8.4. Rwandese farmer planting potato seedlings in the field.

and of specialised seedling producers. Most farmers preferred to grow their own seedlings to reduce costs. In the case of HTPS, there is an option of specialised multipliers to produce seed tubers from HTPS to sell to potato farmers minimising change. This was the initial strategy used for shallot bulbs produced in Thailand for introduction in Indonesia, but unfortunately, no lessons can be learned, as it never got off the ground because of the import ban that was installed.

An advantage is that HTPS is not entering a perfect seed system. Currently, potato starting material is often unavailable and/or unaffordable. In the shallot case, farmers deal with a constant lack of quality seed. In both the shallot and tomato case, farmers deal with uncertainty regarding seed quality. For tomatoes, analytical quality of seed can be low resulting in low germination. Farmers needed to pay a higher price for hybrid seed of improved varieties representing a barrier for adoption. For shallots, physiological quality of seed is low resulting in low yields. Farmers can now pay a similar or lower price for hybrid seed of improved varieties representing a driver for adoption. This can be similar for HTPS: companies can make quality seed available to farmers at similar or lower price level.

In terms of farm systems, the main barrier is the compatibility of fragile seedlings with conditions in traditional potato areas. Potatoes are traditionally grown in heavy soils as part of rain-fed, low-input farm systems. In the shallot case, it was more effective to move into new areas and work with new farmers. A study was conducted to identify the most suitable cultivation areas and develop an effective introduction strategy. Based on the results, the companies decided to focus their investments on the capacity building of vegetable farmers. A similar 'land suitability study' was conducted for true potato seed in Indonesia but has yet to be conducted in East Africa.

Potato breeding companies may benefit greatly from a study as it remains unclear whether HTPS technology is best suited for traditional highland potato farm systems or not.

Another barrier in terms of farm systems is posed by the plant growth period. The shallot case clearly shows that farmers are very much focused on growth period. A short growth period may well be one of the most desirable traits looked for by smallholders in East Africa because of extremely high land pressure. Hence, direct sowing of HTPS by farmers is highly unlikely to become a success due to the extended growth period of plants. Larger farms in the lowlands could engage in potato production with direct sowing as land pressure is lower. In this case, potato breeding companies would need to develop varieties, which are suitable for warmer conditions. Beumer and Stemerding (2021) call for the launch of a hybrid potato breeding programme for the lowland tropics.

Market systems can also represent a bottleneck. Visible traits such as skin colour, flesh colour, tuber size and taste, are prerequisites for a variety to become competitive. The shallot case shows that improved varieties should be of similar or higher quality than existing varieties. In that regard it is essential to invest in breeding for local demand, to assure that HTPS varieties that are introduced are competitive at the level of the consumer. HTPS companies could focus on the processing market because of the lack of local processing varieties. However, the tomato case shows how it is easier to focus on the bulk market rather than a high-end niche market as price premiums for quality are still limited or non-existent in developing countries. If potato breeding companies want to focus on this specialised market, they will need to build partnerships with local processing companies to provide price premiums for farmers.

In addition to the barriers mentioned above, there is a regulatory barrier for the introduction of HTPS. Variety registration regulation and seed certification are based on the vegetative multiplication system. The regulation will have to be adapted to accommodate HTPS requiring collaboration with the relevant government bodies. Seed regulations have a national, regional, and international angle. In practice, the national regulations supersede the regional and international regulation. Hence, it would be most pragmatic to start with national regulation, before entering in discussions of regional and international regulation.

8.8.5 Conclusions

HTPS technology has potential to strengthen the smallholder potato sector in Sub-Saharan Africa. It offers an alternative for the current potato seed system based on tetraploid varieties, which are cumbersome to improve genetically, and which are multiplied slowly through vegetative seed systems. In addition, HTPS is easy to transport and store, has no dormancy, and hardly suffers from seed-borne diseases. These significant promises of HTPS could remove constraints plaguing the development of the potato sector in Sub-Saharan Africa. For its successful introduction, stakeholders will need to realise promises of the innovation and overcome barriers to adoption. This chapter analysed promises and barriers looking at the seed, farm, and market system. Efforts of Dutch vegetable seed companies, EWS and Rijk Zwaan introducing improved tomato varieties in Tanzania, and De Groot & Slot and Bejo introducing true-seed shallots in Indonesia, offer lessons learned when developing a strategy for HTPS.

The SEVIA project in Tanzania (2013-2020) demonstrated that main barriers to adoption of tomato varieties were posed by the seed and farm system. The investment in seed of improved varieties was worthwhile, only if tomato farmers improved their full-field production practices, and prior nursery care. There were no barriers regarding the market system, but there were also no incentives for adoption: tomato is mostly a commodity in Tanzania and there is no diversified market. For successful adoption, an outreach programme was needed to train farmers in good agricultural practices and demonstrate the added value of quality seed, as well as investments in setting up specialised nurseries and training tomato producers on seedling raising were key. The 'True Seed Shallot demonstration project' in Indonesia (2018-2020) sought to introduce TSS varieties requiring a transformation of the seed, farm, and market system. The companies decided to promote TSS outside traditional shallot production areas where the potential positive impact of their innovation was larger. Vegetable farmers, familiar with seedlings while unfamiliar with shallots, were trained in shallot production from seed. An outreach programme was required again to train farmers in good agricultural practices and demonstrate the added value of quality seed plus to teach farmers about shallot production.

HTPS, like improved shallot and tomato varieties, requires transformations of the seed, farm, and market systems. Either a nursery step, followed by transplantation of the seedling is required, or direct seeding can be done, but this lengthens the growing cycle, which is tedious. The tomato case shows that most farmers prefer to produce their own seedlings to reduce costs, while others can be served by specialised seedling growers. The shallot case shows that it might be preferable to work with farmers with seedling experience rather than farmers used to bulbs. Specialised HTPS seedling growers could go a step further, and produce seed tubers, in which case ware potato farmers do not need to change their practices. HTPS will also require changes in the farm system as horticultural skills are required to realise the potential of varieties. This finding seems applicable for all improved varieties: without additional skills, adoption of an improved variety is not economical. Market system promises which contribute to adoption are improved marketability and extended shelf life of produce. Also, the ability of farmers to produce outside the main season thanks to short plant cycles and disease resistance can be a driver. In the case of HTPS, processing quality can be an additional beneficial characteristic.

For HTPS, the challenge is to find a balance between disruption and integration. HTPS is introduced in an imperfect, but familiar system. The promises of the innovation can fuel change of the seed, farm, and market system. However, several barriers for adoption of HTPS remain: these barriers are real but seem surmountable provided that the improved variety meets farmer and consumer preferences. The case studies on tomato and shallot demonstrate that it is possible to realise transformation in a relatively short time through the implementation of development projects focused first and foremost on capacity building. Moreover, there needs to be a business case with secure market demand, which farmers can tap into. It is important to stress that the technology also needs to be introduced in an affordable manner: the high costs of quality seed of improved varieties remain a barrier for many risk-averse smallholders. In summary, farmers need to be familiarised with a technology and recognise its profitability. Subsequently, HTPS technology can be mainstreamed in the seed, farm, and market system minimising disruption and maximising innovation.

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Chapter 9. Corporate social responsibility and hybrid potato breeding: balancing economic, environmental and social challenges

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Abstract

Hybrid potato breeding is an emerging technology that can have a strong impact on the potato sector by replacing seed potatoes with true seeds. The Netherlands is a world leader in certified seed potatoes and a number of Dutch companies play a pivotal role in the development of this technology. This implies a certain responsibility for the consequences and conditions of its implementation and we therefore explored how Dutch potato breeding companies see their role and responsibility especially in low- and middle-income countries in the context of the United Nations Sustainable Development Goals (SDGs). From interviews, it appears that most potato breeding companies emphasise the promising role of hybrid potato breeding in achieving SDGs. They also stress that their core business is at the heart of corporate social responsibility as it contributes to the SDGs. We also observed that for the introduction of new varieties they often rely on trickle-down mechanisms, where local farmers are rather passive recipients, rather than being actively involved in strategic choices of innovation. It may explain why the concept of responsible research and innovation (RRI), which emphasises the active involvement of society and affected stakeholders, is relatively unknown in the sector. The main approach in the sector may be labelled as a 'solution strategy' where dominant actors rely on their expertise to solve problems. However, the attainment of SDGs should rather be considered as a wicked problem, characterised by complexity, uncertainty and multiple actor's perspectives. A 'negotiation strategy', which is more inclusive and stresses the need of negotiation between different perspectives and interests, may fit better. From the perspective of RRI it is argued that insights from participatory breeding and farmer variety selection traditions and the concept of benefit sharing may be considered as promising negotiation strategies that can contribute to potato breeding practices for the attainment of SDGs.

Paul C. Struik, Peter R. Gildemacher, Dirk Stemerding and Pim Lindhout (eds.)
Impact of hybrid potato

DOI: 10.3920/978-90-8686-946-6_9, © J.A.A. Swart and I. van de Poel, 2023

Keywords: HTPS-technology, sustainable development goals, corporate social responsibility, responsible research and innovation

9.1 Introduction

As an emerging innovation in potato breeding, 'hybrid true potato seed' (HTPS) technology has the potential to contribute significantly to the Sustainable Development Goals (SDGs) of the United Nations. This is especially relevant for low- and middle-income countries (LMICs) where potato is an important staple crop. The Dutch seed potato sector as a dominant actor in certified high quality seed potatoes may potentially play an important, if not decisive role, in exploiting this potential. Indeed, several Dutch companies, i.e. Solynta, HZPC, and Aardevo, are currently developing diploid hybrid potato varieties and expect market introduction within a couple of years, while Bejo has already registered a tetraploid hybrid variety. In this chapter we aim to critically reflect on what role Dutch potato companies see for themselves in this respect, what opportunities and uncertainties they perceive, and which strategies they follow.

To this end, we investigate the activities of Dutch potato companies through the lens of 'corporate social responsibility' (CSR) and 'responsible research and innovation' (RRI). CSR has been defined as 'the responsibility of enterprises for their impacts on society' by the European Commission (2011), while RRI has been understood by the European Union as 'the on-going process of aligning research and innovation to the values, needs and expectations of society' (EC, 2014). The core idea of both CSR and RRI is that companies should in their operations respect societal values as well as contribute to the so-called Grand Societal Challenges (Voegtlin *et al.*, 2022), like SDGs.

This chapter is structured as follows. We first shortly discuss existing potato production systems and the potential contribution of HTPS. We then introduce the concepts of CSR and RRI in the context of the SDGs. The following section presents our research questions and methods. Subsequently, we describe the results of our empirical investigation based on interviews with Dutch potato breeding companies. The next section outlines our conclusions with respect to our empirical research questions. In the final section, we critically reflect on our findings, and we will make suggestions how Dutch potato companies can develop strategies that help better exploit the potential of HTPS for LMICs.

9.2 Potato production systems and the potential impact of HTPS

Farmers in LMICs mostly rely for their food on traditional crop varieties which are adapted to local conditions as part of what is called the 'informal agricultural or seed system'. In such systems, farmers mostly rely on own farm-based seeds and tubers, without a clear separation between seed selection, seed production, and seed diffusion, which happen mostly within the local farming community (Louwaars and De Boef, 2012).

Informal seed systems are characterised by institutional organisation and labour relations that are mostly based on casual employment, kinship, or personal or social relations instead of contractual arrangements. Informal systems are further characterised by an absence of specialisation, low capital investments, small enterprises, mingled with a focus on non-farming components, a dominant role for women, and no or a limited role for formal institutions. Innovations are often more social than technical (Chakrabarti, 2014). Thus, the informal system is not just a seed system but rather a community system (Lammerts van Bueren *et al.*, 2018).

In contrast, formal seed systems are characterised by clearly distinguished steps in the value chain, sometimes performed by different organisations and companies with regard to breeding, multiplication, production, marketing, and retail (Figure 9.1). Potato breeding companies, which are mostly based in high income countries (HICs), have an important role and are often organised through branch organisations. Formal systems are strongly guided by scientific methodologies, controlled multiplication and production. Policy and legal frameworks play an important role through facilitating investments in breeding, regulating access to genetic resources, and ensuring seed quality. Yields in formal systems are much higher as compared to informal systems. Whereas potato yields of 40 t/ha are possible in HICs such as the Netherlands, East African yields often remain below 10 t/ha (De Vries *et al.*, 2016).

