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Connecting smallholder tomato producers to improved seed in West Africa

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Abstract

Background: Environmental heterogeneity, emerging pathogens and limited access to financial and agricultural inputs prevent farmers from producing consistent crop yields in many developing countries. Yield instability impedes establishment of processing and export industries, thereby inhibiting economic development. Modern varieties offer significant increases in yield stability.

Results: A deeply collaborative, multi-national germplasm trialing network was established in West Africa to identify tomato varieties well adapted to each country and mobilize those varieties into local seed distribution networks alongside an integrated pest management program. Research partners in seven West African countries evaluated over 100 tomato varieties for resistance to tomato leaf curl disease (ToLCD). Using biotechnology, the identity and distribution of the key viruses (begomoviruses) causing ToLCD in these countries were identified, and a vector-independent inoculation method (agroinoculation) was developed. The trials identified a set of high-performing varieties with resistance. Agroinoculation with the three prevalent begomoviruses confirmed resistance.

Conclusions: These trial results fulfill the new Economic Community of West African States harmonized seed regulation policy, which requires at least 2 years of national performance trials prior to commercialization of a tomato variety. To compete with a rapidly expanding canned tomato import industry, West African growers need to increase productivity and processing capacity; therefore, we also assessed processing and export trade data for fresh and processed tomatoes from each of the seven countries.

Keywords: Smallholder, Africa, Virus resistance, Seed systems

Background

Vegetable farmers in the Sudano-Sahelian zone of West Africa (SSA) face many constraints to agricultural productivity. South of the Sahara Desert, north of the humid Guinean region, the Sudano-Sahelian zone presents difficult environmental conditions including poor soil fertility [1], extreme heat and insufficient or unpredictable water supply [2], all of which have only become more precarious due to climate change [3]. Biotic stresses create additional losses, with newly emerging plant diseases and pests causing decreased yields and serious reductions in produce quality [4–6]. In the developed world, these challenges can often be managed by technologies such as drip irrigation or pesticides. Farmers in West Africa, however, often lack the financial means or physical access to technical solutions that can mitigate their risks. Furthermore, improved seed is minimally available on a commercial basis in West Africa. This is particularly true for vegetables [7, 8]. High-yielding, adapted vegetable varieties with resistance to pathogens are even more important for smallholder farmers, especially given the high incidence of nutritional deficiency and malnutrition in the region [8, 9]. Technology adoption is dependent

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on available assets; therefore, technologies that require fewer assets will be more readily adopted [10]. Infrastructure constraints also play a major role in limiting the success of smallholders in West Africa post-harvest [9, 11]. In West Africa, lack of climate-controlled shipping, roads in poor condition and few operational processing facilities limit farmers' capacity to successfully move their products to market [12, 13].

West African farmers, particularly smallholders, need the means and opportunity to improve both their actual yields and the predictability of their yields to ensure a consistent supply of vegetables. Improved diagnostics and management of diseases and pests, as well as access to inputs and irrigation, will be necessary to provide consistent production of quality produce in unpredictable markets. Studies have shown that fresh tomato prices in Ghana and Burkina Faso can fluctuate as much as 80% [14], making grower income extremely unpredictable. Investments in infrastructure, including roads, electrification, cold chain and processing plants, must increase dramatically to ensure that farmers can access necessary inputs, transport their produce safely and efficiently, and process it into value-added products that can either be exported or stored [15]. Increased yield potential, stability and quality are in turn likely to attract additional investment, giving farmers access to inputs and improving infrastructure for transportation, processing and export.

In West Africa, smallholder farmers producing tomatoes have small plots (e.g., 0.5 hectares) that are hand cultivated and watered by a variety of methods by furrow, flood, gravity, drip irrigation, or sprinklers. Typically, these growers plant a range of determinate open-pollinated varieties (e.g., pear-shaped processing types to round fresh market types), purchased in small quantities or seed saved from year to year, and having few or no resistance genes. In some cases, seed of hybrid varieties may be utilized, but this may be more expensive or difficult to find, and are expensive, especially for smallholders in rural areas [7, 8, 16]. Fields are established with transplants produced in seed beds, and varying levels of fertilizer is used depending on the availability. The yields are modest, and the price depends on seasonal availability. There are also examples of commercial tomato production, often associated with canneries (e.g., in Senegal). Here hybrid seed is used as well as larger fields and more modern technologies, e.g., use of tractors for cultivation, application of fertilizer and pesticides and drip irrigation. However, this type of tomato production in West Africa remains relatively uncommon.

