World Vegetable Center

International Vegetable Breeding:

A Strategy to Create Development Impact at Scale

July 2019

World Vegetable Center

The World Vegetable Center, an international nonprofit institute for vegetable research and development, mobilizes resources from the public and private sector to realize the potential of vegetables for healthier lives and more resilient livelihoods. WorldVeg's globally important genebank, improved varieties, production, and postharvest methods help farmers increase vegetable harvests, raise incomes in poor rural and urban households, create jobs, and provide healthier, more nutritious diets for families and communities.

Support for World Vegetable Center activities is provided by project donors and the following long-term strategic donors: Republic of China (Taiwan), UK aid from the UK government, United States Agency for International Development (USAID), Australian Centre for International Agricultural Research (ACIAR), Germany, Thailand, Philippines, Korea, and Japan.

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Publication No. 19-838

Editorial assistance: Kathy Chen
Graphic design: Vanna Liu

Printed in Taiwan

Suggested citation

World Vegetable Center. 2019. International Vegetable Breeding: A Strategy to Create Development Impact at Scale. World Vegetable Center, Shanhua, Taiwan. Publication No. 19-838. 31 p.

International Vegetable Breeding

A Strategy to Create Development Impact at Scale

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FOREWORD

The world's current food systems are not resulting in increasingly healthy, high-quality diets. Undernutrition, micronutrient deficiencies and overnutrition affect billions of people worldwide. Low quality diets—containing too little fruit, vegetables and other wholesome foods, and too much fat, sugar and salt—are adversely affecting human health. Increased production and consumption of vegetables contributes to improved nutrition through greater dietary diversity and value addition, income gains and job creation in the food supply system, from seed to retail.

The World Vegetable Center is contributing to this through the development of vegetable varieties that are higher-yielding per unit of land, water, nutrients and labor, more resilient to biotic and abiotic stresses, more nutritious, and with better taste and shelf-life qualities. Vegetable breeding has been at the forefront of the work of the World Vegetable Center since it started operations in 1973. Since then, the Center has amassed the world's largest public collection of vegetable genetic resources, which supports vegetable breeding programs globally.

However, the vegetable sector has radically changed over the last thirty years: laws and regulations have changed, the role of the private sector in vegetable breeding has expanded, there has been rapid adoption of vegetable hybrids as well as a loss of traditional vegetables, and there have been technological advances, particularly in the application of genomic tools in plant breeding. While the formal vegetable seed sector rapidly developed in some parts of the world, most of Africa and some parts of Asia are lagging behind. Vegetable farmers in these regions continue to rely on informal seed and imported seeds of varieties not well adapted to the local needs.

Seed sector development in Africa and Asia will need to focus on strengthening the formal sector in particular for 'global' vegetables, such as tomato, pepper, onion and some more traditional ones, such as amaranth. Rapid urbanization increases demand for such vegetables, creating new opportunities for rural and peri-urban farmers. The World Vegetable Center is, therefore, building stronger partnerships with private seed companies in Africa and Asia. Quality seed of improved varieties needs to have multiple strengths, in particular good pest and disease resistance, tolerance to abiotic stresses such as heat and drought, and high nutritional content. Varieties also need to be robust to tolerate suboptimal storage and transport conditions and must be attractive to consumers in terms of taste, texture, shape, color etc. Meanwhile, informal seed systems will remain very important for the vast majority of traditional vegetables, relying on farmer-to-farmer seed exchange, community-based seed selection and conservation, and public sector seed distribution.

These trends affect the way that the Center conducts international breeding research. We need to be sensitive to the complexity of vegetable seed systems—recognizing that countries, and vegetable species within countries, can be at different levels of vegetable seed sector development and that there is a need for an integrated approach, strengthening both formal and informal seed systems.

This document reflects the current thinking within the World Vegetable Center on how our breeding research can contribute to realizing the Center's mission, i.e. to contribute to realizing the potential of vegetables for healthier lives and more resilient livelihoods. This strategy will be updated from time to time as new opportunities and challenges emerge.

Marco Wopereis
Director General
World Vegetable Center

List of acronyms

ACIAR	Australian Centre for International Agricultural Research
APSA	The Asia & Pacific Seed Association
AFSTA	African Seed Trade Association
AVBC	Africa Vegetable Breeding Consortium
AVRDC	Asian Vegetable Research and Development Center
CIMMYT	International Maize and Wheat Improvement Center
CIP	International Potato Center
DFID	Department for International Development (United Kingdom)
IMIN	International Mungbean Improvement Network
IRRI	International Rice Research Institute
IPM	Integrated pest management
IVTC	International Vegetable Training Course
MYMD	Mungbean yellow mosaic disease
NARS	National agricultural research system
QTL	Quantitative trait locus
R&D	Research and development
TYLCD	Tomato yellow leaf curl disease
USAID	United States Agency for International Development
WorldVeg	World Vegetable Center

1. INTRODUCTION

It is commonly understood that "good seed makes a good crop". Much less understood is that delivering good seed to millions of smallholder farmers in developing countries involves a complex chain of basic and applied research and contributions of public organizations, private seed companies, and a large network of distributors. The World Vegetable Center (WorldVeg), formerly known as the Asian Vegetable Research Development Center (AVRDC), has facilitated the production of quality seed for farmers in the tropics since the start of the Center's operations during 1973. Seed systems in developing countries have changed much since then and continue to evolve, driven by changes in markets, policies and technologies. This document presents the current thinking within WorldVeg regarding how to create large-scale improvements to the lives of smallholder farmers in developing countries through international vegetable breeding.

Recent studies show that WorldVeg breeding products have been widely adopted by farmers in Asia and Africa (Table 1). In Southeast Asia, an estimated 0.5 million smallholder farm households are using tomato and chili pepper varieties containing WorldVeg-developed germplasm (Turner, 2016). In India, 0.6 million farm households are using WorldVeg tomato and chili germplasm (Schreinemachers *et al*., 2017a). In Bangladesh, India, Myanmar and Pakistan, mungbean

varieties developed by WorldVeg are planted on 1.8 million hectares and used by an estimated 1.2 million farm households (Schreinemachers *et al*., 2019). In Kenya and Tanzania, improved amaranth varieties are estimated to reach 231,000 farm households (Ochieng et al., 2019). In East and Southern Africa, WorldVeg breeding lines account for 50% of formal tomato seed production and 98% of formal African eggplant seed production (Schreinemachers et al., 2017b).

Table 1 Adoption of World Vegetable Center vegetables lines in Asia and Africa.

Crop (year of data)	WorldVeg-related varieties	Planted area (1,000 ha)	Adoption rate (% area planted)	Farmers benefiting (1,000s)
African eggplant:				
- Tanzania (2014-15)	2	5.3	100.0	n.a.
Amaranth:				
- Tanzania (2017)	6	11.1	20.0	174.2
- Kenya (2017)	6	0.4	47.1	56.85
Chili pepper:				
- India (2014)	39	105.4	20.3	241.0
- Southeast Asia (2014)	11	49.9	n.a.	207.9
Mungbean:				
- Bangladesh (2017)	6	116.7	67.0	100.8
- India (2017)	3	654.4	26.7	467.5
- Myanmar (2017)	5	822.1	77.5	432.7
- Pakistan (2017)	5	165.9	92.8	188.5
Tomato:				
- India (2014)	61	99.4	35.4	318.6
- Southeast Asia (2014)	33	71.8	n.a.	287.4
- Tanzania (2014-15)	2	27.1	77.2	n.a.

