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RESEARCH ARTICLE

The contribution of international vegetable breeding to private seed companies in India

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Abstract Crop breeding research by international agricultural research centers usually serves public sector crop breeding, but does it still have a role when research and development have shifted to the private sector? This paper explores this question for vegetables in India using data from 27 private companies and 9 public organizations. We focus on tomato (*Solanum lycopersicum* L.) and chili pepper (*Capsicum annuum* L.)—two of India's most important vegetables, and the role of international germplasm received from the World Vegetable Center. Results show that as the role of the private sector in vegetable breeding increased, and with it the share of hybrids in the market, the role of international agricultural research shifted from the provision of ready-made varieties to the provision of specific resistance traits. Still, international germplasm continued to be used in varietal development with 11.6 t (14 % of the total market) of hybrid tomato seed and 15.0 t (13 %) of hybrid chili pepper seed sold in 2014 containing international germplasm in its pedigree. We estimate that over half a million farmers use such seed. We conclude that for tomato and chili pepper, international breeding needs to focus on pre-breeding research, capacity strengthening of smaller seed companies, and the delivery of open-pollinated varieties for marginal environments.

Keywords Crop breeding · Resistance breeding · Seed policy · World Vegetable Center

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Introduction

A good crop starts with good seed. 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 importance of good seed for smallholder farm incomes and food security is increasingly well understood (Access to Seeds Foundation 2016). The importance of international crop breeding research in supplying improved open-pollinated breeding lines to national agricultural research systems (NARS) in developing countries is also

widely recognized (Morris 2002; Lantican et al. 2005; Thiele et al. 2006; Brennan and Malabayabas 2011). Much less understood is the role of international research in supplying breeding material to private companies, especially in vegetables. This is a relevant line of inquiry, because after a wave of seed sector reforms in developing countries in the 1990s, the private seed sector is flourishing in many parts of the world (Access to Seeds Foundation 2016).

One might argue that where private companies dominate breeding research and seed production, international crop breeding is no longer as important because the investment by private companies in research and development dwarfs that of international agricultural research centers. This paper therefore explores the contribution of crop breeding research by international agricultural research centers to crops dominated by the private sector. We use the case of vegetables in India and focus on tomato (*Solanum lycopersicum* L.) and chili pepper (*Capsicum annuum* L.), two of the country's most important vegetables. These are also crops in which hybrid seed production has had a large impact, thus attracting much private sector investment.

In India, before seed sector liberalization in 1988, crop breeding research was primarily done by the institutes of the Indian Council of Agricultural Research (ICAR), such as the Indian Agricultural Research Institute (IARI), and state agricultural universities. Formal seed production was done by the National Seeds Corporation, state seed corporations, and a handful of private companies. Informal seed production of open-pollinated varieties by farmers, farmer associations and local companies was the main source of seed supply. Seed sector reform allowed unrestricted import of vegetable seed (subject to tariffs and phytosanitary regulations) and allowed foreign and large domestic companies to enter seed production (Pray et al. 2001).

The reform led to rapid expansion of private seed production for crops in which hybrid seed production was possible, such as cotton, pearl millet, sorghum, maize and many vegetables (Morris et al. 1998; Pray et al. 2001; Kolady et al. 2012), and slower but steady growth in private seed production of other crops such as rice and wheat (Tripp and Pal 2001; Matuschke et al. 2007; Spielman et al. 2013). For vegetables, the reform led to rapid growth in private sector research and development (R&D) and a parallel demise in the importance of national and state seed corporations. Intellectual property rights protection for new plant varieties, introduced in 2001, further boosted private crop breeding research (Kolady et al. 2012). Currently there are about 850 seed companies (mostly seed producers) operating in India in 2014, of which about 50 have capacity in crop breeding research (Reddy et al. 2014).

The World Vegetable Center is the only nonprofit international agricultural research center with a worldwide mandate for vegetable research and development. The Center's genebank contains more than 8300 accessions each of tomato and pepper (Schreinemachers et al. 2014; Ebert and Chou 2015). Its breeding programs focus on the development of improved open-pollinated vegetable lines suitable for tropical and subtropical conditions. Genebank accessions are made available through standard material transfer agreements (SMTAs) while improved breeding lines are made available through material transfer agreements (MTAs) as public goods for global use. Over 22 thousand seed samples of tomato and over 33 thousand seed samples of pepper were supplied to institutions 138 countries from 2001 to 2013 (Ebert and Chou 2015; Reddy et al. 2015). For both species, 80 % of the seed shipments were improved breeding lines and 20 % were germplasm accessions (Ebert and Chou 2015; Reddy et al. 2015). India has been the main recipient, receiving 16 % of all pepper samples distributed worldwide (Reddy et al. 2015). Lin et al. (2013) mentioned that private companies received 64 % of the seed samples sent to India. The World Vegetable Center's tomato and pepper breeding programs are located in Taiwan and seed shipments to India are channeled through the Center's genebank and the National Bureau of Plant Genetic Resources (NBPGR), New Delhi. Local breeding programs use these samples as parent material in their own crop improvement programs. The adoption of varieties by farmers is therefore the result of a collaborative effort between international agricultural research, national agricultural systems, and seed companies.