According to the International Labour Organization (ILO, 2018), worldwide more than 60% of world's employed population is in the informal economy and for Africa this is more than 85%. However, there is no sharp line between the formal and the informal system. They may interact and some farmers dovetail informal and formal farming, which may infuse new varieties and knowledge into the informal system. Formal systems may also utilise genetic resources from the informal system in order to develop varieties with particular traits (Figure 9.1).

Application of HTPS in the informal system may include several cultivation strategies varying from sowing true potato seed directly by farmers, to seed tuber production by companies based on hybrid true potato seeds. It has the potential to contribute to an improvement of potato production in LMICs, and so to the achievement of Sustainable Development Goals (SDGs) in particular SDG-2 aimed at food security and sustainable agriculture (see other chapters in this volume and UN-DESA, n.y.). The knowledge and skills required to make HTPS technology a success, however, largely stem from the formal seed system, in which Western potato companies

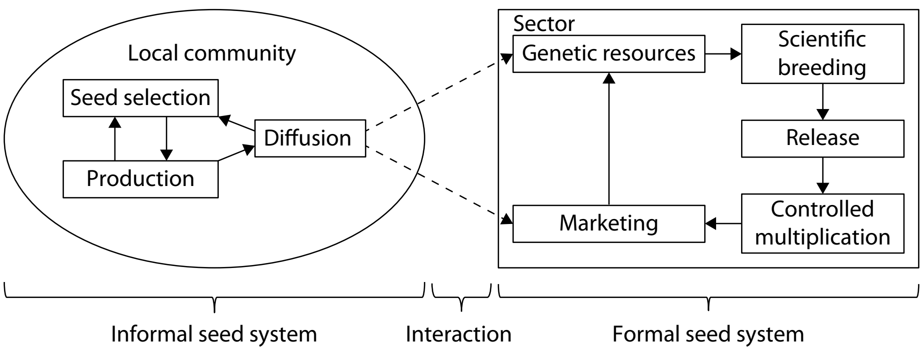

Figure 9.1. The informal and formal seed systems and some interactions between them (after Louwaars and De Boef, 2012).

are dominant. The introduction of HTPS in LMICs may lead to a greater dependence of small farmers on Western breeding companies. It will require adaptations of current farm-based systems to the formal system. However, farm-based seed systems are often embedded in local community structures and seed interventions are therefore complex, far-reaching, controversial and will fail if the local community and its local knowledge is not involved or at least considered (Almekinders *et al.*, 2019; Stemerding *et al.* 2021; see also Chapter 7).

While exploiting the potential of HTPS in LMICs may be in the self-interest of Dutch potato companies, there are a number of reasons to assess this technology through the lens of both CSR and RRI. First, the market in LMICs is uncertain and some companies might therefore prefer for economic reasons to focus on Western markets, ignoring the SDG-potential of HTPS technology in LMICS. CSR may motivate to keep the SDG perspective in focus. Second, what is required is much more than the commercial availability of hybrid potato seed, plantlets or tubers. Rather, the innovation will affect – as described above – the existing informal potato production system, and from a CSR and RRI perspective these effects should be taken into account in the company's innovation and marketing strategies. In particular, it will require tailoring hybrid technology to the local circumstances and requirements of farmers in the informal system.

9.3 Corporate social responsibility and responsible research and innovation in the context of Sustainable Development Goals

Like other global societal challenges, SDGs are complex, uncertain and value-laden (Voegtlin *et al.*, 2022). This is because their attainment requires a combination of social, institutional, technical, economic and political measures, taking into account diverse socio-technical system conditions. We only partly understand these challenges and conditions and we also lack agreement on how they can be best understood. They are value-laden, in the sense that value judgements are required in both understanding and addressing them. Realising SDGs is therefore best seen as an unstructured or 'wicked' problem (Ludwig *et al.*, 2021). In contrast to structured or 'tame' problems there is no agreed formulation of what the problem is about. Different stakeholders may perceive the problem differently and also radically disagree about solutions (Rittel and Webber, 1973).

Considering abating hunger as a tame and straightforward problem that can be solved solely by better varieties and higher yields, ignores underlying factors and causes associated with social injustice, political interests, and institutional and legal shortcomings in the food system. In this context, various authors have discussed how companies through CSR and RRI can respond to wicked problems (Imaz and Eizagirre, 2020; Ludwig *et al.*, 2021; Voegtlin *et al.*, 2022).

9.3.1 Corporate social responsibility

Corporate Social Responsibility (CSR) is a management concept stressing that it is not only the interests of the owners of a company (shareholders) and the employees or suppliers (direct stakeholders) that count, but also wider social and environmental issues and imperatives. According to the UN Industrial Development Organization (UNIDO, n.d.):

> 'corporate social responsibility is a management concept whereby companies integrate social and environmental concerns in their business operations and interactions with their stakeholders. CSR is generally understood as being the way through which a company achieves a balance of economic, environmental and social imperatives ('Triple-Bottom-Line-Approach'), while at the same time addressing the expectations of shareholders and stakeholders.'

CSR is often linked with the UN SDGs in the sense that it asks for how much a company can or will contribute to these goals. According to the United Nations Global Compact[5], currently, world-wide 14,272 companies (including large, medium, and small companies) have signed up to the 10 CSR Global Impacts principles of the UN, which implies a commitment to contributing to the UN SDGs.

CSR has sometimes been criticised as being too reactive and being too much based on instrumental and symbolic reasons rather than a contribution to society. Porter and Kramer (2006) therefore argue that CSR should be closely connected to corporate strategy in the sense that it should not be restricted to philanthropy, but rather should closely connect to the core activities and corporate strategy of the company. The company should ask itself: how can we contribute to wider society and to the UN SDGs, while making a profit? This requires the development of a corporate strategy that adds value for the company as well as for the wider society.

CSR has also been criticised as being based too much on voluntary commitments and being used instrumentally for avoiding government regulation. The experiences with Responsible Care in the chemical industry since the 1980s are instructive (Givel, 2007; King and Lenox, 2000). Responsible Care is an industry-wide initiative to improve the environmental and safety performance of chemical companies. It is aimed at creating a set of minimal, but voluntary, rules that the whole industry should abide by, thus creating a level playing field. The idea was that it would become attractive for all companies to live by the rules and thereby to contribute to a better image of the chemical industry as a whole. At the same time, it has been criticised as an attempt to postpone government regulation. One of the important lessons learned from Responsible Care in the chemical industry is that it is important to have some form of external auditing to check whether companies indeed live up to such voluntary self-regulatory codes.

9.3.2 Responsible research and innovation

The concept of RRI in particular stresses the need for opening up the innovation process to a wider range of moral concerns and societal stakeholders (Von Schomberg, 2013). RRI stresses four conditions that should be taken into account with respect to research, technology development and innovation efforts of an organisation (Stilgoe *et al.*, 2013):

- anticipation: innovation should take into account potential future developments;
- inclusiveness: involve stakeholders and the public;
- reflexivity: reflect on underlying value systems;
- responsiveness: provide an answer to social concerns.

[5] https://tinyurl.com/2cuh2zvx.

There is limited experience with RRI in industry (Van de Poel *et al.*, 2017). One reason is that the concept is still rather unknown among industries, and that companies might feel that it requires quite substantial investments without immediate business benefits (Dreyer *et al.*, 2017; Gurzawska *et al.*, 2017). One suggested strategy to overcome this is to build on existing RRI-like activities that many companies already undertake, like for example risk assessment, life cycle analysis or strategic planning, and to broaden these with wider ethical concerns and the inclusion of stakeholders (Van de Poel *et al.*, 2020).

A more strategic barrier for RRI is that companies are often hesitant to allow other stakeholders access to their innovation process. An important reason is that innovation is often considered as the key to competitive advantage. Many companies therefore want to protect their innovations if not through intellectual property rights and patents then at least by keeping certain technical details and strategic considerations secret.

While traditionally CSR has been focused on preventing harm, a focus on SDGs would allow companies to make a positive societal contribution. It would, however, require companies to make CSR and their contribution to the SDGs not something accidental that is peripheral to their corporate strategy but part of the core activities of the firm (Imaz and Eizagirre, 2020). RRI is even more challenging as compared to CSR, because it opens up strategic business decisions and the company's innovation process to external influences from stakeholders that may be affected by the innovation (e.g. in their livelihood), but who do not have a commercial stake or share in the company itself (as most farmers in LMICs). As mentioned above, companies may be reluctant to do so because it may conflict with their commercial interests and constraints. As compared to CSR, it requires probably measures and steps above the level of individual companies to make it affordable.

9.4 Research questions and methods

This chapter aims to explore whether, and if so, how potato companies aim to contribute to societal goals, like SDG-2, through the development and use of HTPS technology. The Dutch potato sector is a strongly formalised system covering breeding, multiplication, production, storage, processing, and retail. In the Netherlands, so-called potato trading houses play an important role as they are active in breeding, multiplication, production, storage, and trading of potatoes. The sector has a strong international role as it is the world's major supplier of certified seed tubers that meet official phytosanitary, variety purity and general appearance requirements and are used to produce ware potatoes. The empirical questions we aim to explore in this chapter are:
1. How do companies view the significance of the hybrid potato and its impact on the Dutch sector?
2. What do Dutch potato companies consider as the potential SDG impact of this technology in LMICs, and what actions do they undertake or perceive to realise this impact?
3. Are Dutch potato companies actively exercising CSR, in particular in relation to the potential of HTPS in LMICs?

We explored these questions by means of scientific and grey literature and interviews with representatives of Dutch potato breeding companies active in hybrid breeding, i.e. Solynta, HZPC, Aardevo, and Agrico, a potato breeding and trading company that does not work on this technology. In addition, we conducted interviews with a representative from the Dutch plant breeding branch organisation Plantum and with spokespersons from organisations in the sector that are not active in potato breeding themselves: the Louis Bolk Institute and Oxfam Novib (Table 9.1). The interviews were conducted in the period August-October, and lasted about 1.5 hour. They were recorded, transcribed, and edited to make them more readable, after which they were checked by the interviewees to correct for inaccuracies. Finally, the draft of this chapter was read by the interviewees to check its accuracy. However, the authors remain fully responsible for the content. As we aim to critically assess the role that Dutch potato companies see for themselves, we also discuss a fourth, more reflective question:

4. What can we add to the opinions among stakeholders in the Dutch potato sector with regard to CSR and hybrid potato by considering these opinions through the lens of RRI?

9.5 Results

Below we describe and discuss the main results from our investigation regarding the three empirical research questions. The fourth research question is discussed later.

9.5.1 The significance of the hybrid potato

Our interviews indicate that three types of innovations can be distinguished through the emergence of HTPS technology: innovation in breeding, propagation and cultivation. 'Breeding innovation' implies an improvement and acceleration of the breeding process which makes it much easier to develop new varieties. However, the development of sufficient inbred parental lines is a lengthy process. The companies that are working on diploid potato hybrids have been working on this for 10 years or more. 'Propagation innovation' implies that true botanical seeds are used for propagation, storage and transport of potato starting material rather than traditional seed tubers. These true seeds are then subsequently used to produce seed tubers or table potatoes. However, local propagation by means of tubers once they are produced from seedlings remains possible, like the current practice of tuber propagation. The interviewees considered this as a significant aspect of hybrid potato breeding, which differs from most vegetable breeding practices where only true seeds are used for propagation. 'Cultivation innovation' involves direct sowing of true seeds in the field or planting plantlets grown from these seeds. This implies completely different forms of potato cultivation and has similarities with vegetable cultivation. According to the Plantum spokesperson, vegetable growers in particular might therefore pick up this innovation easier than traditional potato growers.

Table 9.1. Brief description of the companies and organisations of which one or more representatives have been interviewed for this chapter (based on the situation in 2021).