Data sources: Schreinemachers *et al*., 2017a; Ochieng *et al*., 2019; Schreinemachers *et al*., 2017b; Schreinemachers *et al*., 2019; Turner, 2016.

Evidence is also accumulating that the large-scale adoption of WorldVeg breeding products has contributed to economic gains for smallholder farmers and consumers. Sequeros et al. (2019) estimated that mungbean varieties developed by WorldVeg in collaboration with the Department of Agricultural Research in Myanmar generated economic gains of US$ 1.4

billion from 2000 to 2016 with 95% of these gains accruing to smallholder farmers. Another study showed that WorldVeg tomato varieties in Tanzania created economic gains for consumers and producers worth US$ 0.25 billion from 1997 to 2014 (Schreinemachers et al., 2017b).

It is important to recognize that impacts were achieved through very different pathways and partnerships depending on crop and location. There are contrasting impact pathways between varieties and hybrids as well as between countries with developed and underdeveloped seed systems. For instance, WorldVeg breeding lines of tomato and chili pepper made a large impact through private sector pathways, but made very little impact through public sector pathways (Turner, 2016). In contrast, mungbean breeding lines created tremendous impact through public sector pathways and negligible impact through private sector pathways (Schreinemachers et al., 2019). This shows that the Center needs to be strategic in how to tailor its breeding products to achieve impact at scale.

2. GOALS AND VISION

2.1 Strategic plan

The WorldVeg vision is "Healthier lives and more resilient livelihoods through greater diversity in what we grow and eat." Vegetable breeding and the scaling of improved germplasm is a key component in the Center's strategy to realize this vision, contributing directly to the United Nations Sustainable Development Goals (SDGs) of no poverty (SDG1), zero hunger (SDG2), and good health and well-being (SDG3).

The Center's research is organized in four outcome-oriented flagship programs with vegetable breeding and genetic conservation and utilization hosted under the flagship "Vegetable Diversity and Improvement." This flagship aims for vegetable growers to have increased access to high quality seed of a diverse range of climate-resilient and nutritious vegetables.

The current focus in WorldVeg breeding programs is on a selection of vegetables of high economic and/or nutritional importance for the following product lines: tomato (dual purpose and fresh market), chili and sweet pepper, bitter gourd, tropical pumpkin, onion, legumes (mungbean, urdbean, vegetable soybean), amaranth, African eggplant, and brassicas (broccoli). Table 2 lists the product lines and vision for 2025. Progress is monitored using breeding pipelines that list the properties of the breeding outputs and facilitate decision-making about the use of these products.

Table 2 World Vegetable Center product lines for vegetable breeding and objectives.

Product	Vision
1. Dual purpose and fresh market tomato	Tropically-adapted dual purpose and fresh market lines are widely used in breeding and derived varieties become very popular in fresh markets, especially for higher total fruit carotenoids (lycopene, beta-carotene) and vitamin C contents, attractive shapes, colors and taste. WorldVeg tomato hybrids tolerating high temperature periods dominate off-season production in South/South East Asia and West Africa; varieties facilitate competitive and profitable tomato processing in India, East and West Africa.
2a. Multiple disease resistant chili pepper lines	High quality WorldVeg chili pepper lines featuring resistance to anthracnose, Phytophthora blight and multiple viral diseases are found in the pedigrees of >50% of varieties marketed in South Asia. Chili breeding also focuses on high potential *C. chinense* cultivars in addition to *C. annuum*.
2b. Tropical sweet pepper lines	Improved WorldVeg sweet pepper lines open the path for seed companies to develop tropically-adapted sweet pepper varieties in a range of colors, shapes and sizes, and rich in carotenoids and vitamin C. Sweet pepper production season and area in the tropics expands and market supplies increase.
3a. Bitter gourd lines and hybrids	WorldVeg bitter gourd lines boost the hybrid vigor and performance of seed company varieties grown in South Asia. Powdery mildew and begomovirus resistances reduce pesticide use and enhance productivity and profit. Different fruit types characterized for major antidiabetic compounds add value and are appreciated by health-conscious consumers.
3b. Multiple virus resistant pumpkin lines	WorldVeg-bred pumpkin lines are a major source of multi-virus resistance to improve seed company varieties and result in reduced pesticide use by growers. WorldVeg pumpkin lines introduced into Africa are noted in markets for both leaves and tasty high quality, low fiber fruit rich in beta-carotene and other carotenoids and phytonutrients.
4. Amaranths	Seed companies develop and market amaranth varieties throughout Africa and Asia using WorldVeg improved lines that are nutrient-rich and contain low levels of antinutrients. Amaranth varieties adapted to heat/drought expand vegetable supplies, especially in the off-season, and grain amaranth supplies become available for use in fortifying maize flour and other cereal products.
5. African eggplants	Seed companies develop and market seed of determinate and indeterminate African eggplant pure line and hybrid cultivars leading to wide availability of African eggplant in markets.
6. Legumes	Legume products include lines developed from three species: mungbean (*Vigna radiata*), urdbean (*Vigna mungo*) and vegetable soybean (*Glycine max*). Resistance to mungbean yellow mosaic disease (MYMD) is the most important trait for all three species. The geographical focus of the breeding program is extended from Asia to Africa.
7. Onions	WorldVeg short-day onion lines demonstrate high marketable yields, resistance to major onion diseases of West Africa, and extended bulb shelf life under ambient storage with low bolting. Adoption of WorldVeg onion varieties by West African farmers enables them to compete with onion imports, and consumers value the locally produced onion for freshness and good taste.
8. Brassicas	Brassicas such as broccoli have high market value and are rich in carotenoids and glucosinolates associated with reduced cancer risk. Heat tolerant open-pollinated lines and hybrids are developed from tolerant germplasm. Doubled haploid technology is used to shorten the time for developing new heat tolerant inbred lines, and cytoplasmic male sterility is tracked using available markers for eventual development of commercial hybrids. New heat tolerant broccoli lines are made available to seed companies and used to develop heat tolerant hybrids.

2.2 Starting and closing breeding programs

WorldVeg does not have a mandate for particular crop species, unlike other international agricultural centers such as IRRI, which has a mandate for rice, or CIMMYT, which has a mandate for maize and wheat. There are 439 vegetable species in the WorldVeg genebank; species selected for breeding change over time as shown in Figure 1.

