Demand-driven vegetable breeding for impact

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Abstract

The success of vegetable breeding programs depends not only on yield but also on the development of cultivars that align with the needs and preferences of actors across the value chain. Pest and disease resistance as well as key quality traits are critically important for ensuring the adoption of new varieties, particularly by smallholder farmers. To achieve this, vegetable breeding must be demand-driven, incorporating comprehensive feedback from users throughout the value chain. At the World Vegetable Center (WorldVeg), breeding efforts begin with strong partnerships with the private seed sector, which shares common objectives for varietal improvement. This collaboration is further validated through a systematic approach that includes experimental diagnostics of pest and disease resistance, field visits to assess performance under real farming conditions, and stakeholder engagement with farmers, nursery owners, traders, exporters, and processors. Participatory cultivar selection, particularly at the final stage before variety registration and release, is a critical component of this approach. A feedback mechanism ensures that breeding decisions are informed by end-user needs, ultimately enhancing the adoption of improved cultivars by smallholder farmers and contributing to sustainable agricultural development.

Key Points

- Pest and disease resistance, quality, and demands of the multitude of actors throughout the value chain are often more important for vegetable breeding programs than yield.
- Partnerships with the private seed sector are key for success in vegetable breeding and WorldVeg collaborates closely with seed companies to guide breeding efforts and reach farmers.
- Validation of seed company feedback includes pest and disease diagnosis, field visits, and discussions with farmers, nursery owners, traders, exporters, and processors.
- Participatory cultivar selection is essential for vegetable breeding programs, especially at the final stage before registration and release.

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The CGIAR Market Intelligence Area of Work aims to maximize the impact and return on investment of breeding programs by integrating market insights, behavioral intelligence, and strategic prioritization. It identifies high-impact opportunities, guides product development, and enhances product adoption and lifecycle management through decision-support tools.

Introduction

To successfully develop and release cultivars that will be adopted by farmers, a breeding program must be demand-driven and consider the needs of all participants throughout the value chain, including producers, traders and retailers, processors, exporters, and consumers. This is especially true for vegetables because users often have strict and diverse requirements that might vary between locations within a country. Vegetable breeding programs are more impactful if aligned with the preferences of value chain actors, thereby contributing to sustainable agriculture, food security, and economic development (Ojiewo et al. 2010; Keatinge et al. 2018).

In a vegetable breeding program, considering farmer-preferred traits is essential for developing cultivars that meet the needs and preferences of farmers. Traits that farmers prefer directly impact the productivity, profitability, and sustainability of farming operations. By prioritizing farmer-preferred traits in vegetable breeding programs, breeders can develop cultivars that address farmers' specific challenges and priorities, ultimately contributing to increased productivity, profitability, and sustainability in agriculture. Some important examples of farmer-preferred traits are crop yield, yield stability across seasons and environments, resistance to locally important pests and diseases, tolerance of abiotic stresses, adaptability to local production conditions and systems, maturity duration (either short or long depending on the crop), and uniformity and consistency.

Processors, such as chili sauce and tomato paste producers, have specific requirements regarding their raw materials. Vegetable breeding programs benefit processors by providing raw materials that meet their requirements for processing efficiency, product consistency, storage stability, sensory appeal, and nutritional value (Schreinemachers et al. 2018). By collaborating with breeders to develop tailored vegetable cultivars, processors can enhance their production processes, optimize product quality, and meet consumer demand for high-quality processed vegetable products.

Similar to processors, certain traits are important for traders, retailers, and exporters, such as shelf-life, drying quality, color retention, packaging compatibility, resistance to postharvest diseases, tolerance of bruising and blemishing, adaptability to transportation, and compliance with consumer preferences (Michalczuk 1997). Exporters consider market preferences, trends, and consumer preferences in destination countries when selecting vegetable cultivars for export. Understanding market demand for specific types, sizes, shapes, colors, and packaging formats helps optimize export strategies and maximize sales opportunities.