Materials and methods

The main data for this study come from a survey of vegetable seed producers in India. We constructed a list of all seed companies and public sector

organizations involved in tomato and pepper breeding and seed production by combining own contacts with information from the Asia and Pacific Seed Association and seed catalogues. The list was gradually refined after visiting each company and asking what other companies and institutions were involved in breeding research on these crops. The final list had 27 private companies and 9 public sector organizations.

Quantitative data were collected using a structured questionnaire survey eliciting information on seed sales of tomato and pepper varieties released since 1988 and for which sales were at least 0.2 t/year. Data were collected from November 2014 to May 2015. The basic method of data collection is similar to that of previous studies (e.g. Morris 2002; Thiele et al. 2006). However, data collection from private companies is much more difficult than from public sector organizations because companies consider their sales data confidential. Each seed producer was therefore visited in person to explain the purpose of the study and to ensure data confidentiality. The data collection required careful persuasion and follow-up.

For each variety, companies were asked if: (1) it is an unmodified World Vegetable Center line; (2) it is a cross of two World Vegetable Center lines; (3) one of the parents is a World Vegetable Center line; (4) some World Vegetable Center material is in the pedigree, but more distant than a parent; or (5) it is a variety unrelated to the World Vegetable Center. We also asked the year the variety had been introduced and the amount of seed produced per year from 2012 to 2014. If the Center's material had been used to develop a new variety, then we asked which traits had been incorporated. From these data we estimated the number of released varieties, the quantity of seed containing genetic material from international vegetable breeding, and the amount containing specific traits. Personal visits were also used to ask in-depth questions about the role of public international germplasm and alternative sources of germplasm.

Nearly all seed producers provided data on their total volume of seed sales (Table 1). Twenty tomato and 17 chili pepper seed producers provided disaggregated seed sales data showing the volume of seed sales that did and did not contain World Vegetable Center germplasm. This included six seed companies that provided variety-specific sales data for tomato derived from World Vegetable Center germplasm, but not for other varieties. Detailed disaggregated sales data for all varieties were provided by 6 tomato and 8 chili pepper producers. Jointly, these companies accounted for about a third of the total hybrid seed market. In the analysis we assumed that seed producers who did not provide data on the volume of seed sales containing World Vegetable Center germplasm did not use the germplasm.

Results

Varieties containing international germplasm

Of the 27 private seed companies that provided data, 9 had global operations (working on several continents), 13 had regional operations across South Asia, and 5 had operations mainly in India. Most private companies were relatively young, with 58 % founded after 1988 and 38 % founded after 2000. The nine public sector seed producers included 2 seed corporations and 7 research organizations. These research organizations were not considered commercial seed producers as they develop new varieties and then license them to other seed producers. The names of all participating companies and organizations are listed in the Appendix.

Most of the commercial seed producers said they had received World Vegetable Center germplasm at some time in their history: 93 % had received pepper germplasm and 85 % had received tomato germplasm. This shows that seed producers were well aware of the Center as a source of germplasm. Other frequently mentioned sources of germplasm included universities in India, the National Bureau of Plant Genetic Resources, the Indian Institute of Horticultural Research, United States universities (University of California, Davis; University of Florida; Cornell University), the United States Department of Agriculture (USDA), own field collections of landraces, and commercially available varieties.

In the period 1988–2014, the surveyed companies sold seed (in amounts >0.2 t/year at the peak) of 216 tomato and 209 chili pepper varieties (Table 2). Of these, 68 tomato varieties (31 %) and 45 chili pepper varieties (22 %) contained the Center's germplasm.