Tomato growers in West Africa are faced with a number of disease and pest problems. Soil-borne diseases include bacterial wilt caused by *Ralstonia solanacearum* and Fusarium wilt caused by *Fusarium oxysporum* f. sp. *lycopersici*; foliar diseases include bacteria spot caused by *Xanthomonas* spp., late blight caused by *Phytophthora infestans* and Septoria blight caused by *Septoria lycopersici*; and mosaic viruses, such as *Tomato mosaic virus* and *Cucumber mosaic virus*, can cause yield loss and produce damage. Pests include worms, such as the cotton bollworm (*Helicoverpa armigera*), nematodes, mining insects, thrips, various aphid species, and mites, e.g., spider mites (*Tetranychus urticae*). Recently, outbreaks of the tomato leaf miner (*Tuta absoluta* (Meyrick) *(Lepidoptera: Gelechiidae)* have caused substantial damage to tomato crops in some West Africa countries [17, 18]. However, in recent years, tomato growers throughout West Africa have struggled with an emerging viral disease known generically as tomato leaf curl disease (ToLCD) [4, 19, 20]. ToLCD in West Africa and other parts of the world is caused by a complex of whitefly (*Bemisia tabaci*)-vectored begomoviruses and betasatellites [4, 21]. Begomoviruses (genus *Begomovirus*) are in the family *Geminiviridae*, characterized by a circular single-stranded DNA genome encapsidated within twinned isometric virions [22, 23]. ToLCD has become the most serious constraint to tomato production in several West African countries over the last decade, in some cases causing up to 100% yield losses [4, 24, 25]. In West Africa, ToLCD has caused such devastating losses that in many cases, farmers have abandoned tomato production entirely [26]. This paper describes a project spanning seven countries that aimed to improve both the quantity and the quality of West African tomatoes and tomato seed and minimize the impact of ToLCD.

Three years of in-country trials of over 100 tomato varieties led to the selection of tomato varieties for commercialization in the region. Variety performance in the trials was based on adaptation to the local environment, resistance to ToLCD, good fruit type and taste according to preferences in the target market(s). This project established an extensive field trialing network with the capacity to evaluate performance under West African conditions of modern germplasm generated anywhere in the world. The trialing network identified the most appropriate varieties for each environment, collaborating with local farmers in a participatory approach. At the same time, the begomoviruses associated with ToLCD in these countries were characterized and a vector-independent method (agroinoculation) for screening tomato varieties for resistance to these viruses under controlled laboratory conditions was developed. Finally, the selection trials satisfied the recently established ECOWAS seed certification policy [27–30], allowing the seed companies and institutions that donated successful varieties to the project to sell their seed in the region. The governments of seven West African countries collaborated to achieve this goal, as well as several US academic and government institutions, AVRDC—The World Vegetable Center, and many seed companies and public breeding institutions from around the world.

The origins of this project trace to an initiative by the United States Agency for International Development (USAID) Integrated Pest Management Collaborative Research Support Program (IPM-CRSP, currently known as IPM Innovation Lab) to improve tomato production in Baguineda, Mali. Outbreaks of ToLCD in the early 2000s had prevented farmers from cultivating tomatoes in this irrigated rice–vegetable production system. To reduce the impact of ToLCD in Baguineda, the IPM-CRSP project worked with local extension officers to implement a 3-month host-free period preceding the primary growing season (September–April). During the host-free period, the primary host species of the virus (tomato) was not grown by any farmers in the area, and an extensive sanitation program was implemented to eliminate old plants from previous crops and volunteers. The host-free period results in a reduction in viral inoculum, including that carried in the local whitefly population, as the life cycle of the whitefly is ~30 days and virus is not transmitted through the eggs of the insect, i.e., transovarially [31]. This can be highly effective at reducing levels of initial inoculum of the virus, reducing populations of the whitefly vector and slowing spread of the virus [19, 32]. A second key aspect of revival of tomato production in Baguineda was the provision of seeds of early maturing, high-yielding hybrids. To assess the relative resistance of these hybrids to ToLCD, a vector-independent method (agroinoculation) was developed that allowed for screening of tomato germplasm for resistance to the predominant begomoviruses associated with ToLCD in West Africa. The tomato host-free period continues to be implemented Baguineda and Kati, Mali.