Quality traits are crucial in vegetable breeding programs as they influence consumer preferences, purchasing decisions, and overall satisfaction (Singh et al. 2020; Behera et al. 2023). Flavor is one of the most critical traits for consumers (Brückner, 2008). Texture and firmness refer to the mouthfeel or physical sensation experienced when consuming a vegetable. Vibrant and appealing colors attract consumers and signify freshness and ripeness. Uniformity in color and absence of discoloration are also important (Oltman et al. 2014; Blahovec 2001). Visual appearance plays a significant role in consumer perception of vegetable quality. Consumers prefer visually appealing vegetables with uniform size, shape, and surface smoothness. The absence of blemishes, bruises, and signs of damage enhances visual appeal. By prioritizing these traits in vegetable breeding and production, farmers, retailers, and marketers can meet consumer preferences and expectations, thus driving demand for high-quality, flavorful, and nutritious vegetables (Tran et al. 2024; Gao et al. 2022).

Nearly all vegetables are highly perishable and require well-coordinated action along the value chain to minimize losses. It is therefore essential to consider the preferences of value chain actors involved in the transportation and storage of vegetables (Figure 1). This brief aims to outline and highlight a successful strategy for developing varieties that address the challenges facing all actors in the value chain, which can be referenced for other crops and systems.

A demand-driven breeding strategy

Demand-driven breeding entails a comprehensive series of steps, starting with a thorough assessment of needs and market dynamics. This begins with a meticulous examination by stakeholders, ranging from farmers and consumers to processors, distributors, and representatives from the public and private seed sectors. Through a combination of surveys, focus groups, and interviews, their preferences, requirements, and challenges are analyzed. Simultaneously, extensive market research is conducted to discern prevailing trends, consumer preferences, nutritional demands, and emerging opportunities within the agricultural landscape.

Figure 1. Diversity of requirements for cultivars by actors along vegetable value chains.

Following this foundational phase, the process moves on to the identification and prioritization of target traits that are either in high demand or possess the potential to confer significant market advantages. These traits encompass a broad spectrum, ranging from yield and disease resistance to attributes such as pest resistance, shelf-life, nutritional quality, flavor, appearance, and suitability for various culinary or processing purposes. This phase serves as a pivotal juncture at which the outcomes of the needs assessment are translated into tangible breeding objectives.

The subsequent stage involves the meticulous evaluation and selection of germplasm, drawing from a diverse array of genetic resources, including both breeding lines and wild relatives. Through rigorous screening techniques, field trials, and laboratory analyses, promising candidates exhibiting the desired traits are identified. This process not only serves to broaden the genetic base but also facilitates the introduction of novel traits into breeding populations, thereby enriching the overall genetic diversity and adaptability of the resultant cultivars.

With the foundational groundwork laid, the breeding strategy is developed, tailored to address the identified target traits and align with prevailing market demand. Modern breeding techniques such as marker-assisted selection and genomic selection are seamlessly integrated into this process, serving to expedite the breeding timeline while enhancing precision and efficacy. Moreover, participatory breeding approaches are embraced to foster stakeholder engagement throughout the breeding continuum, thereby ensuring that the resultant cultivars resonate with end-users and stakeholders alike.

The subsequent phases encompass crossbreeding and population development, through which selected parental lines are strategically crossed to engender diverse populations harboring combinations of desirable traits. Through recurrent selection, hybridization, backcrossing, and other advanced breeding methods, efforts are made to enhance trait expression and genetic stability within the breeding populations. Multilocation field trials are then conducted under representative environmental conditions to rigorously evaluate the performance of breeding populations and advanced lines across diverse agroecosystems.

Stakeholder engagement remains a cornerstone throughout this iterative process, with farmers, processors, distributors, and consumers actively involved in on-farm trials, taste tests, and surveys to provide invaluable feedback on cultivar performance and acceptability. This stakeholder input serves as a crucial determinant in guiding breeding decisions, prioritization, and varietal selection, ensuring that the resultant cultivars resonate with end-user preferences and market demand.

Upon the successful culmination of the breeding cycle, superior cultivars embodying the desired traits are released as new commercial cultivars. Collaborative efforts with seed companies, agricultural extension services, and other pertinent stakeholders facilitate the widespread dissemination and adoption of these improved cultivars among farmers. Technical support, training, and marketing assistance are provided to empower farmers with the requisite knowledge and resources to seamlessly integrate these novel cultivars into their agricultural practices.