For a subset of 39 tomato and 37 chili pepper varieties containing World Vegetable Center material we know the year of introduction. Plotting the cumulative number of varieties containing such material against time shows that the Center's germplasm has

Table 1 Level of participation in the study by private and public seed producers in India, 2014

	Tomato		Chili pepper	
	Private companies	Public sector	Private companies	Public sector
Seed producers approached for the study	27	8	26	8
Of which provided data on				
Total volume of seed sales	25	8	24	8
Seed sales volume containing World Vegetable Center material	12	8	9	8
Seed sales disaggregated by varieties[a]	6	0	8	0
Total market share of those companies providing seed sales by variety (%)[b]	28.5	0	37.7	0

[a] Six more private companies provided variety-specific sales data for those varieties that contained World Vegetable Center germplasm, but not for other varieties

[b] In % of the total market size by volume

Table 2 Number of commercial tomato and chili pepper varieties produced by 36 seed producers in India in 1988–2014 and the role of World Vegetable Center germplasm in these

	Tomato			Chili pepper		
	All seed producers	Private companies	Public sector	All seed producers	Private companies	Public sector
Varieties commercialized	216	187	29	209	187	22
Of which						
With World Vegetable Center material	68	61	7	45	39	6
Without World Vegetable Center material	148	126	22	164	148	16

continued to be incorporated in commercial tomato and chili pepper varieties since 1995, all of which were hybrids (Fig. 1).

Furthermore, for a subset of 136 tomato and 110 chili pepper varieties we have more detailed data on the extent to which they harbor the Center's material in their pedigree (Table 3). The data show that until 1995, when the private seed sector started to develop, nearly half of these tomato varieties were unmodified World Vegetable Center lines, but after 1995 the Center's material was more commonly used as a parent or as a source of specific traits. Also for chili pepper after 1995, the Center's material was mostly used as either a parent or as a source of specific traits.

Traits used and traits prioritized

As private seed companies in India currently tend to use World Vegetable Center material as a source of plant traits rather than as a source of ready-made varieties, it is important to understand which traits were used, and which traits they currently prioritize in their breeding programs.

For 59 tomato and 37 chili pepper varieties with the Center's germplasm in their pedigree, private seed companies disclosed which traits were used. For tomato varieties, bacterial wilt resistance, tomato yellow leaf curl virus (TYLCV) resistance, and early blight resistance were the three most frequently used traits (Table 4). About 7 % of the hybrid tomato seed sales of private companies in 2014 had the first two traits, while 5 % had early blight resistance. Almost half of the seed companies used World Vegetable Center material as a source of TYLCV resistance in one or more of their varieties currently sold, and one-third of the companies used the Center's material as a source of bacterial wilt resistance. Seventy percent of the private seed companies also mentioned these two resistance traits as a priority in their ongoing tomato breeding programs, while another 55 % percent

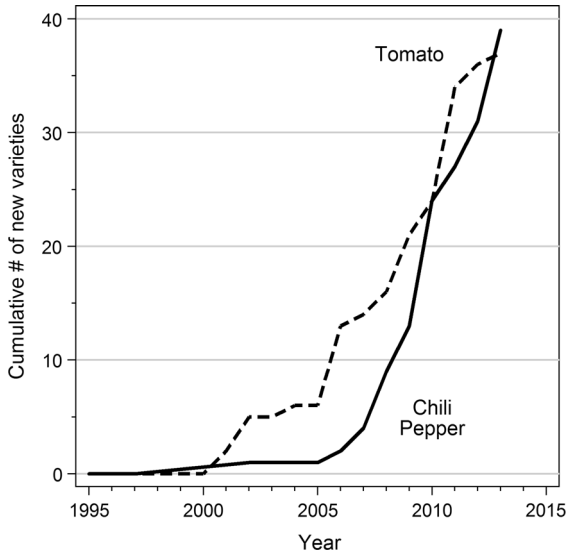

Fig. 1 Cumulative number of new hybrid varieties of tomato and chili pepper with World Vegetable Center material in their pedigree, by private seed companies in India, 1995–2013

mentioned early blight resistance. Another widely used trait was root-knot nematode resistance. The Center's developed traits such as high lycopene, color, taste, short maturity, heat tolerance, and long shelf-life were not, or not knowingly, incorporated into commercial tomato seed. Heat tolerance, early blight resistance, high yield, and long shelf-life were also frequently mentioned as priority traits for tomato breeding, but only one seed company mentioned taste and nutritional value as a priority.