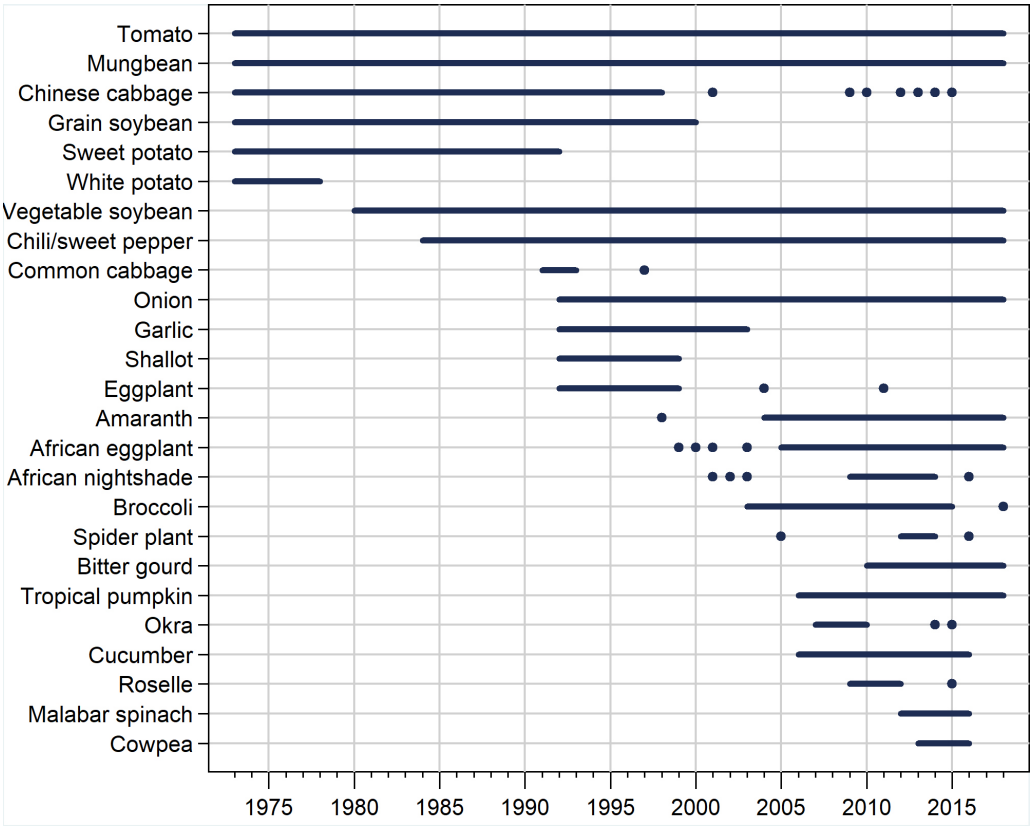

Figure 1 World Vegetable Center vegetable breeding, 1973-2018.

Note: Figure only shows crops with at least 4 years of breeding efforts. For some of the minor vegetables "breeding" usually means evaluating accessions for certain traits, but not necessarily that lines were crossed. There is much variation in the intensity of breeding programs between crops and over time, which is not shown here. *Source*: WorldVeg annual reports, medium-term plans and operational plans, 1973-2018.

For instance, the Center had a sweet potato breeding program for 20 years, but transferred all its sweet potato germplasm to the International Potato Center (CIP) in Lima, Peru in 1992-1993, after which the Center added shallot, onion, garlic and eggplant to its portfolio. Chinese cabbage breeding was scaled down during the mid-1990s after the program had reached most of its targets and resources were subsequently shifted to African vegetables, including amaranth and African eggplant. Common cabbage faced difficulties in seed production under hot and humid conditions in the lower elevations of southwestern Taiwan (AVRDC, 1994: p.75).

A strategic selection of crops for breeding is important to focus efforts and optimize impact. The following considerations are relevant: a) economic importance of the crop and potential to increase farm incomes; b) the potential of the crop to contribute to better human nutrition; c) the availability of genetic resources for breeding; d) the potential to solve significant problems cost-effectively through breeding; e) possible synergies with existing private or public sector breeding programs; f) ease of seed production and other technical considerations; and g) costs of research and the likelihood of attracting funding. Some of this information needs to be obtained from seed companies. Annex 1 shows an example of a survey used to collect data about a possible expansion of the Center's cucurbit breeding program to include luffa.

Not all breeding programs need to be long-term to create impact. A breeding program can target the development of a particular trait using the genetic diversity available in the genebank. This can be done if there is a well-articulated demand from seed companies for a particular trait that is not available in the genetic base used by the companies, but may be available in the Center's genebank. An example is begomovirus resistance in okra. The Center has a clear strength in such trait discovery because of its access to diverse genetic resources.

3. SCALING PATHWAYS OF WORLDVEG BREEDING PRODUCTS

Seed systems in many developing countries are undergoing rapid change, which was started by a wave of seed sector reforms in the 1990s. India provides a good example. Before seed sector liberalization in 1988, the public sector controlled crop breeding research and formal seed production. Yet, informal seed supplies of open-pollinated varieties dominated the market as the public sector was unable to deliver seed to most farmers. Seed sector reform, including better protection of intellectual property rights, led to a rapid expansion of the private seed sector in cotton, maize, millets, sorghum and vegetables and a diminishing role of state seed corporations (Morris et al., 1998; Pray *et al*., 2001; Kolady et al., 2012). The Access to Seeds Index (2019b) shows that nearly all major seed companies tracked by the index do breeding research in India and invest heavily in R&D and technological innovation. Seed production of tomatoes and chilies has shifted from open-pollinated varieties during the 1990s to over 90% hybrids in case of tomato now, which is also confirmed by Access to Seeds Foundation (2019b). The seed sector is flourishing in India and in other parts of the world where

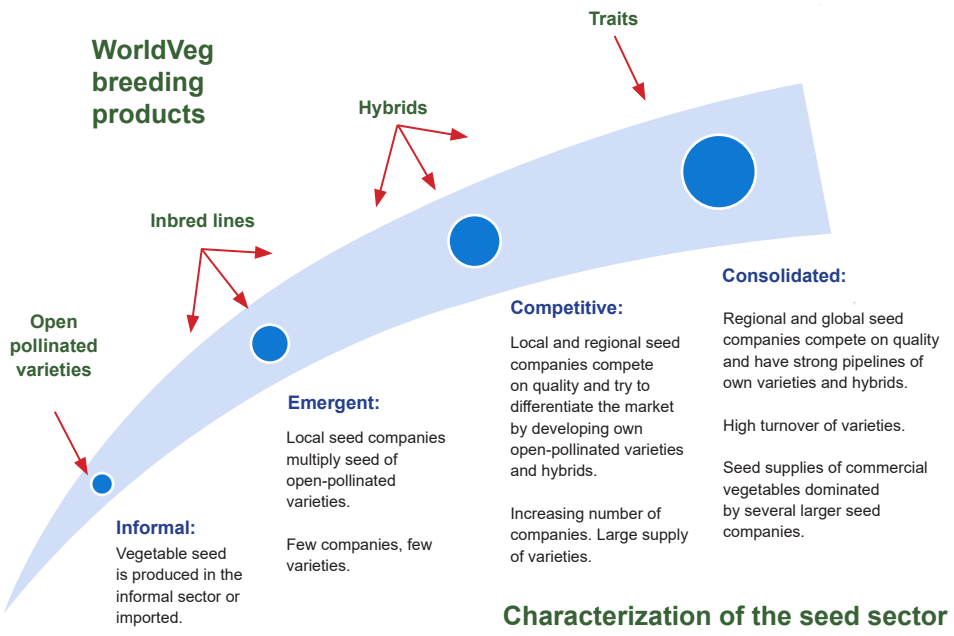

Figure 2. WorldVeg breeding products target the varying needs of the vegetable seed sector

an enabling environment for the private seed sector has been created (Access to Seeds Foundation, 2019a).