The journey, however, does not conclude with a cultivar release; rather, it extends into the realms of monitoring and impact assessment. Ongoing monitoring endeavors to track the adoption and performance of released cultivars in real-world agricultural settings, while impact assessments seek to quantify the economic, social, and environmental benefits conferred by these improved cultivars upon stakeholders and the broader food system.

In this dynamic continuum, the ethos of continuous improvement and iteration reigns supreme. Market dynamics, consumer preferences, and emerging challenges are continuously reassessed to refine breeding priorities and strategies. Advancements in breeding technologies, genetic resources, and scientific knowledge are seamlessly incorporated to bolster the efficacy, efficiency, and resilience of the breeding program, thereby ensuring its relevance and impact in the ever-evolving agricultural landscape.

Engaging the right stakeholders

To guide demand-driven breeding programs, information-gathering is essential. It is challenging to be able to obtain information on the needs and demands of the various stakeholders throughout the value chain, especially across a wide geography. More difficult is ensuring that the right information is obtained in a systematic way.

The vegetable seed sector differs significantly from that of most staple crops, as it is primarily driven by private-sector innovation rather than national agricultural research and extension systems (NARES). Historically, in the 1960s, NARES in Asia and Africa focused on staple crops and neglected vegetables because of the priority of ensuring adequate calories and protein. Private-sector involvement was limited due to regulatory barriers and doubts about smallholder farmers' willingness to pay for quality seed. Companies in Asia and Africa mainly imported exotic-origin seeds, sometimes lacking suitability for local markets, and focused on multiplying landrace cultivars without breeding. In the late 1980s and early 1990s, market liberalization led to private-sector entry, particularly in Asia, although Africa's sector lagged, with limited hybrid seed production and research investment. This resulted in heavy reliance on imported seeds and limited competition (Schreinemachers et al. 2021). As of 2018, the global vegetable seed market was valued at USD 6.2 billion, with USD 930 million invested annually in research and development. In India, the second largest vegetable market, approximately 85% of vegetable seed grown by farmers is sourced from the private seed sector (Ram, 2019).

To enhance private-sector engagement, WorldVeg established two consortia: the Asia and Pacific Seed Association (APSA)-World Vegetable Center Breeding Consortium in 2017 and the Africa Vegetable Breeding Consortium (AVBC) in 2018. These consortia are public-private partnerships aimed at maximizing the impact of WorldVeg's vegetable breeding programs. By fostering collaboration between public research institutions and private companies, these consortia facilitate the development and dissemination of improved vegetable cultivars tailored to local market needs.

As for-profit companies, seed companies must deliver products (seed) that will be bought by farmers. Therefore, the private seed sector has an excellent understanding of farmer demands, but also of processor, trader, exporter, and consumer demands. By doing so, they can support the profitability of actors in the vegetable value chain and the satisfaction of consumers, which allows the seed companies to be profitable. WorldVeg researchers conduct annual surveys to systematically gather insights and feedback from private seed companies. This ongoing dialogue ensures that the breeding programs remain responsive to the evolving needs and preferences of farmers, seed companies, and other actors in the vegetable value chain. This proactive approach helps to guide research priorities, refine breeding strategies, and, ultimately, enhance the adoption and impact of improved vegetable cultivars (Figures 2 and 3).

These consortia serve as a pivotal platform for facilitating meaningful interactions between WorldVeg breeders and representatives from seed companies. Through annual workshops and direct engagement opportunities, private company breeders gain valuable insights into the latest genetic offerings from WorldVeg and engage in one-on-one discussions with WorldVeg breeders to address specific challenges within their breeding programs.

This collaborative exchange enables seed company breeders to articulate their unique difficulties and requirements, fostering a bespoke, à la carte selection approach to genetic solutions. By leveraging this intimate understanding of market demands and breeding challenges, WorldVeg breeders can propose tailored genetic solutions that directly address the specific needs of seed companies. This personalized approach, grounded in close collaboration and ongoing support, is instrumental in driving the success of the adoption of WorldVeg genetics.