For chili pepper, the most widely used World Vegetable Center traits were cytoplasmic male sterility (CMS) and high yield, incorporated in 4 and 5 % of hybrid seed sales of private seed companies, respectively (Table 5). The CMS trait is important for cost effective hybrid seed production as it permits commercial hybridization without manual emasculation, thereby reducing the cost of hybrid seed production by 40 % compared to manual emasculation (Lin et al. 2013). However, CMS ranked low as a priority for future breeding. Unlike breeding for pest and disease resistance, which is a continuous effort as pathogens overcome resistance, CMS is a one-time technological breakthrough—though stepwise improvements in the technology are possible. Anthracnose resistance and virus resistance were given the highest priority in chili pepper breeding, mentioned by 80 % of the seed companies. Among the virus resistance traits, *Cucumber mosaic virus* (CMV) resistance and *Chili veinal mottle virus* (ChiVMV) resistance were the most important traits. High fruit yield was also regularly mentioned as a priority. The Center's pepper germplasm has been widely used by Indian pepper researchers for several other strategic and applied research purposes (Reddy et al. 2015).

Role of international germplasm in current seed sales

Current (2014) tomato seed sales of the surveyed seed producers were estimated to be 91.5 t (Table 6). Of this, 85 t are hybrids and 6.5 t are open-pollinated varieties produced by public sector institutions. Our data capture nearly 100 % of the hybrid seed market, as several company executives estimated the total hybrid tomato seed market at 80–90 t/year. However, the total market for open-pollinated varieties is much larger because most of it is produced in the unregulated market by farmers and small local producers. For the hybrid seed market, 11.6 t was estimated to

Table 3 Commercial tomato and chili pepper varieties produced by 28 private seed companies in India from 1988 to 2014, and the contribution of World Vegetable Center germplasm

	Tomato		Chili pepper	
	≤1995	>1995	≤1995	>1995
Unique varieties commercialized	37	99	12	98
Of which (% of varieties)				
Unmodified World Vegetable Center lines	48.6	0.0	0.0	0.0
Cross of two World Vegetable Center lines	2.7	1.0	0.0	1.0
One parent is a World Vegetable Center line	2.7	24.2	0.0	25.5
Some World Vegetable Center material, but more distant than a parent	0.0	14.1	0.0	11.2
Variety unrelated to the World Vegetable Center	45.9	60.6	100.0	62.2

Table 4 Use of World Vegetable Center-developed plant and fruit traits in tomato hybrid seed production by private seed companies in India, 2014

Traits (causal agent of disease)	Varieties containing the trait	Seed sales containing the trait (t)	Companies using the trait in any of their varieties (%)	Priority trait in breeding (% of companies)
Bacterial wilt (*Ralstonia solanacearum*) resistance	21	5.9	29	70
Fusarium wilt (*Fusarium oxysporum* f. sp. *lycopersici*) resistance	2	–	5	10
Gray leaf spot (*Stemphylium solani*) resistance	–	–	–	–
Late blight (*Phytophthora infestans*) resistance	1	0.3	5	40
Tomato mosaic virus (TMV) resistance	5	0.7	14	15
Tomato yellow leaf curl virus (TYLCV) resistance	40	5.6	48	70
High lycopene/beta-carotene content	–	–	–	5
Heat tolerance	2	–	–	55
Early blight (*Alternaria solani*) resistance	8	4.3	14	55
Root-knot nematode (*Meloidogyne* spp.) resistance	2	2.8	5	25
High yield	12	–	5	50
Short duration	5	0.1	5	25
Color or size	20	1.0	10	25
Taste	8	–	–	5
Long shelf-life	9	–	–	45

Columns 2–4 are based on the response of 11 private seed companies that used World Vegetable Center germplasm in some of their varieties. Column 5 is based on the response of 20 private seed companies

contain World Vegetable Center-developed germplasm—a market share of 14 %.

As for chili pepper, our data suggest that the total market size was 125.1 t of seed in 2014, of which 120 t was hybrid seed. Again, this captures about the entire hybrid seed market, which company executives estimated to be 110–125 t. World Vegetable Center germplasm was found in 15.0 t of hybrid seed, which accounted for 13 % of the hybrid pepper seed market. Global and regional private seed companies dominate the Indian hybrid seed market, controlling 92 % of estimated volume of seed sales for tomato and 91 % for chili pepper (Fig. 2). Global companies made little use of World Vegetable Center germplasm, which was found in only 1 % of their tomato and 4 % of their chili pepper sales by volume. The Center's germplasm made the largest absolute contribution to regional companies where it was incorporated in 19 % of tomato seed sales and 16 % of the chili pepper seed sales. Yet, in relative terms, the Center's germplasm was the most important to public sector institutions, as 38 % of public sector hybrid tomato seed and 72 % of public sector chili pepper seed contained its germplasm (see also Table 6).