Company	Description
Solynta	A private seed company that was founded in 2009 by former employees of Monsanto to develop commercial hybrid potato technology. The company was the first to successfully develop HTPS technology based on diploid inbred lines that could be used for hybridisation. As a scale-up company, it has not yet a financial turnover in the seed market but raised 21 million euros in venture capital in 2021. The number of employees is ca. 70. The company currently focuses on the introduction of hybrid potato among smallholders in East Africa and is performing field experiments in this region. It has two hybrid varieties submitted for registration at the Dutch Board of Plant Varieties. Website: https://www.solynta.com
HZPC	A potato trading house organised as a two-tier board company where all shares are owned and certified by the 'Vereniging HZPC' (Association HZPC) with about 900 members. Only (former) farmers, (former) breeders and (former) staff members may purchase and hold certificates. The company comprises breeding, agronomic research, cultivation, and international trade of seed tubers and is active in 96 countries. Its financial turnover is ca. 320 million euro (harvest season 2020-2021). The number of employees is ca. 400. The company started its research on HTPS technology in 2009 after Solynta was established. It considers HTPS technology especially beneficial in and for LMICs in e.g. Africa and South East Asia. The company is currently performing field experiments in these countries. Website: https://www.hzpc.com/en
Agrico	A potato trading house organised as a cooperative with about 900 farmer members. The company comprises breeding, agronomic research, cultivation, and international trade of seed potatoes in 80 countries. Its financial turnover is ca. 293 million euro (harvest season 2020-2021). The number of employees is ca. 270. The company is not actively involved in hybrid potato breeding, but there is pre-competitive collaboration with companies involved in this technology. It also does not rule out the possibility of using this technology in the future by entering partnerships with companies working with this technology. Website: https://www.agricopotatoes.com
Aardevo	A joint venture of the American food company Simplot and the German seed company KWS. KWS is best known for breeding sugar beet, corn, cereals, and vegetable crops, while Simplot, a big name in potato chip processing, also focuses on many other crops as well as fertiliser and animal feed production. Aardevo does not produce itself commercial products but aims to contribute to both its parent companies by developing new potato varieties through diploid hybrid breeding technology. The number of employees is ca. 20. The company is engaged in diploid hybrid breeding since 2011 and focuses on the development of hybrid varieties for Northwest Europe and North America. Website: https://www.aardevo.com/en
Bejo	A private company engaged in breeding and trading of hybrid vegetable seeds. The company is active in more than 30 countries. Its financial turnover is ca. 325 million euro (harvest season 2020-2021). The number of employees is ca. 1900. The company started its research on TPS in the late 1980s and turned to hybrid tetraploid potato breeding in 2013 but also conducts research into diploid hybrid breeding. One hybrid tetraploid variety has already been officially registered at the Dutch Board of Plant Varieties. The company focuses with its hybrid breeding programme on Africa and Central America. Website: https://www.bejo.nl
Plantum	Dutch Branch association for plant breeders. It is organised in several crop breeding sections as vegetables, floriculture and also potatoes. A more overarching activity is representing general interests of its member breeding companies as e.g. research policy, breeding rights, phytosanitary issues and CSR issues. To this end, it consults, for example, with policymakers and as an employer's organisation with unions. As a branch organisation Plantum is also involved in societal discussions on role of breeding companies in food security policies. The number of employees is ca. 20. Website: https://plantum.nl

Table 9.1. Continued.

Louis Bolk Institute	A knowledge not-for-profit institute that previously operated mainly from a biodynamic vision, but nowadays aims to stimulate sustainable forms of agriculture from a holistic system perspective, given that most food is still produced with less sustainable, conventional agricultural methods. The institute has 55 employees and its financial turnover is about 4.5 million. The institute does not breed crops itself, but mainly tries to generate practical knowledge that has an impact on the farming business itself through collaboration with Wageningen University as well as companies. Website: https://louisbolk.nl/en
Oxfam Novib	Dutch development NGO affiliated with OXFAM International. The NGO is mainly active in African and Southeast Asian LMICs. It focuses on numerous themes such as poverty, hunger, refugee aid and women's rights. Oxfam Novib emphasises and promotes the important role of informal seed systems and smallholder farmers in plant breeding, seed production and agro-biodiversity conservation. Website: https://www.oxfamnovib.nl/donors-partners/about-oxfam/our-story

Four of the five breeding companies we interviewed consider the emergence of HTPS as an important innovation in breeding, cultivation and trading of potatoes. Faster breeding of potato varieties; easier cross-breeding of desirable characteristics such as disease and salt resistance; higher productivity; faster propagation of starting material; and lower storage and transport costs are mentioned advantages. However, Agrico has a more neutral stance about the technology and it believes that current tetraploid, non-hybrid breeding can meet the diverse requirements of growers and markets already quite well.

HZPC's strategy focuses on what we have called breeding innovation as it is for this company primarily a way of generating new and better varieties which can more easily be exported through true seeds to other countries, where they can be propagated in the traditional way through seed tuber production. Because vegetative propagation of hybrid seed potatoes is still possible, financial margins are lower as compared to non-potato crops. According to the company, seed tuber cultivation is therefore not really threatened and may even increase in some countries because new hybrid varieties can perhaps grow in areas where this is currently not possible, e.g. tropical lowlands.

The company Bejo is cautious about diploid hybrid breeding of potatoes and focuses mainly on tetraploid hybrid breeding. Although the uniformity of tetraploid hybrids is lower as compared to diploid hybrids, it is similar to other vegetables; a very high uniformity is according to this company only necessary in some cases (such as growing potatoes for crisps).

As newcomers in the sector, Solynta and Bejo both emphasise, besides breeding innovation, also propagation and cultivation innovation as a characteristic of the HTPS technology. According to Solynta, new hybrid varieties will be introduced every few years by means of hybrid breeding and it expects that Dutch cultivation and the worldwide export of seed tubers may even disappear in the longer term. According to the company, potato growing will become similar to vegetable cultivation, with fast variety turnover, which is not possible with conventional breeding.

However, propagation innovation requires that hybrid seed can be produced in sufficient amounts through the crossing of two parental lines. According to the Bejo spokesperson, this is a problem with diploid hybrid breeding because potatoes have never been selected for high seed production due to the conventional tuber propagation. This was a reason for the Bejo company to focus on tetraploid breeding where true seed production is higher. Low real seed production is currently not an important issue for HZPC as this company mainly focuses on breeding innovation and not on propagation.

Although the interviewees indicated that the Dutch potato sector will not be strongly affected by hybrid breeding in the short term, it has already led to the entry of new companies like Bejo and Solynta in the breeding sector. Both have an origin in vegetable breeding. Also the parent companies KWS and Simplot of the Aardevo joint venture do not belong to the traditional seed potato breeding and trading companies. The changing playing field is also reflected in the views on intellectual property rights. According to the spokespersons of both trading houses, HZPC and Agrico, the plant breeders' rights system is well-functioning and promotes innovation through the right to use protected varieties for one's own breeding purposes. The spokesperson for the Louis Bolk Institute also endorses this. According to HZPC, patents on genetic traits are not desirable and may inhibit further development. And, so far as patents exist, they should be made available for all actors in the sector. Conversely, the companies coming from outside the conventional potato breeding tradition, believe that patents have and should have a role in hybrid breeding because of the high costs of hybrid breeding. Another consequence that surfaced in the interviews is that the emergence of hybrid breeding may lead in the longer term to disappearance of smaller potato breeding companies because this technology is expensive and it takes many years to develop the required parent inbred lines.

9.5.2 The perceived potential of hybrid true potato seed in low- and middle-income countries

As Figure 9.1 shows, the informal and formal potato systems are quite separate worlds, despite some interactions. Because of its scientific and technological background, HTPS technology may primarily be considered as part of the formal sector. This fits to the strategy of Aardevo, which focuses on North America and Northwest Europe, although a spill-over effect is conceivable towards LMICs in the longer term. In contrast, Solynta, HZPC and Bejo focus primarily on LMICs (in East Africa or East Asia) with their hybrid potato breeding efforts. Also the Louis Bolk Institute expects the greatest application of hybrids in LMICs. This is because the prospects for improvement in terms of increasing production and reducing diseases are highest in these countries and also enable new business opportunities. According to the companies, working on HTPS, the technology can make a significant contribution to the SDGs, especially with regard to food security and sustainability. The spokespersons for Plantum, the Louis Bolk Institute and Oxfam Novib endorse these potential benefits.

An important question therefore is what the impact of the hybrid potato could be in LMICs. Growing potato crops directly from diploid hybrid seeds or plantlets is not expected to be done by farmers in LMICs themselves as it requires a lot of knowledge, skills, and experience. It is more likely that special nurseries will be created to produce seedling transplants or seedling tubers. These nursery companies will probably sell high-producing tubers or plantlets to the larger farmers in these countries and may therefore function as 'boundary spanners', i.e. actors that enable the translation of information over knowledge and social boundaries, between the formal and informal system (Tushman, 1977). We have visualised this in Figure 9.2. However, the company Bejo indicates that for their tetraploid hybrids such nursery companies are not necessary because their varieties are stronger and more resilient and the true seed will be sold to, and grown directly by farmers, just as with vegetables.

As a conclusion, the interviewees expect that vegetative propagation through tubers will still take place in LMICs with the hybrid true seed varieties. But it is expected that there will still be a continuous demand for healthy hybrid starting material because diseases will accumulate in subsequent seasons. It is also expected that through a trickle-down process, in which farmers in a village or neighbourhood pass on tubers to each other or buy them on local markets, these varieties will gradually reach smallholders in the informal sector and from there a continuous demand for these varieties may also arise, especially if they perform better.

Such a trickle-down process raises the question to what extent the breeding companies will enforce their breeder's rights on the new varieties in LMICs. Informal exchange of seeds is a strongly culturally embedded practice in these countries and in practice it is difficult to enforce plant breeders' rights in such contexts. The answers of our interviewees indicate that except for larger, more commercial companies, companies will probably not enforce their rights on smallholders, similar to the current situation with traditional potato varieties. Nevertheless, Oxfam Novib indicated that there are still concerns that commercial potato breeders will enforce their breeders' right towards small farmers in the future.

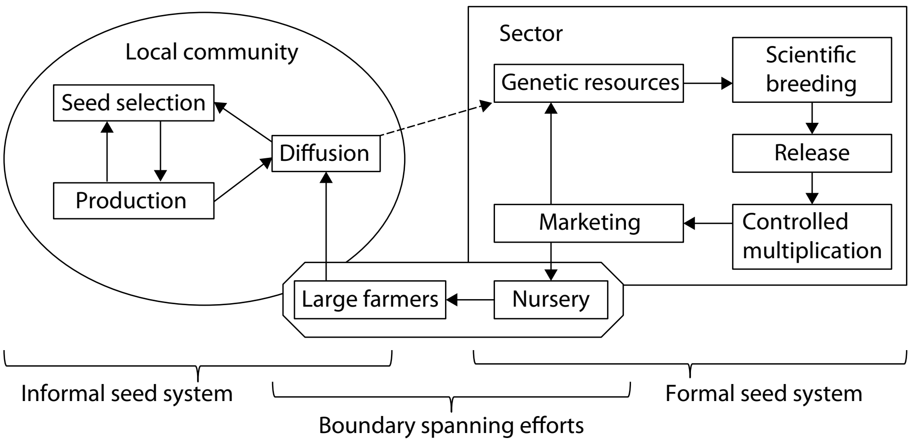

Figure 9.2. Hypothetical role of a nursery as a boundary spanning effort between the formal and informal system of hybrid potato cultivation, see also Figure 9.1.

Hybrid varieties played an important role in the Green Revolution which sparked a lot of discussion about the possible disappearance of local varieties, increased farmers' dependence on external inputs of seeds, fertilisers and pesticides, and financial constraints on farmers (Kloppenburg, 2004). In general, these effects were not expected to occur with HTPS. According to our interviewees, farmers are already well-acquainted with hybrid crops (e.g. vegetables, cereals) and the inputs they require.

9.5.3 Corporate social responsibility activities of Dutch potato companies

Two interpretations of CSR emerged from our interviews. On the one hand, CSR concerns concrete, performative business operations to meet legal, social and health standards. This refers to the companies' contribution to, for example, CO_2 reduction, the prevention of child labour, and good employment practices. On the other hand, the interviewees strongly emphasised that CSR is also about the company's contribution to SDGs through the development of better potato varieties and the delivering of these to LIMCs. In line with the suggestion made by Porter and Kramer (2006) (see an earlier section of this chapter), most interviewees considered their core business as an CSR-effort itself as it contributes – in their view – to the world food supply, poverty reduction and sustainable production. For example, HZPC mentioned that it is prepared to supply seed potatoes to countries at war in the Middle East if the food situation so requires, even if that implies some financial risks and conflicts with international rules.

According to the breeding companies, potatoes can help achieve SDGs because this crop is not only the fourth food crop in the world, but also the most efficient crop in the world in terms of production per hectare and water use. Further breeding of the potato may contribute even more to food security, higher yields, reduced pesticide use, disease resistance, salt resistance and storage properties. In order to make that contribution, the companies active in LIMCs, emphasise the role of capacity building and the need to have offices or departments in these countries. Most of them also conduct field trials there, and maintain contacts with companies and institutions that are relevant for this. We referred to these previously as boundary spanning efforts (Figure 9.2).