In March 2004, a workshop of government agricultural researchers from many West African nations selected tomato as the highest priority crop. The increasing incidence of ToLCD was identified as a major constraint requiring immediate attention. The demonstrated need for improved tomato germplasm, and the decision by the consortium of West African governments to focus their efforts on tomato coincided with the initiation of the Agricultural Biotechnology Support Project II (ABSPII) in the USA, a project supported by Cornell University and USAID [33, 34]. The ABSPII research team was assembled from two US universities, Cornell and University of California Davis, the AVRDC, and the national agricultural research services (NARS) of Benin, Burkina Faso, Ghana, Mali, Niger, Senegal and Togo was tasked to address the ToLCD epidemic and to improve the quality of germplasm available in West Africa. The project had four main goals: identify and commercialize ToLCD-resistant tomato germplasm well suited to each country; develop an understanding of begomoviruses causing ToLCD in West Africa and a capacity to screening tomato varieties for resistance with a vector-independent method; develop a self-sustaining system that could work with any crop; and most importantly, establish protocols and research connections that could continue to function after donor support was removed. In the best circumstances, improved seed is inconsistently available in West Africa [7, 8, 16]. For those varieties that performed well, the project could demonstrate the commercial potential for the seed companies and public institutions donating to the project.

The new ECOWAS seed regulations establish unified seed quality control and certification in ECOWAS member countries [27–30]. The regulations require that at least 2 years of variety trials are conducted at multiple locations by an official quality control and certification service, or any other accredited private body [27–30]. Certification also requires laboratory analysis of the seed to ensure standards are met, such as germination [30]. If the national variety release committee determines that a variety surpasses quality standards in one country (e.g., it surpasses the performance of a check variety in the trials), it is placed in the West African Catalogue of Plant Species and Varieties (WACPSV) and can be grown and sold anywhere in the ECOWAS region [27–30]. The old system did not require variety trials take place at multiple locations, or by an accredited entity. Previously, an individual, typically the breeder or a seed company representative would submit a variety to the National Certification Authority. Certification was provided as long as the 3 years of data were submitted. This system allowed a company or individual submitting the variety to make the determination that the variety should be commercialized. Whereas the old system was simple and more similar to that used in the developed world, the new system will require that trials are completed by independent agronomists in order to determine whether the variety performs well enough to be commercialized in a given environment. Ideally, this change will ensure that high-quality seed reaches the marketplace and will not deter companies from entering this already underdeveloped market.

Over 100 varieties that were previously unavailable in the region were distributed to a network of agricultural researchers brought together through this project. At each location, the local team of researchers was provided the same tools to conduct ToLCD resistance trials. Through results obtained in this trialing network, we have identified varieties with high levels of resistance to the viruses that cause ToLCD and that have the greatest promise for improving tomato yields in West Africa.