As a result of these changes, WorldVeg has adapted its own seed scaling strategy while recognizing variation between countries in levels of seed sector development and different levels of private sector interest in different crops (Figure 2).

It is important to realize that within a country, different vegetable species can be at different stages of this process and that different types of companies, e.g. large multinationals versus small local seed producers, have different needs. A competitive seed sector ensures farmers have a choice of varieties and brands, and seed companies have the incentive to deliver high quality seed at competitive prices. WorldVeg does not prefer any particular size or type of seed company and collaborates with various types of companies committed to the production of high quality seed. The Center's vegetable breeding programs develop four types of breeding products to capture these different needs (Table 3). A glossary of terms is included in Annex 2.

Table 3. World Vegetable Center breeding products and client profiles.

Product	Description	Example	Client profile
Open-pollinated varieties	Lines or genebank accessions that can be commercialized after local selection trials.	'Tanya' and 'Tengeru-97' are popular WorldVeg tomato varieties in Africa.	Local seed companies with initial capacity in seed production. Research institutes able to scale varieties.
Inbred lines	Lines pyramiding multiple traits with good plant and fruit characteristics.	All lines in the Center's seed catalogue combine multiple traits with good yields.	Local and regional seed companies and research institutes able to develop own varieties and hybrids; or large companies that want to diversify their genetic base.
Hybrids	Set of two inbred parental lines to produce a particular hybrid.	WorldVeg developed a tomato hybrid suitable for processing for Kagome, Japan.	Local and regional seed companies with capacity in seed production with or without their own R&D.
Traits	Disease resistance, heat tolerance, insect resistance.	The Center identified genebank accessions with disease resistance and introgressed this trait into breeding lines	Any seed company with an advanced R&D program.

3.1 Open-pollinated varieties

In the past, the Center focused on developing improved breeding lines. Local partners would test the lines in performance trials and then select the best performers for release as varieties. However, many of the released varieties reached only small numbers of farmers because of the limited capacity of national systems to produce and distribute seed and promote varieties.

There are important exceptions: In South Asia, mungbean lines developed together with the national agricultural research systems (NARS) and released as open-pollinated varieties have been widely adopted. The varieties had very substantial advantages over traditional varieties in terms of yield, disease resistance, short maturity, and synchronized ripening. WorldVeg and NARS did extensive promotion of the varieties to farmers. Seed multiplication was addressed through seed villages as described in Section 5.4 below.

In Tanzania, open-pollinated tomato varieties 'Tanya' and 'Tengeru-97', African eggplant varieties 'DB3' and 'Tengeru White', and amaranth variety 'Madiira 1' were developed by WorldVeg and released by national partner Horti-Tengeru. WorldVeg promoted these varieties to farmers through farmer training and the distribution of seed kits, and local seed companies picked them up when they saw increasing demand from farmers. WorldVeg supported this effort by producing large quantities of breeder seed to support the Tanzania Agricultural Seed Agency, which is charged with the responsibility to produce foundation seed. WorldVeg also introduced a seed extractor from Taiwan to solve a bottleneck in large-scale seed production.

These examples show that the development of readymade open-pollinated varieties can lead to impact at scale if there is a formal seed system with an initial capacity in seed production, although limited capacity in R&D, as in Tanzania in the early 1990s. Ready-to-release varieties can facilitate the entry of new companies in seed production and help kickstart private seed sector development. This approach is suitable for crops in which private seed production is underdeveloped, possibly because the demand for quality seed is low. Such crops typically include many traditional vegetables that are consumed rather than sold, and grain legumes such as mungbean for which farmers recycle seed or rely on informal seed supplies. For instance, half of the mungbean farmers in Pakistan purchase grains from the market to use as seed and a quarter use seed from their own harvest (Rani et al., 2018).

These conditions may change over time. A growing private seed sector

may develop its own R&D capacity to strengthen its competitiveness, or traditional vegetables may become popular among urban consumers and create demand for quality seed among commercial producers, as has been observed for amaranth in Tanzania (Ochieng et al., 2019).

3.2 Inbred lines

Inbred lines are advanced breeding lines ready to be used as open-pollinated varieties that combine multiple desirable traits: high yield, disease/insect resistance, heat tolerance, fruit color and shape and skin pattern, early yield, plant vigor, harvesting durability, shelf life, and nutrient content. Often, they pyramid disease resistances of multiple sources; for instance, tomato lines may carry combinations of *Ty1/Ty3, Ty2*, and *Ty5* genes to condition resistance to Tomato yellow leaf curl disease (TYLCD). "Ready to use" means that inbred lines exhibit good horticultural phenotypes, express traits with low linkage drag, and have a good combining ability.

Seed producers may use these inbred lines for commercial release after local testing or for breeding purposes. A recent study for India showed that before the country's seed sector reforms in the mid-1990s, WorldVeg-related varieties released in India were nearly always direct releases of inbred lines, but after the reforms, when the seed sector became more sophisticated, it became more usual to use WorldVeg inbred lines as hybrid parents or as a source of particular traits (Schreinemachers et al., 2017a).

As much as possible, WorldVeg breeders try to make the characteristics of inbred lines commercial or near-commercial to conform to the requirements of the main markets, so that minimal effort will be needed to develop open-pollinated varieties or generate hybrids. However, some markets are highly segmented with a large diversity of fruit or leaf types. Companies may therefore, assess that it takes them too long to incorporate WorldVeg inbred lines into their varieties. It is important that the Center's vegetable breeders have a good understanding of the different market demands and agree on projects with seed companies to tailor inbred lines to their particular needs.

The Center does recognize that large multinational companies may have less interest in WorldVeg inbred lines, as these may not fit easily in their own breeding pipelines. These companies may have a stronger interest in specific traits, as discussed below. Still, WorldVeg inbred lines may be of interest to broaden the genetic base of their own breeding programs. Commercial breeding programs often use other company's hybrids as sources of genetic variability in their own programs—a

practice that narrows the genetic base over time. For instance, a WorldVeg study showed that all commercial bitter gourd hybrids in Asia are closely related (Dhillon et al., 2016). This finding raised the interest of seed companies in WorldVeg breeding lines of bitter gourd, which use only genebank accessions, not commercial varieties, and therefore harbor novel sources of genetic variability of traits such as disease resistance.

3.3 Hybrids

When local seed companies grow and competition intensifies, companies will need to innovate to maintain or increase their market share by offering their own proprietary varieties. Hybrid seed production then becomes important. Other companies cannot reproduce the hybrid without both parental lines, which creates a tool for protecting intellectual property rights while also stimulating market demand.