This second interpretation of CSR, i.e. the focus of CSR on SDGs, applies to both conventional and hybrid breeding, whereby hybrid breeding may lead to faster development of varieties and more easily incorporation of new traits. It is one of the main reasons for adopting this technology. The view that contributing to food production for the world market and LMICs is to be considered as a kind of CSR was supported also by the Louis Bolk Institute. However, the interviewees from Plantum and Oxfam Novib indicated that CSR in their opinion requires additional activities that go beyond contributing to the SDGs through the company's core business, such as taking the perspectives of local farmers as a starting point or even actually involving them in the company's core business.

The interviewees indicated that the costs of CSR do not play a major role in taking CSR measures. They argue that CSR should be considered as a prudential activity in the longer term that also may contribute to the public reputation of the company. But ultimately, CSR must fit into the financial constraints within which a company has to operate. Both Agrico and HZPC publish reports in which their CSR policy is paying attention to both distinguished interpretations of CSR. These companies are active across the entire value chain (from breeding to the export of seed potatoes) and are present in multiple countries. HZPC issues a biennial CSR/sustainability report that is produced by an external party using the Global Reporting Initiative Standards (see https://www.globalreporting.org). Agrico employs a special CSR officer and adheres to Dutch NEN standards (https://www.nen.nl/en) when drawing up the CSR report. However, there are no external audits of these reports. The other breeding companies, which mainly focus on breeding and trading (hybrid) seeds and not tubers, do not have public CSR reports but they endorse the importance of corporate responsibility, care for the environment, social security, care for employees and cooperation with farmers.

9.6 Preliminary conclusions

Based on our results we can answer our empirical research questions as stated before:

- Hybrid potato breeding implies three types of innovations, namely a breeding, propagation and a cultivation innovation.
- All but one of the interviewed companies and organisations are positive about the potentialities and impact of hybrid breeding.
- Although it is not expected that the Dutch potato sector will strongly be affected by the emergence of HTPS technology in the shorter term, we see the entry of new firms which stronger stick to the possible use of patents on genetic traits.
- All companies active in hybrid breeding (fore)see a significant contribution to SDGs of this technology.
- The impact of hybrid breeding on the informal sector in LMICs is, according to most of our interviewees, likely to go through the classic trickle-down process.
- In contrast to tetraploid hybrid breeding, diploid hybrid breeding will probably lead to the establishment of special nursery companies supplying starting material to local farmers.
- It is expected that future practices of dealing with plant breeders' rights will probably not deviate much from the current situation.
- Worldwide, potato production may increase locally through improved varieties that can be grown at places where this is currently not yet possible.
- All interviewees endorse the importance of CSR. Besides concrete measures as care for the environment, social security and care for employees, the possible contribution to SDGs by trading improved varieties (as core activities of the breeding and trading companies) is in itself considered as CSR.
- Costs do not play a major role in taking CSR measures, although they must fit within the financial constraints in which the companies operate.
- Only the trading companies in our set of interviewees publish public SCR and/or sustainability reports using external criteria.

Thus, as a general conclusion, most of our interviewees stressed the potentially promising contribution of HTPS to the attainment of SDG-2 (see also Lindhout *et al.*, 2017). Moreover, they emphasised that their core business (i.e. breeding, cultivating and/or trading potato varieties) is at the heart of CSR as it contributes to the SDGs. More specifically, hybrid breeding is expected to contribute to the SDGs through the development of improved varieties that will subsequently trickle down to the informal sector.

9.7 Towards an RRI-based strategy for hybrid breeding

Although most companies we interviewed see themselves as making a contribution to the SDGs in LMICs, they tend to state this contribution in terms of 'trickle-down', in which local farmers are just passive receivers, rather than being actively involved. As observed above, this reluctance to address local requirements and to include farmers in technological innovation may in part be due to the unfamiliarity of RRI in industrial circles and the need to keep certain technical processes secret as a company's main competitive asset. Obviously, HTPS technology can be considered such an asset. This raises the question what companies can additionally do to contribute to SDG-2 (food security and sustainability) and how RRI as an approach might help them in this respect.

As described above, SDGs may be considered as wicked problems that are characterised by complexity, uncertainty and the involvement of multiple actor's perspectives and values. According to Ludwig *et al.* (2021) such wicked problems are 'commonly mis-framed as tame problems that appeal to the expertise of dominant actors and their responses as solutions.' In this context these authors distinguish two strategies: 'a solution strategy that legitimises the responses of dominant actors as solutions, and a negotiation strategy that highlights the contested status of grand societal challenges and the need for negotiation between heterogeneous interests and perspectives (p. 2).

We observe that the interviewed companies, as dominant actors, mainly apply the solution strategy, as evidenced by low or no active involvement of local farmers or their representing organisations in the HTPS technology itself and the expectation that the new varieties will spread through a trickle-down process.

While a solution strategy may be useful and can lead to a substantial contribution to SDGs, it may be nevertheless in danger of not being accepted by relevant stakeholders as it may ignore the root cause of a problem, or being too inflexible to deal with local conditions and insights (see also Chapter 2). In contrast, a negotiation strategy considers different responses to a wicked problem and does so in conversation with a wide range of stakeholders. It is therefore more inclusive and deliberative in nature. Below, we explore participatory plant breeding (PPB), farmer variety selection (PVS), and benefit sharing as possible negotiation strategies for hybrid potato breeding in LMICs. PPB and PVS may help companies to do more justice to local needs, and to the diversity among farmers in LMICs. Benefit sharing may be necessary to ensure that HTPS technology remains accessible for local farmers in LMICs. Together, PPB, PVS and benefit sharing make up, we believe, viable RRI strategies for potato companies that want to contribute to SDG-2 through a negotiation strategy.

9.7.1 Responsible innovation with regard to breeding: involving smallholders in potato breeding

The concept of RRI emphasises the responsibility of those in control of a technology for possible negative consequences for society and the environment. It also stresses the involvement of and responsiveness towards affected stakeholders. We think that the concept of PPB may suggest ways to bring RRI into practice in potato breeding. PPB is defined by Ceccarelli and Grando (2020: p. 1) as 'the participation of clients (more often, but not only, farmers) in all the most important decisions during all the stages of a plant breeding program'. PPB is aimed at achieving food sovereignty, i.e. 'the right of peoples to healthy and culturally appropriate food produced through ecologically sound and sustainable methods, and their right to define their own food and agriculture systems' (Nyéléni, 2007). According to Ceccarelli and Grando (2020), PPB is an alternative ('a reversal') of the dominant seed system in which 'agricultural production, seed production, varietal innovation, and conservation of genetic resources are functionally separated and delegated to specialised scientists' (p. 10). The authors distinguish several stages in the so-called breeding cycle (Figure 9.3).

Especially stage 7 is interesting as it highlights the step of deciding who will participate in the process, which is not only a knowledge but also a social and cultural issue. Participatory breeding requires however more than just the participation of farmers in the breeding cycles. It also raises the question how practical farmer knowledge of varieties (in their own agronomic context) can be integrated with techno-scientific knowledge (Almekinders, 2011). In addition, PPB often aims to use local varieties (i.e. varieties adapted to the local context with regard to climate, soil, flavours, cooking traditions, etc.). Because of this, issues as ownership and property rights might be at stake.

Incorporating hybrid breeding in PPB makes the breeding cycle more complicated through the technical and scientific work needed for development, improvement and maintenance of parental inbred lines. These activities often take many years and may be considered as part of stage 3 in Figure 9.3. One of the issues at stake here is the practice of secrecy, and we may also question if farmers can really play a decisive and direct role in this often highly technological stage, but public scientific institutions could have a role here.

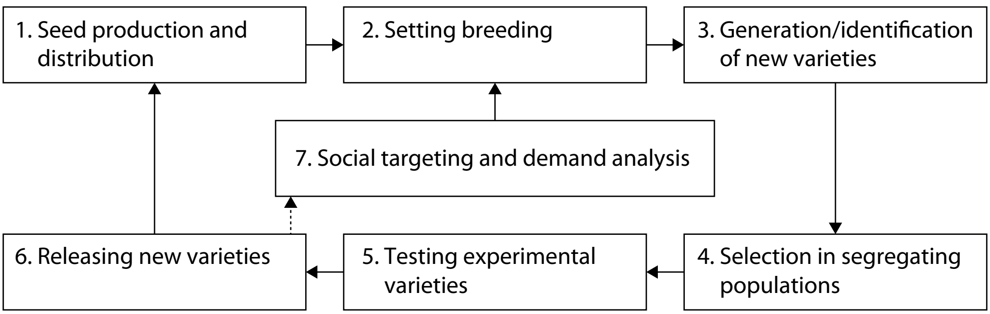

Figure 9.3. Schematic overview of the stages in the breeding cycle in general (based on Ceccarelli and Grando, 2020). The dashed arrow probably indicates that stage 7 may also be passed, implying the absence of societal interaction.

Although Li *et al.* (2013) argue that PPB is still possible with hybrid breeding, e.g. through involving farmers in the process of choosing the types of parental lines (e.g. as part of stages 3 and 7), these obstacles may make it difficult to bring a PPB strategy into practice for HTPS breeding. As an alternative, farmer variety selection (PVS) may be considered as a lighter version of PPB (Ceccarelli and Grando, 2020) which is much easier to organise. According to this model, farmers' participation begins during variety testing (stage 5). An example of PVS in potato breeding is the role of so-called 'farmer breeders' in the Dutch potato sector. These farmers, sometimes called 'hobby breeders', are often older farmers with a lot of experience in potato cultivation. They identify and select potentially promising potato varieties that were bred by e.g. trading houses (Almekinders *et al.*, 2014). Similarly, Halewood *et al.* (2007) sketch different modes of cooperation between smallholders and private companies in the breeding cycle. It demonstrates that PPB-elements may be combined with commercial breeding and that several versions of PPB distinguished by the level of the involvement of different stakeholders, are possible (see also Chapter 10).

9.7.2 Hybrid potato breeding as a common good

The possible rise of hybrid breeding is expected to lead to a changing playing field in the potato sector. New players rooted in vegetable breeding are entering the potato sector and they tend to operate on the basis of business models that require a stronger adherence to established property rights than conventional potato companies do. As a consequence, HTPS may become less available for smallholders. Therefore, taking into account the diversity of local needs through PPB and PVS is not enough, we also need to ensure that HTPS technology and the resulting varieties and parental lines remain available to smallholder and/or public research institutions in LMICs. Currently, the technology is mainly in the hands of private or cooperative Western-based companies and not publicly available. As far as we know no public research institutes are currently developing inbred parental potato lines.

During an international workshop on hybrid breeding with participants from diverse LMICs (Swart and Stemerding, 2020), it was concluded that HTPS technology was a promising technology for African smallholders, but that new breeding platforms and participation of a wider set of stakeholders were needed in the African context. In an opinion paper in Nature Plants (Beumer and Stemerding, 2021) it is argued that the technology may contribute to SDGs but 'to realise this promise, it is crucial that hybrid diploid breeding be made widely accessible' (p. 1530). The authors observe that this is currently not the case because the inbred parental lines, which are absolutely needed to breed hybrid varieties, are kept in secrecy by companies to protect their big investments as they are bound by economic constraints. Their space for making available the underlying genetics for smallholders and public research institutes is therefore limited.

However, the development of hybrid breeding technology is also based on public (academic and local) knowledge and shared genetic resources (Beumer *et al.*, 2021). Because of its potentially large public significance and impact, it may be considered as a common good: a resource that should be accessible to all members of a society or a group that are dependent on or have an interest for it (see e.g. https://iasc-commons.org/about-commons/). To deal with these contrasting aspects, Beumer and colleagues plea for making hybrid technology better available to LMICs by setting up breeding consortia for hybrid potatoes directed to the needs of small farmers in the informal system (Beumer and Stemerding, 2021; Beumer *et al.*, 2021). The basic idea is that breeding companies should make their parental lines available to public breeding institutes exclusively working for smallholder farmers, while they may still apply their intellectual property rights to farmers and breeders that do not belong to the informal system.

Clearly, establishing such a platform transcends the capacities of individual companies that have to operate in a global and highly competitive environment. An international, collective effort to achieve a level playing field is therefore needed between breeding companies, governmental institutions, NGOs, charities, and local smallholder representatives (see also NFP, 2021). While PBS and PVS focus on possible negotiation strategies of individual companies with their stakeholders, the concept of benefit sharing requires cooperation between companies and institutional parties and involves collective decision-making. Recognising the common good character of hybrid breeding, such an initiative should thus distinguish between different partners from the formal and informal systems with regard to breeding rights and accessibility of the hybrid varieties. During the 2020 conference on hybrid potato breeding (Stemerding *et al.*, 2021) it was stressed that there is already a long tradition of cooperation and exchange of knowledge, supported by governmental and sector-wide institutions, especially in the Netherlands. It is precisely this tradition that has the potential to institutionalise corporate social responsibility at the sector level in an international context, in order to give stakeholders a significant voice at multiple levels over the value chain with respect to hybrid breeding.