Farm-level adoption

Over the last two decades, many open-pollinated tomato and chili pepper varieties that were popular with farmers and had been developed by public

Table 5 Use of World Vegetable Center-developed plant and fruit traits in chili pepper hybrid seed production by private seed companies in India, 2014

Traits (causal agent)	Varieties containing the trait	Seed sales containing the trait (tons)	Companies using the trait in any of their varieties (%)	Priority trait in breeding (% of companies)
Anthracnose (*Colletotrichum* spp.) resistance	1	–	11	80
Aphid (*Myzus persicae*) resistance	3	0.7	11	10
Bacterial wilt (*Ralstonia solanacearum*) resistance	3	1.4	16	10
Chili veinal mottle virus (ChiVMV) resistance	3	0.6	11	30
Cucumber mosaic virus (CMV) resistance	1	0.1	5	45
Cytoplasmic male sterility	13	5.2	5	15
Phytophthora blight (*Phytophthora capsici*) resistance	1	0.3	5	–
Potato virus Y (PVY) resistance	2	0.5	26	15
High yield	14	5.6	32	40
Short duration	1	–	5	25
Color or size	3	0.7	11	35
Taste	3	0.3	11	5
Long shelf-life	1	0.9	5	15

Columns 2–4 are based on the response of 8 private seed companies that used World Vegetable Center germplasm in some of their varieties. Column 5 is based on the response of 20 private seed companies

Table 6 Seed sales of commercial tomato and chili pepper varieties produced by 28 seed producers in India in 2014 and the role of World Vegetable Center germplasm in these

	Tomato			Chili pepper		
	All seed producers	Private companies	Public sector	All seed producers	Private companies	Public sector
Seed sales (t)	91.5	81.5	10.0	125.1	117.6	7.6
Of which						
Hybrids (t)	85.0	81.4	3.7	120.0	117.6	2.4
OPVs (t)	6.5	0.2	6.3	5.1	0.0	5.1
Seed sales with World Vegetable Center-developed material (t)	11.9	10.2	1.7	15.8	13.3	2.6
Of which						
Hybrids (t)	11.6	10.2	1.4	15.0	13.3	1.8
OPVs (t)	0.3	0.0	0.3	0.8	0.0	0.8
Seed producers (n)	33	25	8	32	24	8

OPVs Open-pollinated varieties

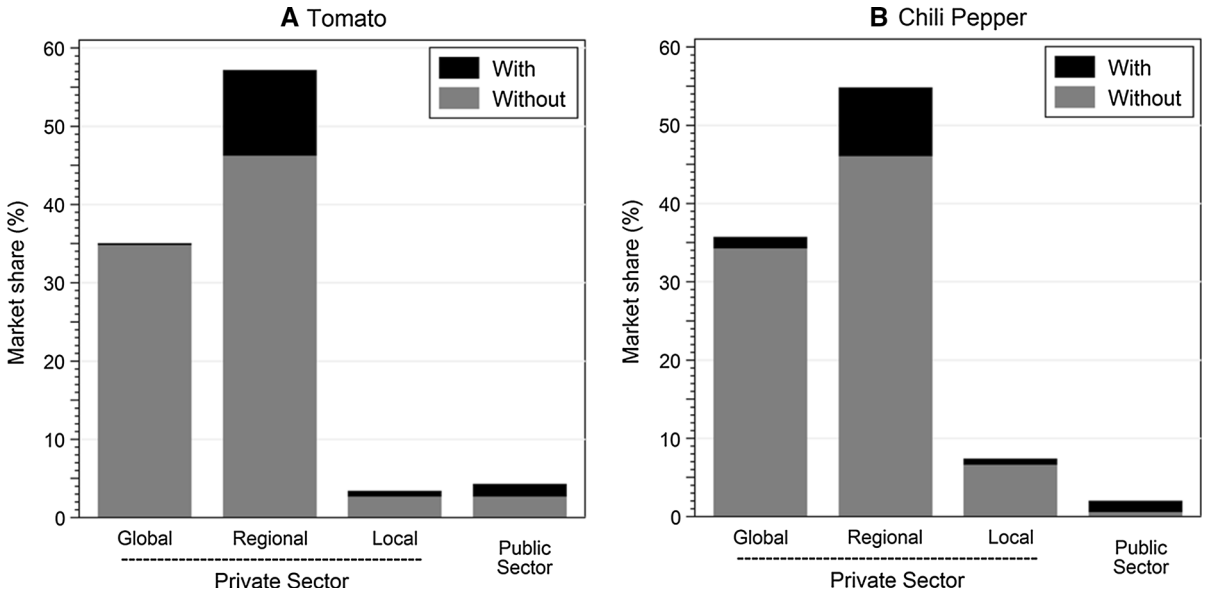

Fig. 2 Market share of the private and public sector in hybrid seed production of tomato (**a**) and chili pepper (**b**) in India, and the use of World Vegetable Center germplasm, 2014. *Notes:* With = Seed has World Vegetable Center germplasm in its pedigree; Without = Seed has no World Vegetable Center germplasm in its pedigree