Seed companies can either purchase hybrid seed in bulk for repackaging under their own brand, or develop their own hybrids. Mounting hybrid development programs is time-consuming and requires significant investment in double haploid or male sterility technologies. Some companies will therefore be interested to acquire readymade hybrids from WorldVeg. The Center can license the inbred parental lines for hybrid seed production to a seed company, while recognizing that it is not the Center's role to engage in commercial seed production.

Company members of the Asia & Pacific Seed Association (APSA)-

WorldVeg Vegetable breeding Consortium and the Africa Vegetable Breeding Consortium (AVBC) can conclude a bilateral agreement with WorldVeg to develop a hybrid for a particular market segment. In the past, WorldVeg has concluded bilateral licensing agreements to develop and commercialize "joint hybrids" in which one parent is a tailor-made WorldVeg line and the other is from the company. In the case of a joint hybrid, the seed company would market the hybrid and pay a royalty to WorldVeg based on the seed sales.

3.4 Traits

Large companies have their own pre-breeding programs to introgress traits into their elite material. These companies prefer early access to WorldVeg inbred lines harboring a novel trait for breeding purposes, as they compete by rapidly commercializing new varieties with novel traits.

Large companies are more interested in particular traits that they may not have themselves, or that are costly and time-consuming to develop. Insect resistance is an important example of such a trait, where WorldVeg scientists identified several new sources of resistance in wild tomato relatives in the Center's genebank and then introgressed this trait into an elite cultivar (Rakha et al., 2015, 2017). This line of investigation has been expanded to other vegetables such as eggplant. Advanced breeding companies may be interested in a single trait, preferably tagged by molecular markers to strengthen their own breeding pipeline.

Pre-breeding projects focused on developing novel traits are suitable for special project funding from member companies of the Center's private seed sector consortia, as explained in the following section.

4. PARTNERSHIPS FOR IMPACT

WorldVeg relies on seed companies and NARS to turn its breeding products into varieties sold to farmers. Seed companies and NARS therefore play an essential role for the Center to realize its vision of healthier diets and more resilient livelihoods. Sound coordination between WorldVeg and its breeding partners enables the Center's breeding programs to tailor their products to the needs of seed producers. The Center has four mechanisms for such coordination, as described below:

4.1 APSA-WorldVeg Vegetable Breeding Consortium

Seed companies are a crucial partner in the Center's efforts to raise the income of smallholder farmers and achieve food and nutrition security. The APSA-WorldVeg Vegetable Breeding Consortium was established in 2017 to strengthen this partnership. Membership is offered to APSA members in good standing with an interest in vegetable breeding. All current members are private seed companies. There were 17 members in 2017 and the consortium expanded to 33 members during 2018 (**Annex 3**) and 40 members during 2019. The consortium has a focus on crops of strong interest to seed companies in Asia, including tomato, pepper (chili and sweet), cucurbits (bitter gourd and tropical pumpkin/winter squash), but also can explore traditional

[1] See https://apsaseed.org/members-programs/apsa-world-vegetable-center-consortium/

vegetables (amaranth and okra) as determined by the consortium members.

The consortium builds on the mutual benefit of WorldVeg and seed companies as illustrated in Figure 3. WorldVeg benefits from private sector investment in its vegetable breeding programs (while recognizing that public sector donors still cover most of the breeding costs). The Center also reduces institutional risk by formalizing its relationships with private companies rather than relying solely on the personal contacts between its staff and private sector breeders. The Center benefits by soliciting feedback about breeding priorities and about the performance of WorldVeg breeding lines across Asia. Finally, companies provide data about how much seed was sold containing the Center's germplasm, which is important for monitoring the Center's impact (see Section 6).

Consortium members are invited to an annual consortium workshop hosted at WorldVeg headquarters in Shanhua, Tainan, Taiwan, which provides an opportunity to interact with WorldVeg breeders and peers from other companies and see new products in the field. Consortium members benefit from a 12-month lead access (from 1 July until 30 June of the following year) to newly-developed breeding lines and can order 10 seed acquisitions per year for free (and additional ones at a charge). The lead access period may appear short, but reflects the fact that the Center's breeding programs are still largely funded by public sector donors. Lead access is geographically restricted to Asia.

Consortium members also may agree to fund special research projects with the Center, either bilaterally or as a group, for instance, to develop a new trait or a tailored hybrid. Seed companies that are not consortium members are excluded from entering into new contractual relationships with the Center. The possibility to collaborate with WorldVeg on a special project is an exclusive benefit for consortium members.

The consortium membership fee is US$ 6,900 per calendar year for medium/large companies (over 100 employees) and US$ 2,900 for small/start-up companies (less than 100 employees). Each member company must commit to a one-year subscription, with annual terms running from 1 January to 31 December. These funds are invested in the Center's vegetable breeding programs and used to manage the consortium and to organize the annual workshop.

[2] Import approvals and permits are at companies cost.

[3] See https://avrdc.org/africa-vegetable-breeding-consortium/

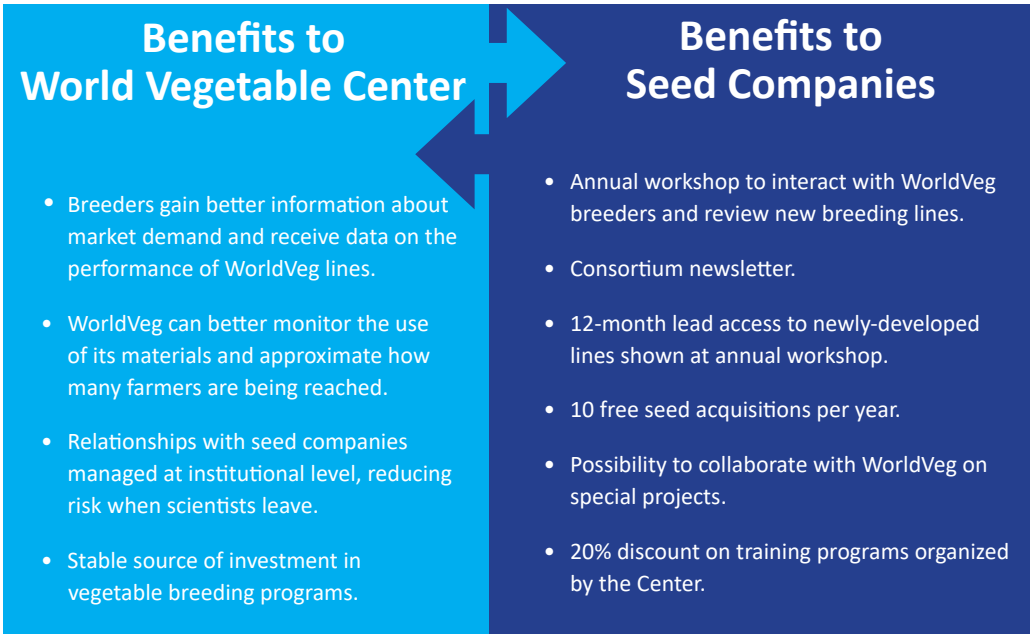

Figure 3. WorldVeg / private seed sector consortia built on mutual benefits

4.2 Africa Vegetable Breeding Consortium (AVBC)

The Africa Vegetable Breeding Consortium (AVBC) was established in 2018 as a joint initiative of WorldVeg and the African Seed Trade Association (AFSTA). AVBC membership is exclusive to AFSTA members in good standing.