9.8 Conclusions

In this chapter, we have considered potato breeding and especially hybrid breeding in the context of SDGs and LMICs from the perspective of corporate social responsibility and responsible research and innovation. Companies involved in hybrid potato breeding stress the role of this technology in the context of the SDGs. However, our interviews indicated that the way and the pace with which new hybrid varieties will reach smallholders will not differ much from the current situation. To deal with the SDG-challenges we elaborated on the concept of CSR and RRI in the context of SDGs, integrating concepts from PPB, PVS and benefit sharing. Recognising the common good character of hybrid breeding we argue, in line with the conclusion of the 2020 conference on hybrid potatoes, for an integrated collective chain approach, requiring the support from supranational institutions, international funding organisations, charities and companies. Such a strategy should not only focus on breeding issues but also on social and institutional aspects including poverty, inequality and injustice.

Acknowledgements

We are grateful to our interviewees for spending their time to our research: Paul van den Wijngaard (Aardevo), Gerard Backx (HZPC), Michel de Bruin and René Vernooij (Agrico), Rien van Bruchem (Bejo), Bram de Jonge (Oxfam Novib), Peter Keijzer (Louis Bolk Institute), Pim Lindhout (Solynta), and Niels Louwaars (Plantum). We also thank the editors, especially

Dirk Stemerding, Paul Struik and Peter Gildemacher of this volume for their comments on earlier versions of this article.

The contribution by Ibo van de Poel is part of the project ValueChange that has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement No 788321. The contribution of J.A.A. Swart is part of the research project 'Responsible Innovation in Dutch Potato Breeding' funded by NWO (file nr. 313-99-301) with additional funding from the Solynta company, Wageningen; the Kramp Group BV, Varsseveld; and the Ubbo Emmius Fund of the University of Groningen.

Ethics approval

This research has been approved by the Human Research Ethics Committee of TU Delft. All interviewees have given their informed consent to participation in the study and use of the results.

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Chapter 10. Hybrid potato breeding for smallholder farmers in developing countries: four models for public-private collaboration

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Abstract

We explore how the potential of hybrid potato breeding can be harnessed for smallholder farmers in low-income countries, using economic theories developed for the governance of commons (or common-pool goods). Despite the great potential of hybrid potato breeding, it comes with major challenges that need to be overcome by public-private collaboration. We explore the strengths and challenges of four possible models for public-private collaboration of how hybrid potato breeding can be made available for smallholder farmers in low-income countries: the charity model, the pre-competitive research model, the breeding consortium model, and the project model. It should be noted that these four models are not mutually exclusive. The four models show that there are different ways of institutionalising public-private partnerships while each of these models have specific strengths and weaknesses when it comes to ensuring smallholder access to innovation. It can be argued that the project model is most likely to ensue if no concerted action is taken to institutionalise the access to hybrid breeding for smallholder farmers. This exploration of the four models of public-private partnerships can be used as a starting point for the public and private sectors to come together and discuss how they can combine their forces for the benefit of smallholder farmers around the world. We are convinced that the way these models will be operationalised will result in much more complex and nuanced collaborations, and involve other aspects that we have not taken in consideration.

Keywords: commons, charity, pre-competitive research, breeding consortium, project

DOI: 10.3920/978-90-8686-946-6_10, © K. Beumer and C.J.M. Almekinders, 2023

10.1 Introduction

This chapter explores how the potential of the powerful new approach of hybrid potato breeding can be harnessed for smallholder farmers in developing countries through public-private collaboration. Potato (*Solanum tuberosum* L.) is an important staple and/or cash crop for many smallholder farmers in Africa, Latin America, and Asia, and it is widely expected to gain greater importance thanks to its relatively healthy nutrient content and ease of cultivation (Haverkort and Struik, 2015). However, the importance of potato for smallholder farmers is held back by the complexity of incorporating the many characteristics they need into a single variety, and by significant constraints to the availability and access to high-quality planting material.

Inbred diploid hybrid breeding in potato (henceforth: hybrid breeding) promises to overcome several of these constraints (Beumer and Edelenbosch, 2019; Beumer and Stemerding, 2021; De Vries *et al.*, 2016). Firstly, this innovative breeding method makes it possible to include new traits faster (Lindhout *et al.*, 2011; Jansky *et al.*, 2016). This enables the development of high-quality varieties with traits that are specifically relevant for smallholder farmers. Secondly, this innovation will enable the multiplication of potato varieties through true botanical seeds. These have significantly lower disease loads as compared to seed potatoes currently used by farmers. As such, the technology has the promise to increase the productivity and income of smallholder farmers, lower the risk of disseminating destructive diseases through tuber seed, and significantly decrease the costs of storage and transport of planting material to remote areas.

It is far from certain, however, that this promise will be realised. Current progress in hybrid potato breeding is already highly promising for smallholder farmers, for example with stacking *Phytophthora* resistance genes (Su *et al.*, 2020). Yet there remain important challenges in ensuring that smallholder farmers in developing countries (henceforth: smallholder farmers) will have access to the benefits of this innovation. Hybrid breeding activities in public sector institutions that target smallholder farmers are currently modest and focus mostly on fundamental research. Hybrid variety development efforts are currently largely concentrated in the private sector and it cannot be taken for granted that traits that are specifically interesting for smallholder farmers, but that hold little commercial relevance otherwise, will be targeted. Nor can it be taken for granted that varieties that do include such beneficial traits will reach smallholder farmers who are often poorly connected to formal seed systems.

In this chapter, we turn to public-private collaborations as a way to overcome these challenges. As we will argue in more detail below, neither the private sector nor the public sector can fully harness the potential of hybrid diploid breeding alone. This raises the question how public-private collaborations can best be organised to enable access for smallholder farmers to the benefits of hybrid potato breeding. We will explore this question from the perspective of the commons, which is especially fruitful in drawing attention to the institutional arrangements for ensuring access. We will explore four models for institutionalising public-private partnerships and will assess the potential of each model in overcoming the challenges of access for smallholder farmers. This is an essential step towards identifying how best to realise the potential of hybrid diploid breeding for smallholder farmers.

The focus on institutional arrangements for public-private partnerships implies that several other important aspects for ensuring access are not addressed. For example, access to improved starting material is also informed by factors such as national regulations for importing true seeds instead of tubers; by cultivation practices that are mediated by ethnicity and gender and class; and by infrastructures and skills that shape whether hybrid potatoes can best be supplied as seed tubers or true seeds. These challenges lie beyond the scope of this chapter. In this contribution, we focus on the innovation of hybrid potato breeding as the resource.

10.2 Commons

In a narrow economic sense, commons, or common-pool goods are defined as goods or resources that are both subtractable and non-excludable (Ostrom, 1990). Goods are subtractable (or rivalrous) when they can be depleted: the use or consumption of the resource by one actor limits the possibility for use or consumption by another. Goods are non-excludable when other actors can access the resource with relative ease.

For decades, economists have assumed that goods that are both subtractable and non-excludable would fall victim to the so-called 'tragedy of the commons' (Hardin, 1968), whereby self-interested individuals would take what they could and soon deplete the resource. The solution to this collective-action problem, so economists argued, was to either fully privatise the resource or make it subject to public regulation. Yet since the 1980s a large number of studies has emerged that demonstrated that such common-pool resources can be sustainably governed by communities themselves (Van Laerhoven and Ostrom, 2007; Ostrom, 2002; 2009; Stern, 2011). This has renewed academic interest in the governance of resources outside government or market structures.

This literature has offered a broader understanding of the commons, where the commons are understood as resources that are: (1) governed by a community of users; (2) in a way that 'exceeds the division between public and private' (Terranova, 2015, p. 9). This perspective is especially helpful in understanding situations where fully public or private ways to ensure access to resources fall short.

This is also the case when it comes to access to hybrid potato breeding for smallholder farmers. On the one hand, we consider that fully privatising hybrid breeding is unlikely to ensure the optimal use of this innovation for smallholder farmers. These farmers are often poorly connected to markets and can hence not be easily reached through conventional market channels that companies are connected to. Smallholder farmers furthermore engage in informal markets where they freely exchange seed, thus violating conventional markets rules in ways that may disincentivise the private sector. Finally, and as a consequence, the private sector has little to no incentive to use hybrid breeding to target traits that are specifically interesting for smallholder farmers, but that hold little to no commercial interest otherwise. Making hybrid potato breeding fully public, on the other hand, is equally unlikely to ensure that it is optimally used to the benefit of smallholder farmers. International and national public institutes (both in the North and the South) have very broad mandates and, at least in the foreseeable future, are unlikely to have sufficient resources to develop the experience, expertise, and institutional capacity in hybrid potato breeding, as some private sector actors do (Beumer and Stemerding, 2021).

In this context, the perspective of the commons helps to draw attention to arrangements where the public and the private sector can form a community to govern the innovation of hybrid breeding according to their own rules and norms. The question, then, is what rules and norms work best to enable and incentivise the community of users from the public and the private sector to optimally use hybrid breeding for smallholder farmers. Or phrased differently, what institutional arrangements ('rules and norms') can be devised to enable the use of hybrid breeding for smallholder farmers?

The importance of institutions in governing access to resources is recognised both in literature on the commons (Ostrom, 1990, 2002) and in literature on technology governance (Khandekar *et al.*, 2016). The latter also highlights that in exploring these institutional arrangements, we should also pay attention to the constitutive role that technological innovations play. A recent article highlighted that innovations like hybrid breeding are both shaped by the institutional arrangements that ensure access, and simultaneously shapes those institutional arrangements as well (Beumer *et al.*, 2020). The institutional structures for ensuring access both enable and constrain what types of innovations can be developed, while innovations like hybrid potato breeding may, in turn, both strengthen and undermine the institutions that enable access for smallholder farmers. This should hence be taken into account in exploring public-private collaborations from a commons perspective.

The public-private partnerships described below are situated in broader institutional structures that can either enable or constrain access to hybrid breeding and its intermediate and end products-principally parental lines and hybrid varieties. The commons literature refers to this as 'multiple layers of nested enterprises' (Ostrom, 1990). For hybrid breeding this includes institutions for intellectual property such as the International Union for the Protection of New Varieties of Plants (UPOV) for breeders' rights and the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS agreement) for patents. This also includes various phytosanitary regulations for ensuring the health and safety of potato cultivation and consumption; international agreements and organisations that enable access to potato genetic material like the gene banks and the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA); funding instruments from national governments and international organisations like the European Commission; and more informal institutions for sharing information and materials.

These institutions affect the accessibility of the benefits of hybrid potato breeding and these institutions themselves may also be subject to change. In what follows, however, we focus on the public-private partnerships and draw upon these other institutional layers only when this is necessary for understanding the public-private partnerships.

10.3 Four models of public-private collaboration

We will explore how hybrid potato breeding can be made accessible for smallholder farmers by describing four different models for public-private collaboration. This exploration addresses situations in which smallholder farmers require other or additional genetic traits to be incorporated by hybrid potato breeding and that this is insufficiently commercially attractive and therefore does not constitute an interesting market segment for the private sector. In such conditions, the private and public sector play complementary roles. While smallholder farmers themselves can play a role in each of these models, the focus of the current paper is on the roles of public and private actors.

The four models are distinguished along the lines of breeding (who profiles the products and develops varieties) and dissemination (who disseminates planting material of these varieties) (Table 10.1). Each of the four models potentially enables smallholder farmers to access the benefits of hybrid potato breeding in different ways. We will assess the strengths and weaknesses of each model in overcoming the challenges of access by smallholder farmers.

It should be noted that these models – simplified representations – are not mutually exclusive: elements of the different models can be combined. We have nevertheless chosen to present these models as neatly distinguished entities as this helps to bring the benefits and drawbacks of each model into sharper focus. These simplified representations are helpful tools for thinking through how to ensure that the benefits of hybrid breeding are accessible to smallholder farmers.