Methods and results

Variety trials

Tomato varieties evaluated during the 3 years of variety trials came from a wide range of multi-national seed companies and public breeding institutions (Table 1) with the understanding that if a variety performed well, that company would consider an arrangement to bring that variety to market in the region. All varieties included in the trials shared the common feature of reported begomovirus resistance (mostly to the invasive Old World monopartite begomovirus *Tomato yellow leaf curl virus* [TYLCV]), which in most cases is derived from one or more of three genes known as *Ty-1* [35], *Ty-2* [36] and *Ty-3* [37]. Originally identified in accessions of wild relatives of tomato such as *Solanum chilense*, *S. peruvianum*, and *S. habrochaites*, these genes have all been introgressed into tomato varieties by breeding. In selecting varieties for inclusion in the trials in West Africa, preference was given to materials bred for semiarid tropical climates, but no other criteria were used so as to avoid limiting the germplasm included in the trials. Seed was donated by 11 private seed companies and five research institutions (Table 1). The 40 tomato varieties selected for the preliminary trials were selected from a range of resistance sources including *S. chilense*, *S. peruvianum*, *S. habrochaites* and *S. pimpinellifolium* and were predominantly hybrid varieties. Trials were conducted from 2005 to 2008 in Mali, Niger, Burkina Faso, Ghana, Senegal, Benin and Togo [38]. The trials were established and maintained by NARS partners at agricultural research stations or in commercial fields in collaboration with local farmers. The 3 years of trials were completed in a total of 22 different locations: eight in Mali, four in Togo, three in Ghana, three in Niger, two in Benin, one in Senegal and one in Burkina Faso. Some trials were repeated in the same locations over the 3 years, while others were relocated to ensure more appropriate climatic conditions and proximity to tomato growing regions to increase ToLCD disease pressure [38]. The first year of the project, the 2005–2006 growing season, saw the systematic evaluation of over 40 begomovirus-resistant tomato varieties in each of the participating countries. Designated as preliminary screens by the partners, these evaluations consisted of non-replicated trials at 11 locations, in which 26 plants of each variety were planted on agricultural research stations and evaluated for disease resistance according to a ToLCD symptom severity scale with 0 = no symptoms, 1 = mild leaf curling, 2 = leaf curling, light green to yellow discoloration and vein purpling; 3 = stunting, distorted growth and strong upward leaf curling and vein swelling and purpling; and 4 = severe stunting and distorted growth, upward leaf curling and vein purpling [39]. Natural levels of virus inoculum, delivered via indigenous populations of whiteflies, were relied upon for disease development in these trials. The regionally popular variety 'Roma VF' (Tropicasem) was always used as a susceptible check. Partners encountered a range of problems in the first year, including insufficient disease pressure, poor seed germination and inconsistent trial management practices across countries. Despite these issues, sufficient data were generated to select 11 promising varieties. The 11 varieties were 'HA 3060' (Hazera Genetics Ltd.), 'Atak' (Enza Zaden Benelux B.V.), 'Bybel' (De Ruiter Seeds Group B.V.), 'Chenoa' (Enza Zaden Benelux B.V.), 'GemPride' (Seminis Inc.), 'Industry DR 10403' (De Ruiter Seeds Group B.V.), 'Lety F1' (De Ruiter Seeds Group B.V.), 'Ponchita' (Enza Zaden Benelux B.V.), 'Realeza' (De Ruiter Seeds Group B.V,), 'Thoriya' (De Ruiter Seeds Group B.V.), 'Yosra' (Enza Zaden Benelux B.V.). 'Roma VF' was always included as a control. The selected varieties were chosen based primarily on demonstrated ToLCD resistance, but also based on yield, resistance to other diseases, or any other horticultural traits.

In the second year of the project, the 2006–2007 growing season also included 11 locations, but four sites were moved closer to tomato growing regions. The three trials in Ghana, Togo and Benin were moved from the South

Table 1 Public and private seed sources providing ToLCD-resistant tomato varieties for inclusion in the West African tomato variety trials 2005–2008

Organization	Location
AVRDC—The World Vegetable Center	Shanhua, Taiwan
CIRAD—French Agricultural Research Centre for International Development	Guadeloupe
De Ruiter Seeds Group B.V.	Bergschenhoek, The Netherlands
Enza Zaden Benelux B.V.	Enkhuizen, The Netherlands
Gentropic—Semillas Tropicales	Sacatepéquez, Guatemala
Harris Moran Seed Company Inc.	Modesto, CA, USA
Hazera Genetics Ltd.	Shikmim, Israel
Hebrew University of Jerusalem	Jerusalem, Israel
Nunhems B.V.	Haelen, The Netherlands
Seminis Inc.	St. Louis, MO, USA
Soli Ltd.	Kiryat Malachi, Israel
Syngenta AG	Basel, Switzerland
Takii & Co., Ltd.	Kyoto, Japan
Tropicasem	Dakar, Senegal
University of Florida	Gainesville, FL, USA
Agricultural Research Organization of Israel—Volcani Center	Bet Dagan Israel