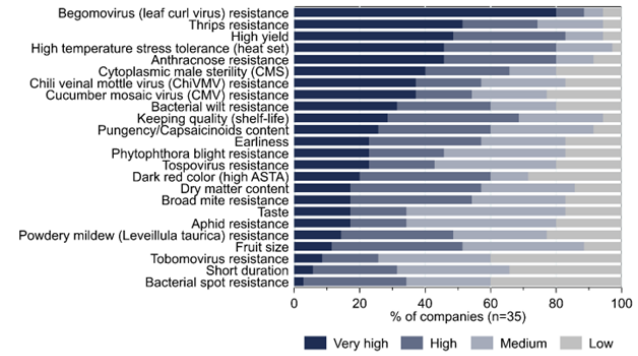

Figure 2. Breeding priorities for peppers as identified by seed companies operating in Asia. Source: Schreinemachers and Lin (2023).

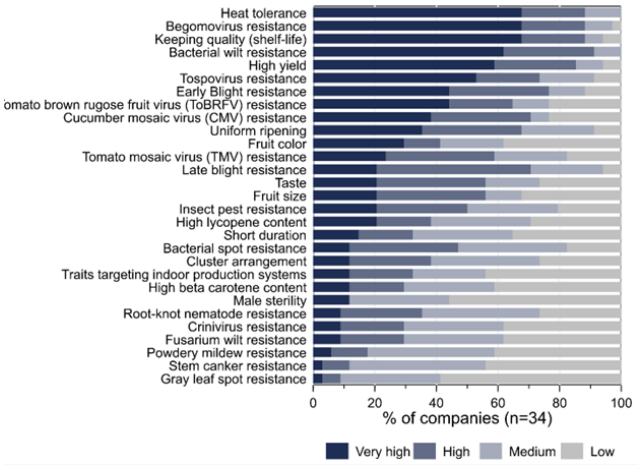

Figure 3. Breeding priorities for tomatoes in 2021 as identified by seed companies operating in Asia. Source: Schreinemachers and Lin (2023).

Validation

Stakeholder engagement and survey responses from key actors in the seed value chain are often insufficient. For example, a company operating in West Africa and providing a significant proportion of seed grown by farmers might not have the most accurate or up-to-date information regarding the problems facing farmers. Therefore, it is essential that we not only collect information from stakeholders but also validate these data through various truthing exercises, outlined below.

Disease surveys

Disease surveys play a crucial role in demand-led breeding efforts by providing invaluable insights into the prevailing conditions and challenges related to diseases encountered by farmers. Within stakeholder meetings, farmers often highlight numerous insights about vegetable diseases. However, identifying the exact disease remains challenging, as symptoms alone might not be enough for accurate diagnosis in the field. It is therefore important to conduct a vegetable disease survey and diagnosis to clearly identify the disease encountered by the farmers. Conducting a vegetable disease survey allows vegetable breeders to gain a comprehensive understanding of the current situation regarding diseases affecting crops in specific regions or across different agroecological zones. This includes identifying the types of diseases present and their prevalence, distribution patterns, and severity. Through surveys, breeders can identify the key disease resistance traits needed in vegetable cultivar development, help prioritize breeding objectives, and focus efforts on developing cultivars with improved resistance to the most damaging pathogens. One such example is an annual virus survey conducted by WorldVeg in Benin, where two viruses, CMV (cucumber mosaic virus; Cucumovirus) and PVMV (pepper veinal mottle virus; Potyvirus), have been commonly identified to cause significant losses in farmers' fields (Zohoungbogbo et al. 2022; 2024). Nonetheless, host resistance to these viruses has not been reported as a target trait for any of the private-sector partners operating in the region.

On-farm validation and discussions with farmers and nursery owners

Often, resources are not available to conduct extensive and systematic disease diagnostic studies. However, important information can be obtained through discussions with farmers and nursery owners operating in the target region, and through in-person observations in farmers' fields. This is especially powerful as a validation of a survey from private-sector seed companies. WorldVeg and our partners routinely visit farmers and nursery owners in the major production regions for our crops, discuss the major challenges facing the farmers, and learn about the management efforts being undertaken to limit losses. In addition, we visit farmers' fields and the major nurseries that provide transplants to farmers and conduct observational disease diagnostics, with support from plant pathologists. Nursery operators are particularly good sources of information because farmers often discuss the challenges they face with nursery providers in hopes of obtaining cultivars with resistance. Therefore, a conversation with a nursery operator can be a highly efficient source of synthesized information regarding the challenges faced by farmers in a particular region.