WorldVeg recognizes that the challenges to seed sector development in Africa are quite different from those in Asia. Local and regional seed companies in Africa are mostly at the "informal" or "emergent" stage in Figure 2. Multinational seed companies, when present, do little to no breeding research inside Africa and restrict their activities mostly to selection trials. The market for hybrid vegetables is underdeveloped, but rapid growth of supermarkets is likely to change this as their suppliers require a constant supply of uniform products. Still, farmers in Africa are sensitive to the price of hybrid seed and need to be convinced that it increases their yield and profit. The AVBC aims to strengthen the capacity of all seed companies in Africa by providing them with varieties, inbred lines and hybrids that meet local market demand. Quality germplasm is not the only constraint in Africa and AVBC plans to work on a range of issues including capacity building, seed market development, seed laws and regulations, and knowledge transfers from Asia to Africa.

The focus of AVBC is on a broad range of vegetables of economic importance in Africa, including African eggplant, amaranth, brassicas, carrot, mungbean, onion, hot and sweet pepper, and tomato. The benefits to WorldVeg and consortium members are the same as in the APSA/WorldVeg Vegetable Breeding Consortium on which it was modeled, and consortium members receive a 12-month lead access to new breeding lines (Figure 3). Lead access is geographically restricted to Africa.

The consortium fee is US$ 6,000 for multinational companies (offices in 2 or more continents), US$ 4,000 for regional companies (offices in 2 or more countries in Africa), and US$ 2,000 for local companies (offices in only 1 country). Multinational companies operating in Africa and Asia may choose to be a member of both consortia. As of April 2019, 10 seed companies had joined AVBC (see Annex 3), including local, regional and multinational companies. Another 8 companies have showed interest to join the AVBC and are expected to sign the consortium agreement.

4.3 Taiwan Seed Industry Exchange Platform

Taiwan is the World Vegetable Center's host country. This platform was established during 2017 to strengthen ties with Taiwan seed companies and public organizations working in vegetable improvement. The platform facilitates information exchange between the Center's researchers and vegetable breeders in Taiwan and fosters special initiatives to serve the interests of Taiwanese companies. Platform membership is free and members receive regular updates and an annual newsletter, as well as invitations to events. There is a dedicated contact person at WorldVeg who can respond to any requests in Mandarin. One of the initiatives of the platform is to collaborate in regenerating WorldVeg genebank accessions, which is done using the facilities and staff of Taiwan seed companies. WorldVeg also offers services such as pest and disease identification and variety trials in Taiwan or at one of its regional locations.

4.4 International Mungbean Improvement Network (IMIN)

Mungbean research and development is mostly done by the NARS and the involvement of private seed companies is limited. WorldVeg therefore uses a tailored approach to mungbean scaling that is different from the approach used to scale commercial vegetables.

The International Mungbean Improvement Network (IMIN) was established during 2016 with funding support of the Australian Centre for International Agricultural Research (ACIAR). It is a collaboration between WorldVeg, the

Queensland Department of Agriculture and Fisheries Australia, the Pulses Research Centre of the Bangladesh Agricultural Research Institute, the Department of Agricultural Research of Myanmar, and the Indian Institute of Pulses Research under the Indian Council of Agricultural Research. The network is set to expand to include other countries in Asia and Africa.

IMIN supports partner institutions in breeding new mungbean lines expressing desirable traits for improved production locally as well as globally, by organizing access to a broad array of germplasm, and putting in place information technology support for breeding. It also builds the international network of mungbean breeders and promotes the crop to donors and investors.

This approach recognizes that past success in international mungbean breeding was achieved through the unconditional sharing of genetic resources between NARS with coordination and know-how provided by WorldVeg. For instance, the development of short-duration, high-yielding varieties resistant to mungbean yellow mosaic disease (MYMD), which is the most serious disease of mungbean in South Asia, was achieved through intensive collaboration with the NARS of Pakistan. This trait is found in about 21% of the cultivated mungbean area in South Asia and Myanmar (Schreinemachers et al., 2019).

It is possible that private seed companies could enter mungbean seed production in the future, which could improve seed supplies as farmers currently rely on the informal seed sector. This is mostly likely to happen in the sprout segment, which is of higher value than the grain and noodle segments. It is important to involve private seed companies in the IMIN and to differentiate mungbean lines and scaling strategies by market segment.

5. APPROACHES TO PILOTING AND SEED SCALING

In the context of this strategy, scaling means maximising the positive impact of WorldVeg breeding products on farmers' incomes and general well-being. It is useful to separate between *horizontal approaches* (sometimes referred to as "scaling-out"), which refer to reaching more seed producers and more farmers, and *vertical approaches* (sometimes referred to as "scaling-up"), which refers to creating the enabling environment for impact to happen and may involve work on policies and partnerships.

Maximizing and sustaining impact requires a balance between horizontal and vertical approaches. The partnership approaches described in Section 4 are the Center's most important pathways to creating impact at scale through international vegetable breeding. However, WorldVeg also uses complementary approaches to promote the adoption of improved vegetable varieties, often in partnership with seed companies or NARS. Particularly where seed systems are underdeveloped, as in most parts of Africa, there is a need to complement the transfer of germplasm to the private or public sector with farm-level promotion of quality seed of improved vegetable varieties, often in combination with good agricultural practices. The Center uses various approaches to do this and examples are provided in the following sections.

5.1 Online seed catalogue

WorldVeg distributes seed samples of (unimproved) germplasm accessions and advanced breeding lines worldwide. The Center has distributed more than 660,000 seed samples to researchers in at least 180 countries since 1973. This has led to the release of at least 188 varieties in 46 countries. Advanced breeding lines are available as global public goods (with the exception of newly developed lines under a 12-month lead access to consortia members), and these are listed in an online seed catalogue. Anyone can order seed samples using an online seed request form.

The transfer of (unimproved) germplasm from the Center's genebank is subject to the Standard Material Transfer Agreement for Germplasm Accessions (SMTA) based on the International Treaty on Plant Genetic Resources for Food and Agriculture. The transfer of improved breeding lines is subject to the Center's own Material Transfer Agreement for World Vegetable Center-developed Genetic Material (MTA2). The Center charges recipients a nominal fee for handling and seed shipment.

5.2 Multi-location testing

There is much to be gained from testing the performance of readily available vegetable varieties of seed companies and WorldVeg breeding lines, particularly in Africa. Little such research has been done and past experience of WorldVeg shows that testing can create much impact. For instance, WorldVeg tomato breeding lines originally developed for Asia were tested in Tanzania over several seasons in the mid-1990s and this research and subsequent promotion created economic gains of US$ 0.25 billion for Tanzania (Schreinemachers et al., 2017b).