research organizations have been replaced by commercial hybrids developed by private seed companies. Seed companies and public sector institutions differ in opinion about the exact share of hybrids in the total area planted. Seed companies estimated it at close to 85 % for tomato and 70 % for chili pepper, whereas public sector institutions estimated it at around 60 % for tomato and 50 % for chili pepper. All experts agreed the hybrid market segment has grown quickly, and that many farmers now prefer to pay for hybrids, particularly in irrigated areas. Public research institutions increasingly have turned to developing hybrid parents and licensing them to private companies, as they are unable to market them to farmers effectively.

We estimated that World Vegetable Center germplasm was incorporated in 11.6 t of tomato and 15.0 t of chili pepper hybrid seed sold annually in India. Assuming an average seed rate of 120 g/ha for tomato and 150 g/ha for chili pepper, as estimated by respondents during the in-depth interviews, this gives a potential area of 96,500 ha planted under tomato and 100,000 ha planted under chili pepper (Table 7). Based on an average planted area of 0.31 ha/farm for tomato and 0.44 ha/farm for chilies (Government of India 2015), this suggests that the Center's material reaches 309 thousand tomato and 229 thousand chili pepper farmers in India per year. However, India is a net exporter of vegetable seed. Seed companies tend to use India as a base for seed production for other countries in South Asia and sometimes even to East Africa and Southeast Asia. Data on vegetable seed exports are difficult to obtain and much of the seed export is informal.

Qualitative feedback of seed company executives and breeders

During the in-depth interviews, seed company executives and vegetable breeders explained that the vegetable seed market is India is highly competitive. The market is highly segmented by many fruit and plant characteristics with different companies dominating different market segments in different locations of India. Seed company executives indicated that new hybrids have a short lifespan. Many resistance traits break down within 5 years and successful varieties are quickly copied by competitors, after which profits disappear. Several executives mentioned that intellectual property rights in India are not being enforced. Due to the slow pace of litigation in India, by the time a court case opens, the variety is most likely already out of the market. Seed company executives and

Table 7 Estimates of farm-level use of World Vegetable Center-developed germplasm in commercial tomato and chili pepper hybrids in India, 2014

	Tomato	Chili pepper
Hybrid seed containing World Vegetable Center germplasm (t/year)	11.6	15.0
Area reached ('000 ha)[a]	96.5	100.0
Farm households reached ('000)[b]	309	229

[a] Assumes an average seed rate of 120 g/ha for tomato and 150 g/ha for chili pepper

[b] Assumes an average planted area of 0.31 ha/farm for tomato and 0.44 ha/farm for chili pepper

breeders are fully aware that under these circumstances, research and development as well as marketing are essential to remain competitive.

Breeders at several companies said that World Vegetable Center material with resistance helped them to cut short the time needed to develop own resistance traits from scratch. Mostly they were interested in specific traits such as tomato resistance against bacterial wilt and *Tomato yellow leaf curl virus* (TYLCV) and resistance in chili against anthracnose and *Chili veinal mottle virus* (ChMV). Twenty seed companies were currently testing TYLCV resistant materials of the Center. Yet it was often mentioned that the Center's traits did not perform well under Indian conditions as pathogen strains and climatic conditions in India are very different from those found in Taiwan or Southeast Asia. Respondents from several companies said the Center's material would be more useful if more of the breeding work and testing could be done in India. The head of the vegetable department of one the largest seed producers in India suggested the World Vegetable Center could collaborate in a consortium of partners in India and consider doing contract research with the National Seed Association of India.

Another theme that clearly emerged from the interviews was the pressure to deliver new varieties rapidly. One private company breeder mentioned that it took him two seasons to purify the Center's material to use as hybrid parents and another 2–3 years to produce new varieties, which he felt was too long given the rapid churning of varieties in the market. Two other breeders mentioned that although the Center's material had useful resistance to diseases, it did not have desired fruit characteristics. The material did therefore not produce varieties in high demand with farmers. It was felt that the Center's material was useful as base material, but not directly as parental material. This observation confirmed our quantitative result: that the direct release of, or crossing of, two of the Center's lines was uncommon after 1995 (Table 3).