10.3.1 The charity model

In this model, the breeding of hybrid diploid potatoes is concentrated in the private sector, while the dissemination of starting material to smallholder farmers is taken up by the public sector and non-governmental organisations (NGOs). Companies have developed homozygous parental lines that form the basis for their hybrid breeding programmes. Varieties that are potentially beneficial for smallholder farmers are then brought to smallholder farmers by government organisations and NGOs, which use their networks to reach smallholder farmers in and outside formal seed systems and offer the hybrid potato either at a reduced rate or even for free – as a form of charity. This model is similar to institutional arrangements for genetically modified crops, where companies develop and own specific crops, which are then made available to farmers in developing countries with the help of public research organisations and NGOs (Rock and Schurman, 2020).

Table 10.1. Key features of four models of public-private partnerships for access to benefits of hybrid potato by smallholder farmers.

Model	Breeding	Dissemination
Charity model	Private	Public and others (NGOs)
Pre-competitive research model	Public	Private
Breeding consortium model	Public and private (structural)	Public and private
Project model	Public and private (projects)	Public and private

The success of this model partly depends on the extent to which traits that benefit smallholder farmers will be part of commercial breeding activities. Companies are driven by profit and hence have most incentives to target those traits that are commercially most interesting. In many cases, such traits are also interesting for smallholder farmers, who can for example also benefit from robust varieties with *Phytophthora* resistance. There may also be smallholder relevant traits that are relatively simple to incorporate – i.e. controlled by one to two genes. In such cases, this model can also function well for smallholder farmers, as the underlying commercial variety can remain the same. This may for example be the case for increasing resistance in potato to diseases caused by viruses or nematodes, assuming such traits are relatively simple to genetically incorporate. The relatively modest work to include such traits may for example be part of corporate social responsibility programmes or funding by philanthropic organisations.

The main strength of this model is that breeding and dissemination to smallholders are each taken up by those actors that currently have the most comparative advantage in these activities. The actors thus complement each other well. Activities with hybrid diploid potato breeding are currently largely concentrated in the private sector, with various companies having gained valuable expertise and experience in developing homozygous parental lines, including novel traits, and developing true botanical seed hybrid potatoes.

Public organisations and non-governmental organisations, in turn, traditionally have mandates in disseminating potato varieties to smallholder farmers. Public organisations like the International Potato Center (CIP) and national agricultural research institutes, as well as NGOs like Asociación Andes and Seed Savers Network Kenya have connections with or represent extensive networks of extension services, farmer organisations, and farmers. These networks can be harnessed to help assure that diploid hybrid potatoes meet the needs of smallholder farmers and are accessible to them.

One main challenge to this model is that the institutional context that shapes private breeding activities mostly provides incentives to focus on traits that are commercially interesting. As mentioned, this does not always coincide with traits that are most beneficial to smallholder farmers. In some cases, smallholder farmers may need traits that are not relevant for farmers that participate in commercial markets or traits that cannot easily be incorporated in commercial varieties, such as traits for cultivating potato in lowland areas in the tropics. While hybrid breeding is certainly a promising avenue for including such traits, when private companies have little incentive to invest money and time in targeting such traits, alternative institutional arrangements are needed. This can involve corporate social responsibility schemes and philanthropic funding.

Related to this is the challenge of identifying what traits are relevant for smallholder farmers in the first place – such as culturally dependent culinary traits, storage traits like dormancy, and resistances against diseases that are mostly prominent in the Global South or those that slow down degeneration. Even if the private sector is willing to work on traits that are only relevant to smallholders, they may not be in the best position to identify what traits are most needed and wanted by smallholder farmers (and in what varieties). To be sure, this is a challenge for the public and private sector alike (Almekinders *et al.*, 2019), but the lack of incentives that breeding companies have to target the needs of smallholder farmers, who are not their target-clients makes this especially difficult. Hence this requires dedicated efforts to elicit the needs of smallholder farmers.

A final challenge in this model lies in clearly distinguishing smallholder farmers targeted by public institutes and NGOs, from the farmers that can be targeted by private companies themselves through their commercial activities. In many cases these distinctions are rather clear, with companies targeting any farmer with access to formal seed markets, while public institutes and NGOs focusing their activities also on the informal sector. Yet this is complicated when formal and informal markets intersect, which is the case for the majority of smallholder farmers: they occasionally purchase seed tubers from formal markets while usually relying on informal channels (Almekinders *et al.*, 2019). Is the public sector in such cases allowed to share hybrid potatoes with these farmers or not? And are farmers allowed to share hybrid potatoes among themselves? These issues may be addressed by making clear agreements that define and delineate smallholder farmers that can be targeted by public institutes and NGOs from the farmers that can be targeted by the private sector through commercial activities (e.g. De Jonge and Munyi, 2016).

The private breeding, public dissemination model builds on the current strengths of the private sector in developing and using homozygous parental lines for hybrid potato breeding and leverages the connections of the public sector with smallholder farmers. Major challenges for this model are to ensure that traits are targeted for which there is no commercial interest, that the needs among smallholders for these traits are identified, and that commercial and non-commercial interests remain clearly delineated (so that they do not dwell in the same waters). Possible solutions to these tensions include public funding for private companies to promote the use of hybrid breeding to target traits for smallholder farmers, giving private money to public institutions to test and deliver quality seed to smallholder farmers, and to elicit knowledge from public and other organisations about farmer demand to private breeding efforts. Finally, clear agreements need to be made about the way hybrid potatoes can be disseminated by public and other institutions to exclusively smallholder farmers.

10.3.2 The pre-competitive research model

In this model, the early stages of hybrid potato breeding are concentrated in the international and/or public sector, while the further selection and dissemination of hybrid potato to smallholder farmers is taken up by the private sector. This can be understood as a form of 'pre-competitive research' or 'pre-breeding'. Here, the public sector could take responsibility for developing homozygous parental lines – perhaps the most expensive part of the hybrid diploid breeding process – which can then be shared either for free to everyone, or to a selected group of companies that made a contribution to finance the pre-competitive research. This model is regularly used for cereal crop varieties from international breeding programmes that are subsequently licensed to predominantly nationally and locally operating companies (Donovan *et al.*, 2021; Yigezu *et al.*, 2021). The model was also used in potato breeding in the Netherlands after World War II (Van Loon, 2019).

Besides decreasing private sector breeding costs, the main strength of this model is that beneficial traits for smallholder farmers are not limited to specific varieties of individual companies who make a dedicated effort at including such traits but that they are included in all the varieties that companies subsequently develop on the basis of the public parental lines. That way, beneficial traits for smallholder farmers can become an integrated part of all hybrid potato varieties.

This model is especially promising for developing parental lines with complex multi-gene determined traits. While companies may take the effort to include one or two more simple traits that are especially relevant for smallholder farmers, including a broad range and more complex traits may require too high an investment for companies who could put those same resources to develop commercially relevant traits. In such a situation, this model offers an attractive solution by letting public organisations develop homozygous parental lines that include such complex traits, which can then be taken up by private companies.

In the case of potato, this model would constitute a relatively stark reversal of the current task distribution, where the private sector is most active in breeding and the public sector is modestly engaged with pre-breeding and dissemination. In other words, this model requires the national or international public sector partners to develop the resources and capacity for hybrid breeding. A recent paper that outlines the steps required to develop diploid parental lines (Zhang *et al.*, 2021) takes a step in this direction by opening up the opportunity for new players to engage in hybrid breeding, including the public sector. Yet in the near future only significant and structural investments could enable the public sector to develop parental lines.

Another challenge in this model is to make sure that varieties with these beneficial traits reach the smallholder farmers. Currently, in most countries the formal private potato seed sector is small and not functioning optimally. Smallholder farmers can certainly constitute an interesting market for the private sector. But large numbers of smallholder farmers source their starting materials from informal seed systems (Almekinders *et al.*, 1994) and hence do not engage in the formal markets that are served by the private sector. Hybrid potato may eventually come to circulate in informal seed systems as well but by that time the starting material will have decreased in quality (while the traits that benefit smallholder farmers may at the same time support longer recycling of the seed). One way to address this is to expand the reach of formal seed systems and the accessibility of quality seed, which is by no means an easy task.

Another way to address this challenge could be for the public sector to share parental lines on the condition that the starting material that is subsequently developed by the private sector is made available to smallholder farmers outside formal markets. A suitable model for this can be found in public health. For example, in the case of avian influenza viruses, the World Health Organization (WHO) coordinates a global network of public sector institutions that monitor the evolution of influenza viruses and prepares materials for vaccine development – a form of pre-competitive research. This is made freely available to the private sector on the condition that a certain percentage of the vaccine produced is made available at cost price or for free to low-income countries (WHO, 2018). Similarly, parental lines developed by the public sector could be shared with the private sector on the condition that a certain percentage of starting material is (freely) shared with smallholder farmers that do not have access to formal markets.

10.3.3 The breeding consortium model

In this model, parental lines are developed by the private sector and are then shared with the public sector under the restrictive mandate to use these exclusively to develop varieties with traits that are specifically relevant for smallholder farmers. This can be understood as a 'breeding consortium' – which has recently been proposed in Nature Plants (Beumer and Stemerding, 2021).

In such consortia, agreements are made about who can make use of the outcomes of the public breeding activities (using private sector parental lines). One common agreement is that the public sector can disseminate the varieties they developed to smallholder farmers at reduced rates or even for free, while the private companies that provided the parental lines will have exclusive access to these varieties for more conventional commercial activities. Like the previous model, this model is specifically suitable for developing varieties with larger numbers of relatively simple traits for smallholders. After all, the variety that includes those traits will strongly resemble the commercial variety whose parental lines were used.

The benefit of this model is that the public sector can make use of the broad range of different parental lines that are developed by companies. The public sector subsequently can concentrate its breeding activities on inserting those traits that make varieties specifically suited to the complex and diverse realities of smallholder farmers. By gaining the exclusive rights to commercialise any variety that is developed using their parental lines, the private sector, in turn, can benefit from public breeding activities without running financial risks themselves. For dissemination and supply of the planting material to smallholder farmers, both public and private sector actors can play a role, as indicated in the former models.

One challenge of this model is that it requires the public and private sectors to agree on clear conditions under which the varieties can be shared with smallholder farmers for free or at reduced rates. In essence, this requires agreement on a clear distinction between smallholder farmers who in principle can access formal seed markets, and smallholder farmers who exclusively rely on informal seed markets and cannot reasonably be said to constitute a market opportunity. However, as was described previously (Section 10.3.1), this distinction is not always so clear-cut. Recent work by De Jonge and Munyi (2016) offers some interesting pointers for how this may be achieved nonetheless.

Finally, this model stands or falls with the ability for private companies and public sector organisations to share parental lines in a confidential and secure way. Therefore, clear agreements need to be made about the way these parental lines (and information about these parental lines) are stored and used. This is arguably easier to manage if various private sector parental lines are shared with one (international) public sector institute instead of many.

10.3.4 The project model

In this model, public and private institutes collaborate on an *ad hoc* basis to tackle specific breeding challenges when there is a shared interest. This can be understood as a form of 'project-based work' and may apply to any of the three former models of collaboration. These collaborations are often initiated by project funding from national governments or large philanthropic organisations, who often require some form of co-funding from companies, and who often focus on urgent issues. The results are then usually partly made public and partly shared exclusively among the participating stakeholders. Dissemination can have a mixed form as well.

This model has been followed in tackling *Phytophthora* with the use of genetic modification techniques in the Netherlands. In the mid-2000s, the Dutch government funded a major joint research project involving several universities, companies, and other stakeholders to use genetic modification to develop late blight resistance (Haverkort *et al.*, 2009).

This model works best in cases of breeding challenges that are specific, that require a certain scale to succeed (i.e. that cannot be tackled by individual companies alone), and that are perceived as urgent by both the public and private sector. This was for example the case with the *Fusarium* fungus (*Fusarium* wilt tropical race 4 or TR4) that may threaten the Cavendish banana with extinction ('Bananageddon'). This challenge is specific (it is one disease), it is urgent, and it threatens both public and private interests. For hybrid potato breeding, it can be envisioned that this is the case for urgent challenges like drought resistance, climate resilience, and other cases whose complex nature may make it too complicated for individual companies to tackle, and where the needs of private parties align to the (public) needs of smallholder farmers.

As should be clear from the examples above, these conditions do not require that the targeted traits are genetically simple. Drought resistance and climate resilience, for example, are complex traits, and it can be envisioned that this model also works for developing a lowland potato for the tropics. Varieties with these traits would then be further developed and disseminated by companies that participated in the project. More important is the distinction between traits that are also interesting for existing commercial markets, like drought resistance and climate resilience, and traits that do not neatly align to existing commercial markets, like those for lowland potato in the tropics. In the latter case, projects are only likely to attract private partners who see sufficient commercial potential for creating new markets in such areas.