More recently, initiatives such as Fair Planet Seeds and the Seeds2B project of the African Agricultural Technology Foundation show the importance of variety trials and their potential to stimulate the demand for and supply of new varieties. WorldVeg is in an ideal position to conduct such trials and is already doing this for tomato, chili pepper and amaranth in Ghana and Nigeria, supported by the UK Department for International Development (DFID). WorldVeg combines variety trials with the testing of other safe pest management methods. For these trials, the Center is using the following stepwise approach to variety testing and scaling:

- *Identify varietal needs*: The varietal needs of farmers and consumers are identified, such as desired market characteristics (e.g. shape, color, taste, shelf life) and required disease resistances.

[4] See https://avrdc.org/impact/

- *Conduct scientifically sound variety trials of about 20 varieties at a time*: Members of the AVBC were invited to contribute varieties, which were tested alongside selected WorldVeg breeding lines. The best performing entries are advanced to multi-location on-farm trials.
- *Demonstration trials of best performing varieties and practices*: The best performing varieties from the variety trials are included in demonstration trials together with good agricultural practices such staking, pruning, mulching, and raised beds to show farmers and other stakeholders elements needed for good performance.
- *Promotion of the preferred varieties*: Farmers can select one to three varieties that they prefer and experiment with these in combination with good agricultural practices on their own farms. Seed is provided for free for one year for about 500 m^2, but no other inputs or payments are made.

The data generated from this approach inform WorldVeg and seed companies, enabling them to fine-tune entries for future trials, target breeding problems, and direct their marketing.

Mini-packets (seed kits or packs) of vegetable seeds are an effective method to promote new varieties, particularly of traditional vegetables for which commercial seed supplies are limited. WorldVeg and local partners distributed over 42,000 seed mini packets to smallholder farmers in Tanzania, Kenya and Uganda from 2013-2017 (Stoilova et al., 2019). Each packet contained seed samples, usually enough to plant a home garden, of about four promising open-pollinated varieties of traditional African vegetables, tomato, capsicum and soybean.

In some countries, private companies have found that mini-packets are a profitable business opportunity. Lal Teer Ltd. in Bangladesh sold 1.3 million vegetable mini-packets in the second year after the company introduced these (Katalyst, 2015). In India, WorldVeg worked with the NGO Krishi Gram Vikas Kendra (KGVK) to produce wall posters containing mini-packets of 20 different vegetables. WorldVeg guaranteed the purchase of the mini-packets in the first years to reduce the risk for the NGO. Yet, realizing the huge market for mini-packets, the NGO staff created a business spin-off that continued to sell many thousands of seed packets (World Vegetable Center, 2016). Mini-packets also can be used for promotion. For instance, the Center distributed large quantities of mungbean seed mini-packets in northwestern India to let farmers try new mungbean varieties (Singh et al., 2007).

5.3 Seed villages

Seed villages provide hands-on training to farmers to improve seed production practices, including seed treatment, line sowing, rogueing (the removal of off-types to maintain seed purity), timely weed control, foliar spraying with fertilizers, and the use of yellow and blue sticky traps (as IPM measures). This model is particularly suitable for open-pollinated cultivars of crops with high volume and low cost seeds (e.g. mungbean, urdbean and vegetable legumes) for which the formal supply of quality seed is insufficient. For instance, WorldVeg has employed the seed village concept to scale improved varieties of mungbean and urdbean in Odisha State, India as well as for mungbean in Uzbekistan. In Odisha, a cluster was formed with 20-30 selected farmers in each seed village. The selection of the variety to be produced in a seed village was determined after conducting farmer participatory evaluation trials. Regular inspections by the project team along with local extension staff were conducted to ensure the implementation of good agricultural practices. Crop cuts were taken to determine the potential yield. In addition, feedback from the farmers on the varietal performance was recorded.

Farmers in seed villages keep sufficient seed for the next planting season and sell the rest to other farmers as "truthfully labelled seeds" (TLS), meaning that the seed meets minimum standards (e.g. purity, germination) as described on the label. The organisation that sells seed as TLS is responsible for meeting the minimum standard. In some countries like Uganda, an alternative system of "quality declared seed" (QDS) is used, meaning that the seed is produced by a registered seed producer responsible for seed quality conforming minimum standards and monitored by the government. In the production of QDS, training and support is imparted to the farmers to run the seed production as a business.

5.4 Capacity building

Improved germplasm is not always the main constraint to creating impact through international vegetable breeding research. Capacity building of private and public sector organizations can be just as important. Afari-sefa et al. (2012) point out that there are very few vegetable breeders in Africa. A growing vegetable seed sector will increase the demand for vegetable breeders, who need to be trained. WorldVeg regularly organizes training courses on particular topics such as tropical vegetable breeding, marker assisted selection, pest and disease identification and management, and genebank management. Available training courses are listed at https://

avrdc.org/join-us/research-and-training-opportunities/. The International Vegetable Training Course (IVTC), organized annually since the early 1980s in cooperation with Kasetsart University in Thailand, is an important vehicle for the Center to train early-career scientists from the public and private sectors. WorldVeg launched a new two-week IVTC course on tropical vegetable breeding during 2019 aimed at giving participants hands-on experience in tropical vegetable breeding. A similar course may be organized in Africa in the future.

5.5 Scaling through partner organizations

WorldVeg breeding products can reach smallholder farmers through projects of other organizations that use these products. For instance, the Cereal Systems Initiative for South Asia, managed by CIMMYT, promoted WorldVeg-developed mungbean varieties in Nepal, and the USAID Horticulture Innovation Lab promoted WorldVeg amaranth varieties in Eastern Africa. The Center actively promotes its breeding products to partners to increase adoption and impact.

6. MONITORING AND EVALUATION

Because the work of the World Vegetable Center is largely funded by public sector donors, it is important to demonstrate that WorldVeg breeding products reach farmers and contribute to better livelihoods. The Center uses a range of methods to monitor and evaluate its reach:

1. Internal varietal release database. The Center continuously records varietal releases, as informed by public or private sector partners, in a centralized online database. It records data on the variety name, country and year of release, name of the company or organization releasing it, pedigree information, and seed type.

2. Seed sales data from vegetable seed companies. WorldVeg consortium members are required to supply data annually about their use of WorldVeg germplasm such as the number of current varieties that contain it and the total quantity of seed sales per year.

3. Expert elicitation surveys. This method is useful to obtain nationally representative estimates of variety adoption for large geographical areas (Maredia and Reyes, 2014). The method is suitable for open-pollinated crops when farmers recycle seed rather than purchase new seed. WorldVeg studies on mungbean in

Asia and amaranth in Africa have applied this method. It is possible to repeat expert elicitation studies over 5-10 year periods to monitor trends in variety adoption. However, there are concerns about the accuracy of the estimates, as it appears that experts tend to overestimate recent varieties and underestimate older varieties (Yigezu et al., 2019).

4. Farm household surveys. Farm household surveys can be costly to administer and time-consuming to analyze, but can provide valuable information about agricultural practices, costs and returns of production, and outcome indicators such as farm income and food expenditures. Farm surveys can provide in-depth information, but are usually done in an irregular fashion and therefore are not very suitable for monitoring the adoption of vegetable varieties. There are also concerns about the accuracy of farm surveys to quantify adoption rates as farmers may not correctly identify the variety they grow (Maredia et al., 2016).