Discussion

India is a case where a sophisticated private seed industry has developed over the past 20 years. This is attributed to the deregulation of seed policy in 1988, leading to tremendous investments in research and development by existing foreign and large domestic companies, and encouraging the initiation of new seed companies, all of which resulted in greater competition in the seed industry (Pray et al. 2001). Liberalization eliminated significant restrictions on the importation of vegetable seeds, including hybrid cultivars developed in other countries, and joint ventures with multinationals (e.g. Peto USA and Indo-American) expanded access to proprietary vegetable germplasm from the USA, Europe, Japan and other countries for use in breeding new cultivars. These increased investments were matched by a significant increase in the number of researchers and area under experimental stations (Pray et al. 2001) made possible by the presence of established public research institutes and many agricultural universities that train plant breeders and scientists in related disciplines such as plant protection, seed technology, and biotechnology. The combination of economic incentives, an enriched genetic base for breeding, and trained human capital to build multidisciplinary breeding teams made possible a surge of improved vegetable cultivars that have benefited farmers.

Implications

The main finding of our study is, as the role of the private sector in vegetable breeding research increased, and with it the importance of hybrids, international agricultural research became more important as a source of specific traits rather than as a source of ready-made tomato varieties. Consequently, the role of international vegetable breeding as

done by the World Vegetable Center should evolve to complement that of the private sector in the region and fill in the critical gaps noted below. We also compare our findings to the experience in maize breeding research, which, like vegetables, has seen a rapid surge in private sector interest.

Pre-breeding research

Long-term development of strategically important traits is often neglected in private sector breeding programs because of the pressure to constantly deliver new varieties. Our study showed most tomato and chili pepper hybrids have a short lifespan and seed companies have mostly short-term breeding targets. Pre-breeding research includes the identification and introgression of resistance genes from wild relatives into elite lines. International agricultural research centers in partnership with public sector institutions in India have a comparative advantage in this area because of in-house availability of genetic resources and proven expertise in trait discovery and development.[1] For maize in Asia, Gerpacio (2003) similarly observed that public sector organizations have tended to shift their role towards pre-breeding and germplasm conservation.

Support of small- and medium-sized seed companies

Our study highlighted the relative importance of international breeding research for small- and medium-sized companies, while global seed companies, on the other hand, made little use of public international germplasm. Farmers and consumers benefit from a healthy and competitive seed sector with strong vegetable breeding programs generating improved cultivars and striving to better satisfy farmers and consumers. The supply of improved breeding lines as non-exclusive, international public goods, helps small- and medium-sized companies with limited own research capacity to develop their own varieties. Studying the role of the private and public sector in maize, Morris et al. (1998) also concluded that international agricultural centers and public sector programs allow small seed companies to compete with large companies. Besides improved germplasm, training in advanced methods of vegetable breeding, particularly the use of molecular markers, also contributes to a more equitable field of competition, but was not assessed in our study.

Improved inbred lines

Despite the commercial success of hybrids, there remains a role for open-pollinated (inbred) varieties, particularly of chili pepper grown in rainfed areas, but also for many other vegetable species that have a smaller market potential or for which hybrid seed production is not viable. For instance, the Center works on many open-pollinated traditional vegetables in Sub-Saharan Africa (Dinssa et al. 2016). Improved inbred lines can also serve multiple purposes, such as inbred varieties, hybrid parental lines, or breeding stocks for isolating desirable traits. For maize, Morris et al. (1998) observed that public sector breeding programs have been important in producing varieties for specific niche environments such as rainfed production systems. However, the capacity of the public sector in seed multiplication and seed distribution tends to be weak and innovative solutions are needed to reach farmers in marginal areas.

Collaboration with private seed companies

The Center's collaboration with seed companies has not been straightforward. The Center often does not receive feedback from seed companies about the performance of its lines and the communication between the Center and private seed companies is irregular. Better communication would help to inform strategic decision-making in breeding programs and better tailor research toward impact. A consortium approach between the World Vegetable Center and private seed companies to deliver specific breeding outputs might create better conditions for impact and information sharing. Such an approach might serve the present situation better than giving all seed producers free and open access to all improved tomato and chili pepper breeding lines. However, we expect that there will continue to be a need for non-exclusive open-pollinated improved

[1] For instance, World Vegetable Center researchers are leading the development of TYLCD resistance, insect resistance, and flavonoids in tomato (Hanson et al. 2000; Kadirvel et al. 2012; Rakha et al. 2015) and are also leading research on the introgression of anthracnose resistance in C. *annuum* chili pepper (Gniffke et al. 2013; Suwor et al. 2015).

breeding lines to serve niche environments and to help smaller companies to maintain competitive. Another consideration would be the establishment of a trust fund to maintain the genetic diversity stored in the Center's genebank as most companies understand the value of this. Such trust fund might, however, not be suitable to fund the Center's breeding programs because companies prefer breeding projects with clear outputs, timelines and budgets.