One downside of this model is that no institutional changes are made to structurally secure access of smallholder farmers to the benefits of hybrid breeding on the long term. The relatively short time span of projects (usually between 2-10 years) is not always sufficient for tackling certain breeding and dissemination challenges. Moreover, the *ad hoc* nature of the collaborations requires stakeholders to be mobilised around urgent issues time and time again. This makes these collaborations especially vulnerable to both economic downturns and 'apocalypse fatigue'. And finally, the lack of structural institutional changes also has the potential downside that no institutional memory is built up. Know-how and routines that are developed in collaborations are at risk of being lost once projects end and new projects thus face relatively high transaction costs as partners have to learn about one another's expertise and way of working time and time again. Neither of these issues is easy to solve without falling back on more long-term institutionalisations of collaborations, which, in the end, would turn the project model in one of the other models.

Another downside of the *ad hoc* nature of project work is that there are no guarantees that sufficient capacity has been built up in preceding years when no project funding was available. For example, the project to develop Covid-19 vaccines succeeded in part because in earlier years actors kept working on mRNA techniques as well as on coronaviruses, even though at that time there was no widely shared sense of urgency. Similarly, in potato, smallholder farmers may come to face urgent challenges related to new potato diseases or climate change that cannot immediately be tackled with project-based collaborations if no capacity has been built on these topics in the preceding years. This underscores the need to strengthen the institutional knowledge base.

10.4 Discussion and conclusions

Hybrid diploid breeding has the potential to benefit smallholder farmers around the world as it can help overcome challenges associated with climate change, poverty, and food security. This requires that hybrid breeding will be used to develop varieties that are suited to the specific contexts and needs of smallholder farmers and that concerted efforts are taken to disseminate those varieties to farmers.

We began this chapter by observing that this does not happen by itself, and that neither the public sector nor the private sector can do this alone. This raises the question of how best to institutionalise public-private partnerships to enable smallholder farmers to gain access to the benefits of hybrid diploid breeding.

By drawing upon the perspective of the commons, we identified four different models for institutionalising public-private collaborations in order for hybrid breeding to benefit smallholder farmers. We called these models the charity model, the pre-competitive research model, the breeding consortium model, and the project-based work model. The four models and their respective strengths and challenges for making hybrid breeding work for smallholder farmers are summarised in Table 10.2.

It can be argued that the project model is most likely to ensue if no concerted action is taken to institutionalise the access to hybrid breeding for smallholder farmers. We believe this will produce suboptimal outcomes for smallholder farmers. Under such institutional arrangements, the incredible potential of hybrid breeding for smallholder farmers will be underused.

As we mentioned before, these models to ensure that hybrid breeding also benefits smallholder farmers are not mutually exclusive and elements of different models can be combined in practice. We have nevertheless chosen to clearly distinguish them in order to bring the relative and potential strengths and weaknesses of each model into sharper focus. The models show that different ways of institutionalising public-private partnerships each have specific strengths and weaknesses when it comes to ensuring smallholder access to innovation. It is our hope that this can be used

Table 10.2. Strengths and challenges of models of public-private partnerships for access to benefits of hybrid potato by smallholder farmers.

Model	Strengths	Challenges
Charity model		
Private sector breeds, public sector disseminates	• Builds on existing strengths of public and private sectors	• Identifying beneficial traits • Distinguishing smallholders with and without market access
Pre-competitive research model		
Public sector develops parental lines, private sector breeds and disseminates	• Decreases private sector breeding costs • Inclusion of beneficial traits across commercial varieties	• Reversal of existing competitive advantages • Dissemination to smallholder farmers in informal markets
Breeding consortium model		
Private sector shares parental lines, public sector breeds and disseminates	• Combining private sector parental lines for public use • Private sector profits from public sector work	• Distinguishing smallholders with and without market access • Ensuring confidential and secure use of parental lines
Project model		
Public and private sector jointly address specific breeding challenges	• Tackling urgent specific challenges that require scale • Suitable for both simple and complex traits	• Ensuring structural attention to smallholder need • Building institutional memory and capacity

as a starting point for the public and private sectors to come together and discuss how they can combine their forces for the benefit of smallholder farmers around the world. We are convinced that the way these models will be operationalised will result in much more complex and nuanced collaborations, and involve other aspects that we have not taken in consideration.

Acknowledgements

We thank Dr Merideth Bonierbale and the editors for their feedback and suggestions.

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Chapter 11. Conclusion: major findings and discussion

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Abstract

Hybrid breeding may revolutionise the potato world, especially in low- and middle-income countries. The major impact will be on yield in remote and challenging agro-environments. We expect that hybrid breeding will increase the turnover of varieties in those environments when new seed systems based on hybrid true potato seed have been established. With faster breeding and multiplication systems, it is possible to produce clean seed and to respond to climate change as well as rapidly changing market and societal needs. For this revolution to happen, the potato production system (of both seed and ware) needs to be radically changed and such changes are not easy to orchestrate. During the introduction of such a potentially disruptive innovative technology, many actors, stakeholders and institutions play a significant role and each of these parties has its own objectives, interests, and concerns. This concluding chapter aims to answer the question how such a radical innovation can be steered in a societally responsible manner to realise global food security and sustainability in potato production. To guide and coordinate the system innovations triggered by the potential of hybrid potato breeding, strong public-private partnerships are required in different links of the potato value chain.

Keywords: hybrid breeding, true potato seed, *Solanum tuberosum*, agro-industrial context, international development context, responsible innovation

11.1 Preamble

This book is about the promises of hybrid breeding as a radical new development in the international potato world. Most importantly, hybrid breeding can speed up potato variety development in response to diverse market and societal needs, and hybrid seed can provide a clean source of planting material that is easy to transport and store. As a result, potato breeding and cultivation may more and more follow the dynamics of the international vegetable sector, characterised by the rapid introduction of new and improved varieties, product diversification, increasing nutritional value and the introduction of resistant and stress-tolerant cultivars. However, the chapters in this book also make clear that technological innovation involves more than just the creation of new products. Indeed, as emphasised in the Chapters 2 and 3, hybrid potato breeding has to be

Paul C. Struik, Peter R. Gildemacher, Dirk Stemerding and Pim Lindhout (eds.)
Impact of hybrid potato

DOI: 10.3920/978-90-8686-946-6_11, © D. Stemerding *et al.*, 2023

considered as a system innovation that may affect almost every step in the potato value chain.[6] It may involve game-changing and disruptive transformations, shaped by a complex interplay of seed-technological, agronomic, commercial, social and political aims and developments. The future of hybrid potato will thus depend on diverse, uncertain and dynamic system conditions, and different future development pathways are possible, as explored in the interactive scenario exercise described in Chapter 3. This raises a very important question that is addressed in several chapters of this book, namely how to guide the future of hybrid potato in desirable directions, in particular with regard to the goals of global food security and sustainability?

11.2 The future of hybrid potato in the agro-industrial context

In the introductory chapter, the agro-industrial and the international development context have been distinguished as two different global system contexts in which the development of hybrid potato breeding can make a difference. Chapter 4 focuses on the agro-industrial context, with the Netherlands as a vibrant centre in the potato world, involved in every aspect of the potato value chain. In potato breeding, there is a significant number of complex traits that need to be selected for, whereby hybrid breeding will allow breeders to respond much quicker to new demands in the market, with a higher turn-over of varieties, than in conventional potato breeding. However, building a new hybrid breeding programme from scratch requires long-term efforts and high investments. Before we can expect improved hybrid potato varieties to reach the agro-industrial market, these varieties will first have to meet the current, high-level and tight-fitting retail and potato processing standards.

Another important benefit accruing from hybrid breeding is the availability of uniform and virtually disease-free true seed as starting material for potato cultivation. Farmers may now grow potatoes from hybrid potato seed, seedlings, mini-tubers or first-generation seed potato tubers. Growing potatoes directly from seed, transplants or mini-tubers will require, however, quite a different agronomy and it remains to be seen what will be the most appropriate cultivation models in different agroecological conditions. As pointed out in Chapter 4, the use of hybrid potato starting material will also imply, for each of these cultivation systems, a significant shift in the creation of added value from the conventional seed tuber grower to the breeding/seed company. Moreover, as true potato seed can reach areas that currently do not have access to high-quality seed potato tubers, hybrid seed may create opportunities for these companies to expand their export market. The emergence of hybrid potato may thus transform as well as strengthen established business models in the agro-industrial potato sector.

In this context, Chapters 3 and 4 also raise the question what this development might mean for the leading position of the Netherlands as the world's biggest exporter of seed potato tubers. According

[6] In a report by the High-Level Panel of Experts on Food Security and Nutrition of the 'Committee on World Food Security', innovation is likewise defined in comprehensive terms as 'changes in the design, production or recycling of goods and services, … including changes in practices, norms, markets and institutional arrangements, which may foster new networks of food production, processing, distribution and consumption' (quoted by Haug *et al*., 2021).

to one of the scenarios discussed in Chapter 3, hybrid potato breeding may lead to further monopolisation in the sector, in line with the current agro-industrial trend towards increasing scale and intensification. In this scenario, two large multinationals control the entire potato value chain and have monopolised breeding know-how and genetic resources. In a radically different alternative scenario, hybrid potato breeding is globally supported by the public availability of parental lines, enabling breeders all over the world to develop a broad range of hybrid potato varieties suited to local conditions. In both these scenarios the Dutch potato sector may lose its dominant position. However, as argued in Chapters 3 and 4, thanks to its strong breeding knowledge infrastructure, the Netherlands might still be the place to invest for seed companies, and the sector could maintain a leading position with a shift of focus to the international marketing of know-how.

The scenario discussion in Chapter 3 also shows an important and interesting tension between the plausibility and desirability of the potato futures discussed. While further monopolisation in the potato seed sector was generally considered as a most realistic prospect (see also Chapter 9 about the changing playing field), public support for local breeding and market diversification was seen by several discussants as a more desirable future, in which hybrid breeding could really benefit both the productivity, sustainability and diversity of potato production systems. This tension between the plausibility and desirability of possible futures underlines the need to better understand the complex interplay of the societal conditions and goals shaping these futures, which may help stakeholders, civil society organisations and policymakers to guide hybrid breeding in the right direction.

An important policy issue, discussed in Chapter 5, is the need for adjustment of global regulatory frameworks to the use and trade of hybrid true potato seed. The official protocol for testing distinctness, uniformity and stability of tuber-based potato varieties has to be adapted to seed-based hybrid varieties. Examination of the value for cultivation and use of hybrid potato varieties also requires a different approach, as well as seed quality control and certification. Although a shift towards export of true potato seed could reduce the need for phytosanitary measures, many countries have not yet opened their borders for the import of hybrid seed. Another widespread concern in the potato sector is the length of the variety registration process, mentioned in Chapter 6. An important issue to consider in this context is the impact of strict and formal seed regulations on the availability and use of hybrid potato seed in the informal seed sector, which remains of overwhelming importance to smallholders in large parts of the world. Indeed, with a view to global food security, there is much to be gained by lowering regulatory thresholds for smallholders and making the formal system more inclusive (De Winter and Lammers, 2022a).

11.3 The future of hybrid potato in the international development context

When we shift the focus from the agro-industrial to the international development context, the dominance of informal seed systems is a crucial difference to take into account in discussions about seed innovation. Globally, 90-95% of seed potato tubers are farm-saved, exchanged within farmers' communities or marketed locally, thus sustaining the livelihood of millions of resource-poor smallholder farmers. There is a clear difference and distance between this informal seed system and the formal, agro-industrial system. In the international development context, therefore, switching from local farmers' varieties to commercial hybrid varieties represents a major shift. As potato productivity in Sub-Saharan Africa remains well below its potential, it is generally agreed that hybrid potato has great potential to contribute to global food security, but not as an innovation standing on its own. The promises of hybrid potato breeding may indeed fuel necessary changes of the seed, farm and market system. However, as argued in Chapter 8, the magnitude of the systemic changes required also indicates the persistence and complexity of the challenges involved, and hence the chances of success.

The system-level challenges associated with the introduction of hybrid potato in the international development context, also have implications for innovation strategies and business development. In various tones, the chapters in this book emphasise the need for partnerships and collaboration between a variety of stakeholders, as neither the private, nor the public sector can fully harness the potential of hybrid breeding alone. For a more detailed discussion of these issues, we will focus in the following on the two main topics that were mentioned in Chapter 1 as an agenda for debate: (1) hybrid potato variety development and selection; and (2) the organisation of hybrid potato seed and value chains.