Visits to markets to view market segmentation changes

Changes in consumer or other user preferences are a strong influencer of market segmentation changes in vegetable crops. In addition to discussions with and surveys from private seed companies, visits to the major markets are a strategic activity to gain an insight into a market's dynamics and future trends. These changes can be observed through various market indicators, such as product turnover rates on shelves and price differentials across different product types. For instance, products that quickly sell out compared with others can indicate strong consumer demand, while price variations based on factors such as shape and color provide valuable insights into consumer preferences, particularly in lower-segment markets. By closely monitoring these market dynamics, breeders and stakeholders can adapt their strategies to meet the evolving demands of consumers effectively.

A vegetable market in Sri Lanka displays the diversity of different market segments of chili and habanero peppers

Stakeholder engagement and participatory selection: validation workshops

Stakeholder workshops are instrumental in promoting stakeholder engagement, knowledge exchange, strategic planning, and collaboration within breeding programs. By harnessing the collective expertise and perspectives of diverse stakeholders, workshops help to ensure that breeding efforts are targeted, relevant, and responsive to the needs of end-users, ultimately contributing to the development of improved crop cultivars that address real-world challenges and opportunities. Recently, the WorldVeg tomato and pepper breeding programs held stakeholder workshops in Benin and Tanzania to validate identified market segments and target product profiles. This exercise is extremely important to ensure that the breeding program's goals align with the needs of the farmers by addressing the important segments and ensuring that the product profile covers all the traits needed for sustainable production. Having a strong understanding of market segmentation and developing sound product profiles allows breeders to better develop breeding pipelines in a more efficient manner, and ultimately develop cultivars that benefit farmers.

Participatory selection

Participatory selection in a vegetable breeding program involves actively involving farmers, consumers, and other stakeholders in the process of selecting and developing new vegetable cultivars (Dhillon et al. 2020). Most of the WorldVeg breeding programs have a global reach, but at the same time are typically based in a single location, with regional operations. As such, most of the participatory selection that occurs in our breeding program is of finished lines. However, some selection occurs throughout the breeding program, from NARES and private-sector partners. Participatory selection in vegetable breeding programs offers numerous benefits that contribute to improved agricultural productivity, food security, and sustainability. By engaging stakeholders throughout the breeding process, breeders can develop cultivars that better meet the diverse needs and priorities of farmers and consumers, ultimately leading to more resilient and sustainable food systems.

Participatory selection of chili and habanero peppers in Kumasi, Ghana

Meeting with traders, collectors, and processors

Because vegetable farmers in the global South are typically smallholders with, on average, about 0.2 ha of production, it is quite common for middlemen to operate in the major vegetable production regions. The first level is what are known as collectors, who work with many smallholder farmers in an area and compile the produce from all the farmers to be sold to the next tier, the trader. Traders frequently operate at the wholesale level and can either focus on export-oriented trading or the domestic or regional level. Traders collect the produce from several collectors operating in a given area and market it wholesale to retailers or processors. The traders, collectors, and processors serve as a valuable source of information because they are actively involved in moving produce from farmers to end-users. Therefore, they are acutely aware of changes in market segmentation and consumer demand.

Habanero peppers in the market in Arusha, Tanzania, which provides insights to breeders on consumer preferences and how the crop is marketed.

Cold-storage facilities in Guntur, Andhra Pradesh, India, where chilies are stored for up to one year for the domestic market.

(a)

(b)

Examples of a collector's operations with snake gourd in Sri Lanka (a) and chilies in Viet Nam (b)

Conclusion

Making an impact in vegetable breeding requires extensive efforts to be demand-driven. Numerous factors are involved in the vegetable value chain and, unlike for other crops, consumers purchase the vegetables directly, not as a processed meal or flour. Therefore, consumer preferences are critically important to consider when conducting a sound breeding program. In addition, farmers, marketers, processors, and other stakeholders have different requirements for the produce. A sound, efficient, and effective 360 feedback system is required to ensure that all demands are met in a breeding program. The private seed sector has an outstanding understanding of these various demands, and these are best evaluated through consortia for priority setting. In addition, validation and truthing efforts must be made to not only guide breeding programs but also to help in predicting the future needs and demands of the actors in the value chain.

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