Study limitations

Data collected for this study relied on the knowledge of vegetable breeders about the pedigree of the inbred lines used in their breeding programs. One problem mentioned by several companies was the frequent movement of breeders from one company to another, as the competition for skilled vegetable breeders is high. Companies also tended to "self down" each other's hybrids and derive lines with desirable traits for use in their own breeding programs. Therefore, breeders might not always know where a particular trait originally came from. It is thus very likely that some varieties, particularly the older ones, unknowingly had traits developed through international agricultural research. We are therefore likely to have underestimated the true contribution of international agricultural research. On the other hand, there might have been some degree of positive response bias; companies that used international public germplasm were more likely to give accurate data than companies that did not. However, we conservatively assumed that all varieties and seed volumes for which it was not explicitly mentioned that World Vegetable Center material was used, did not contain such material.

Conclusion

After the 1988 seed sector reform in India, improved open-pollinated vegetable lines produced by international vegetable breeding have continued to be used by the rapidly expanding private seed sector to develop hybrids. We found 61 tomato hybrids and 39 chili pepper hybrids currently on the market containing World Vegetable Center material in their pedigrees, accounting for 14 and 13 % of the tomato and chili pepper hybrid seed market, respectively, and potentially reaching over 0.5 million farmers annually. However, the role of international vegetable breeding has changed, as breeding lines are more frequently used as base material to obtain specific traits than as ready-made lines for crossing or varietal release. We therefore conclude that the international breeding of tomato and chili pepper needs to orient itself towards pre-breeding research, capacity building of smaller seed companies to strengthen competition in the seed sector, and the development of specific inbred lines for niche production systems. A consortium approach between the World Vegetable Center and private seed companies might fit the present situation better than giving free and open access to all improved breeding lines.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

List of private companies and public organizations that contributed to the study.

Private companies (global)

1. Advanta Ltd.
2. East West Seed India Pvt. Ltd.
3. HM Clause India Pvt. Ltd.
4. Enza Zaden India Pvt. Ltd.
5. Bayer CropScience Vegetable Seeds
6. Rijk Zwaan B.V.
7. Syngenta India Ltd.
8. Monsanto/Seminis

9. United Genetics India Pvt. Ltd.

Private companies (regional)

10. Ajeet Seeds Ltd.
11. Bejo Sheetal Seeds Pvt. Ltd.
12. Bharat Nursery Pvt. Ltd.
13. I&B Seeds Private Pvt. Ltd.
14. JK Agri Genetics Ltd.
15. Krishidhan Vegetable Seeds India Pvt. Ltd.
16. Maharashtra Hybrid Seeds Company Pvt. Ltd. (Mahyco)
17. Namdhari Seeds Pvt. Ltd.
18. Nath Bio-Genes (India) Ltd.
19. Nirmal Seeds Pvt. Ltd.
20. Rasi Seeds Pvt. Ltd
21. SeedWorks India Pvt. Ltd. (acquired by Bayer CropScience in June 2015)
22. VNR Seeds Pvt. Ltd.

Private companies (local)

23. Ankur Seeds Pvt. Ltd.
24. Bioseed Research India Pvt. Ltd.
25. Indo-American
26. Tulasi Seeds Pvt. Ltd.
27. Nuziveedu Seeds Ltd.

Public corporations

28. Tarai Development Corporation
29. National Seed Corporation

Research organizations

30. Indian Agricultural Research Institute (IARI, New Delhi)
31. Indian Institute of Horticultural Research (IIHR, Bengaluru)
32. Indian Institute of Vegetable Research (IIVR, Varanasi)
33. Punjab Agricultural University (PAU, Ludhiana)
34. Dr. Y.S.R. Horticultural University (YSRHU, Venkataramannagudem)
35. G.B. Pant University of Agriculture and Technology (GBPU&T, Pantnagar)
36. Himachal Pradesh Agricultural University (HPAU, Palampur)

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