11.3.1 Hybrid potato variety development and selection

A major promise of hybrid potato breeding is that it will boost variety development and selection. In the wording of Chapter 2, breeding companies will develop new hybrid cultivars that are tested in target markets over the globe, where local users can participate in selecting the best adapted cultivars. In the international development context of Sub-Saharan Africa, hybrid breeding may thus target potato traits that are especially relevant for attaining food and nutrient security, including the development of cultivars that are adapted to cultivation in the lowland tropics. However, as emphasised in Chapter 7, to tailor varieties to the specifics of farmer demand, a solid understanding is required of the wide diversity of farmers and farming systems, in terms of resource endowments and the local agroecological, socioeconomic and cultural conditions in which farmers operate. While, according to formal, agro-industrial sector standards, quality seed is high-yielding, uniform, genetically pure, healthy, and in the proper physiological stage, this may not fully match with the needs and meanings that compose quality in the eyes of smallholder farmers (Kilwinger, 2022). This raises the question how to accommodate, with the development of hybrid potato varieties, the heterogeneity among farmers in Sub-Saharan Africa. In answer to this question, Chapter 7 recommends to closely involve farmers and other stakeholders in the design and evaluation of new varieties, in order to enhance the likelihood of a good fit between hybrid breeding and farmers' multiple realities.

As food security policies are mostly centred around commercialisation of agriculture and 'market-led technology adoption' (De Winter and Lammers, 2022b), there is a crucial role to play for breeding companies in targeting variety development to smallholders' needs. In Chapter 6, it is observed that, without a substantial market demand, we cannot expect that traits that are specifically interesting for smallholder farmers will receive much attention within commercial breeding programmes. International potato breeding companies are currently mostly offering best-bet varieties from their available portfolios to selected African countries. With a faster and more targeted approach, a hybrid potato breeding programme offers new and promising opportunities, but its development is a highly time-consuming and costly undertaking. When hybrid seed reaches the African market as a commercial, formal seed source, it may possibly only be suitable and affordable for market-oriented better-off farmers. As noted in Chapter 6, a dedicated hybrid potato breeding programme for Sub-Saharan Africa will therefore require joint public-private efforts, an issue that we will return to below in a discussion on responsible innovation strategies.

11.3.2 Hybrid potato seed and value chains

The starting material for hybrid potato is clean true seed that can be multiplied quickly and is easy to transport and store. When growing potatoes, farmers may thus start with seed, but they could also use seedlings transplanted from a greenhouse or nursery into the field, or use first generation (seedling) seed potato tubers. Since direct sowing or using seedlings both are quite demanding and risky procedures, we can expect that smallholder potato farmers will generally prefer to continue using tubers as they are familiar with this vigorous starting material. Moreover, accustomed to informal seed systems, farmers may keep reproducing and exchanging these tubers as high-quality planting material within their communities. Yet, with the need to regularly refresh this material, especially under conditions of high pressure of pests and diseases, farmers will depend on a continual supply of first-generation hybrid potato seed tubers. These tubers might be made available through a decentralised intermediary infrastructure, with growers specialised in raising vulnerable seedlings from tiny potato seeds, and in harvesting and selling seedling tubers for potato cultivation. A formal commercial hybrid seed system may thus function as a continuous input source that can provide disease-free tubers to the informal system (Stemerding *et al.*, 2020). However, as Chapters 7 and 8 make clear, in the (African) international development context, such a system transformation is to be regarded as one of the major bottlenecks for an introduction of hybrid potato to the benefit of smallholder farmers.

Hybrid potato seed can be produced on a large scale by international breeding companies at a few highly specialised locations. The abundant availability of true potato seed may put an end to the lack of clean and high-quality planting material, which is generally seen as a very important barrier to improving smallholder potato production and food security. But it will require an enabling institutional and policy environment in the main potato production regions. An intermediary infrastructure with growers who can supply farmers with suitable planting material is one crucial precondition. Another precondition is (inter)national regulation which enables trade and marketing of hybrid potato seed. In practice, as noted in Chapter 6, all levels of regulation – seed importation, variety registration and seed certification – place severe restrictions on the availability of new (potato) planting material. An additional hurdle for the introduction of hybrid potato is the necessary adjustment, as described in Chapter 5, of the extant rules for seed potato tubers to true potato seed.

When hybrid potato varieties do become commercially available in the (African) international development context, it is not yet obvious that smallholder farmers will have full access to these varieties. For the many resource-poor and risk-averse smallholders the price of certified planting material will be crucially important, and it remains to be seen how much hybrid potato seed or planting material will cost. As we noted above, this planting material may be attractive and affordable only for more well-to-do farmers. However, a possible scenario that is mentioned in Chapter 9 (and suggested in other chapters as well) is that hybrid potato 'trickles down' through informal networks, in which tubers produced by better-off and market-oriented potato farmers are locally circulated or traded to smallholders. Thus, hybrid potato might create a much-needed bridge between the formal and informal seed sectors (Stemerding *et al.*, 2020). Another way to create such a bridge between the formal and informal systems, suggested in Chapter 6, is to commercialise hybrid potato varieties under 'truthful labelling' instead of formal certification.

Further down the seed value chain, issues arise with regard to the cultivation and marketing of hybrid potato varieties. Chapters 6 and 7 both emphasise the great diversity in farm households and agroecological and socioeconomic farming conditions in Sub-Saharan Africa. Most potato farmers are smallholders, working under rainfed and low-input conditions. They typically use home-saved seed tubers with a short dormancy, allowing planting in multiple rainy seasons within one calendar year, but which are also subject to seed degeneration, with seed-borne diseases being a major yield-limiting factor. Hybrid breeding has the potential to more efficiently and effectively target potato breeding to high-yielding varieties, with short seed tuber dormancy, disease and pest resistance, and heat and drought tolerance as especially desirable traits for African potato farmers. Hybrid breeding may also respond to new and more diverse market incentives, resulting from growing potato consumption and increased processing in Africa, although access to these markets will remain a key challenge for the many smallholder farmers.

11.3.3 Disruption or integration?

In the various chapters of this book, we find two different perspectives on the kind of changes and improvements that hybrid breeding could or should bring in this international development context. On the one hand, hybrid potato breeding is discussed as a game changer that may cause disruptive change, with hybrid potato as a driver of potato sector transformation in Sub-Saharan Africa, aiming at the creation of commercial hybrid seed value chains. From this perspective, regionally prevailing farming habits, culture and traditions are perceived as barriers that have to be surmounted. On the other hand, we find pleas, in particular in Chapter 7, for an approach in which breeding innovations and system adaptations are tailored towards the needs and capabilities of different farm household types. Starting points, from this perspective, are the agroecological and socioeconomic farming conditions to which hybrid varieties and seed value chains should be attuned.

As noted in Chapter 8, the introduction of hybrid potato seed will require either transformation of existing seed, farm and market systems, or integration in these systems. The more radical the transformation – with hybrid seed based on an agro-industrial variety portfolio, requiring labour- and capital-intensive crop management – the more obstacles will be created to the adoption of this seed by smallholder farmers. The more radical the integration – with hybrid varieties tailored to the practices, preferences and needs of smallholder farmers – the less likely that companies will see a business model for dedicated seed development and production. The tension between these two scenarios, raises the question, posed in Chapter 8, how to find a balance between disruption and integration. Indeed, how to navigate between these two scenarios in hybrid potato breeding with the aim to serve global food security in sustainable ways?

11.4 Responsible innovation strategies

Responsible innovation has been introduced in Chapter 3 as an approach that takes into account the complexities and uncertainties of innovation, while seeking ways in which innovation can respond to major societal challenges like food security and sustainability. The chapter describes how a broad variety of stakeholders has been involved in a process of mutual learning, to find out how a desirable future for hybrid potato breeding would look like. What do stakeholders see as important challenges and goals to which hybrid potato breeding should respond, and how to create optimal conditions for a successful development of this innovation from this point of view? In addressing these questions, the chapter also seeks to understand the complex interplay of societal conditions and goals that shape the future of hybrid potato, whereby this future finally will depend on the economic, social, and policy decisions that are adopted by the different parties involved.

Chapters 9 and 10 are both highly relevant for this discussion. Chapter 9 examines how Dutch breeding companies see their own role and responsibility with regard to hybrid potato breeding in the international development context, in particular with a view on Sustainable Development Goals (SDGs). It considers corporate social responsibility (CSR) as a frame that may stimulate companies to embrace SDGs in their innovation strategies, even though companies, for economic reasons, might prefer to focus on more secure agro-industrial markets. From interviews with representatives of the main Dutch potato breeding companies, the chapter concludes that most companies see hybrid breeding as an important innovation that can make a significant contribution to SDGs, especially with regard to food security and sustainability. Moreover, variety development and global seed trade are seen by these companies as core activities that give substance to their CSR efforts. Resource-poor smallholder farmers may benefit in this view from improved, commercially produced seed through a 'trickle down' process, as mentioned above, from the formal sector to informal community networks. By contrast, the authors of Chapter 9 emphasise the complexity of seed interventions that, without a more in-depth understanding of farmers' diverse conditions and needs, are usually doomed to fail. In their view, there is a need for more inclusive breeding strategies targeting smallholder farmers. These strategies should make available hybrid potato breeding knowledge and technology also as a 'common good', through collective action, involving both private and public stakeholders, including farmer communities.

In line with this discussion, Chapter 10 explores how the powerful new approach of hybrid potato breeding can be harnessed for smallholder farmers through public-private collaboration. Starting point in this chapter is the observation that hybrid breeding activities in public sector institutions are currently modest, while it cannot be taken for granted that traits that are specifically interesting for smallholder farmers, but hold little commercial value otherwise, will be targeted by the private sector. As neither the public sector nor the private sector can fully harness the potential of hybrid potato breeding, public-private collaboration will be needed to facilitate the development and dissemination of varieties that are suited to the specific contexts and needs of smallholder farmers. This chapter uses the perspective of the commons to explore the strengths and weaknesses of different partnership models, and to assess the potential of each model to enable hybrid breeding for smallholder farmers, in response to the challenges of poverty, food security and climate change. Like the preceding chapter, this chapter suggests collective action with the aim to create optimal conditions for public-private collaboration. Both chapters thus seek to find fertile ground for responsible innovation strategies, in search of a balance between system disruption and integration.

11.5 Final considerations

In this book hybrid potato futures are discussed, with food security as an all-important consideration. As the food provision in large parts of the world is highly dependent on smallholder farming, a thorough understanding of the interplay between food system dynamics and smallholder diversity is critical. It makes clear that seed interventions require a delicate balancing act: introducing viable and scalable innovations while meeting a wide variety of smallholder needs and requirements (De Winter and Lammers, 2022b). In the foregoing it was concluded that, in order to enable such a balancing act, collective action is needed, in particular aiming at public-private partnerships. Chapter 10 contains a highly valuable discussion of different models upon which such partnerships can be based (see also De Winter and Lammers, 2022c). However, a number of important questions remain to be answered. Who could take the lead in establishing such partnerships in the case of hybrid potato breeding? How to reconcile different and conflicting interests in a playing field with, on the one hand, public breeding and extension services in decline and, on the other hand, globally operating agro-industrial companies, reluctant to share information and materials? Would there be a need for 'brokerage' in the potato sector at the national and international level (Klerkx *et al.*, 2009), with organisations acting as intermediaries, supporting 'commons-based' institutional change? And again, who could take up this responsibility for a more collaborative and inclusive social ordering?

In addition to these challenging questions, there is another more fundamental issue to consider in debates about possible hybrid potato futures. Public-private partnerships may indeed support smallholder farmers with more dedicated products of hybrid seed innovation, but still will principally remain dependent on knowledge and technologies emerging from the international agro-industrial innovation system. As described in Chapters 4 and 9, the Dutch potato sector is keen to maintain a leading role in seed innovation and seed companies position themselves as key players in achieving food security, thus reframing global societal challenges as market opportunities and catalysts for commercial innovation. In response to this dominant innovation discourse, we also see a counter movement in food systems debates, emphasising the aim of food sovereignty, based on less corporate and technology-driven and more agroecological and diversity oriented self-sufficient practices of farming (Montenegro de Wit *et al.*, 2021). This opposition also manifests itself in the existence of the Alliance for Food Sovereignty in Africa (AFSA) alongside the Alliance for a Green Revolution in Africa (AGRA), which raises an important question that is not confronted directly in this book. Do we consider potato sectors in the international development context first of all as growth markets for new products of agro-industrial breeding, or as sectors that urgently need to strengthen their own breeding and seed production capacity? In other words, should the agenda for debate only consider issues of seed quality, or issues of seed sovereignty as well?

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