5. DNA fingerprinting. This is the most reliable method to quantify adoption rates of improved crop varieties (Floro IV et al., 2018; Kosmowski et al., 2018; Maredia et al., 2016). It requires sample collection from a nationally representative group of farmers and the use of molecular markers. WorldVeg is currently employing this method in combination with farm household surveys to quantify adoption and impact of amaranth varieties in Tanzania ("Amazing Amaranth" project funded by the Federal Ministry of Economic Cooperation and Development, Germany; 2018-2021).

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ANNEXES

Annex 1: Sample questionnaire used for the ex-ante assessment of new breeding programs

Purpose of this questionnaire

The World Vegetable Center is considering to start a new vegetable breeding program on luffa. New breeding programs mean a long-term commitment from our organization and a substantial investment of resources. To make an informed decision, we would like to ask for your feedback. World Vegetable Center does not have a marketing division that would provide us with market information and we thus rely on the feedback from seed companies, as our main direct clients and partners, to make the right decision. Your help is therefore much appreciated.

Details of the person completing the questionnaire

This information is only collected to allow us to contact you for any follow-up, if required. All information you provide will be treated as strictly confidential.

First Name:	
Last Name:	
Job title:	
E-mail:	
Company name:	
Country:	

1. Luffa

1.1 <u>Market assessment</u>

1.1.1 What countries are the main markets for luffa seed?

1.1.2 What is the estimated total size of the (formal seed) market for luffa in each of these countries?

1.1.3 What are the main luffa plant types per country?

1.1.4 What are the main luffa fruit types per country?

1.1.5 What is your assessment for market growth of luffa for the next 10 years?

☐ Expect strong growth ☐ Expect moderate growth ☐ Expect little to no growth

1.1.6 How segmented is the market for luffa by country or region?

1.2 <u>Comparative advantage of World Vegetable Center in luffa breeding</u>

1.2.1 What should be the breeding priorities (traits) for a WorldVeg luffa breeding program? Please rank, starting from the most important trait.

1.2.2 Please describe the potential impact of a WorldVeg luffa breeding program?

1.2.3 Are there any major technical challenges to overcome (e.g. special seed production issues) if WorldVeg took up luffa breeding?

1.2.4 Do you have any other recommendations for a WorldVeg luffa breeding program?

1.2.5 Are there vegetables, outside the current WorldVeg portfolio for Asia (which currently includes chili and sweet pepper, tomato, bitter gourd, pumpkin/winter squash, mungbean, vegetable soybean, and rootstocks) that deserve a higher priority than luffa breeding?

☐ Yes ☐ No

If yes, which one?

Annex 2: Glossary of selected terms

Accession

Plant material (plant, seed, or vegetative parts) collected and conserved in a genebank and usually referring to unimproved material. The WorldVeg genebank identifies accessions using a unique vegetable introduction (VI) number to maintain discrete identities during evaluation, regeneration, conservation and distribution. All WorldVeg accessions are held in the public domain.

Breeding line

Improved lines, purified accessions (inbred lines), segregating populations etc., which are developed through various breeding methods including several cycles of simple, mass, pedigree (self-pollination), recurrent (sib-pollination) selections and back-crossing. WorldVeg breeding lines are identified using four letters and four numbers (e.g. AVPP9905: AV=Asian Vegetable; PP=peppers; 99=it became available for distribution in 1999; 05=the line number).

Variety

A purified germplasm accession, improved line or hybrid, which is formally recommended and notified (released or catalogued) by a national government agency for commercial cultivation after a formal evaluation process (usually involving multi-location testing). In countries with deregulated seed laws, formal release of a vegetable variety may not be mandatory.

Open-pollinated line

A purified germplasm accession, improved inbred line or population of which the seed can be saved either through selfing (in self-pollinating crops such as tomato, eggplant, mungbean) or through controlled pollination (in cross and often cross-pollinated crops, such as amaranth, broccoli, onion, pepper) and replanted. open-pollinated lines are important for all WorldVeg target crops in most of Asia and Africa where formal seed systems are underdeveloped.

Hybrid

F1 progeny derived from two purified parental lines. Seeds from a hybrid crop can not be used for sowing a next season's crop and are an important mechanism for seed companies to protect their intellectual property.

Trait

Inherited desirable characteristic (controlled by genes) used in introgression and recombination breeding. Commonly used traits/genes developed by WorldVeg are resistance against various fungal, bacterial and viral diseases in most vegetables. Traits such as male sterility (e.g. in pepper) and gynoecism (e.g. in bitter gourd and cucumber) are important for cost-effective production of hybrid seed.

Annex 3: WorldVeg Vegetable Breeding Consortia in 2018

Africa Vegetable Breeding Consortium (AVBC):

1. Bakker Brothers Seeds, Netherlands
2. East West Seed International, Thailand
3. Meru Agro-Tours & Consultants Co. Ltd., Tanzania
4. NOVA GENETIC, France
5. Premier Seed Nigeria Limited, Nigeria
6. Rijk Zwaan Afrisem Ltd., Tanzania
7. SeedCo International Limited, Botswana
8. Simlaw Seeds Company Ltd., Kenya
9. Techniseeds Limited, Nigeria
10. Zamoho, Mali

APSA/WorldVeg Vegetable Breeding Consortium:

1. Advanta Seed (United Phosphorus Limited Group), India
2. Ankur Seeds Pvt. Ltd., India
3. Clover Seed Co., Ltd., Hong Kong
4. East-West Seed International Ltd., Thailand
5. Enza Zaden Asia Sdn Bhd, Malaysia
6. HM Clause India Pvt. Ltd., India
7. I & B Seeds Pvt. Ltd., India
8. JK Agri Genetics Ltd., India
9. Kagome & Co., Ltd., Japan
10. Kalash Seeds Pvt. Ltd., India
11. Kaveri Seed Co., Ltd., India
12. KF Bioplant Pvt. Ltd., India
13. Mahindra Agri Solutions Ltd., India
14. Metahelix Life Sciences Pvt. Ltd., India
15. Musashino Seed Co., Ltd., Japan
16. Namdhari Seeds Pvt. Ltd., India
17. Nethra Enterprises Pvt. Ltd., India
18. Noble Seeds Pvt. Ltd., India
19. Nongwoo Seed India Pvt. Ltd., India
20. Nunhems BV, Netherlands
21. PT. BISI International Tbk, Indonesia
22. PT. East West Seed Indonesia
23. Rijk Zwaan, Netherlands
24. Sakata Seed Corporation, Japan
25. Sattva Seeds Pvt. Ltd., India
26. SeedWorks International Pvt. Ltd., India
27. Sing-Flow Seed Trading Co., Ltd., Taiwan
28. Sungro Seeds Pvt. Ltd., India
29. Syngenta Asia Pacific Pte. Ltd., Singapore
30. Takii & Co., Ltd., Japan
31. Tokita Seed India Pvt. Ltd., India
32. United Genetics India Pvt. Ltd., India
33. VNR Seeds Pvt. Ltd., India

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