to North, and the single trial in Niger was moved West, all to be closer to the tomato growing regions. Over 70 varieties were trialed. These included the 11 varieties selected in the first year (advanced trials), as well as over 60 new varieties that were trialed in preliminary screens. These preliminary screens were conducted similarly to the advanced trials, but without replication. In these trials, most of the varieties with resistance to TYLCV showed moderate to high levels of resistance to ToLCD (ratings of 0–2 and good yields), whereas the susceptible check 'Roma VF' showed obvious and strong symptoms (ratings of 3–4 and low yield). Of the more than 60 new varieties tested, many showed substantial levels of ToLCD resistance, and 20 were selected by at least one of the collaborators from the participating countries for inclusion in the third year of the project. Having learned from the mistakes of the previous year, the project partners developed a detailed trialing protocol for the second year in order to resolve inconsistencies among locations and to ensure the statistical relevance of the data. Specific practices related to site selection, seedling nursery establishment, and field management strategies including pesticide and fertilizer applications were standardized across locations. Entries were transplanted into 6.0 m by 1.5 m plots, each having 36 plants arranged in three rows of 12 plants. Three replicate plots of each variety were planted, for a total of 108 plants per variety. The plot design was a randomized complete block. Trials were maintained as if for commercial production, with pesticide applications being used to control diseases and pests other than whiteflies. In addition, attempts were made to plant the trials in areas known to be free of other important regional pathogens, such as root-knot nematode, Fusarium wilt, and bacterial wilt. Only the middle 10 plants in each plot were evaluated for resistance to ToLCD to eliminate edge effects. Plants were evaluated at flowering, fruiting, and first harvest with the ToLCD symptom severity scale. In addition, three randomly selected plants from each plot were evaluated for yield, which was extrapolated to tons per hectare, and for various other traits, such as fruits per plant, average fruit weight, and average fruit size. Overall, the results of the second year's trials were outstanding. The trials showed a marked improvement in quality over the previous year, indicating the value of hands-on experience in the development of germplasm trialing capacity. With few exceptions, the trials showed significant improvements in yield over typical tomato yields in the region. At the end of the second season, the four top varieties based on ToLCD resistance, yield and farmer preferences were selected for the third year of trials. Collaborators from each country also selected two additional varieties based on local performance and preferences. In several locations, NARS trial coordinators solicited farmer opinions on the varieties being evaluated. Farmers were very enthusiastic about the new varieties and provided helpful guidance for fruit type selection, typically showing a preference for medium-sized firm fruit that stood up well to shipping. In Mali, farmers ranked the varieties from highest to lowest preference as: 'Industry DR 10403' (De Ruiter Seeds Group B.V.), 'HA 3060' (Hazera Genetics Ltd.), 'HMX 4810' (Harris Moran Seed Company Inc.), 'Cheyenne E448' (Syngenta AG) and 'GemPride' (Seminis Inc.).

The third year of trials (2007–2008) included multi-location trials of top performing varieties evaluated under conditions encountered in commercial production at 10 locations. The varieties used for this trial were selected by each NARS partner submitting a list of the top four varieties from the advanced trials that they wanted to be included in the multi-location trials of the third year. Most of the NARS partners selected the same top four varieties for inclusion in the multi-location trials: 'Atak' (Enza Zaden Benelux B.V.), 'Bybal' (Enza Zaden Benelux B.V.), 'GemPride' (Seminis Inc.) and 'Industry DR 10403' (De Ruiter Seeds Group B.V.). Unfortunately, De Ruiter Seeds did not have a sufficient supply of 'Industry DR 10403' for inclusion in the trials. As a result, 'Yosra' (Enza Zaden Benelux B.V.) was selected to replace 'Industry DR 10403' as the fourth variety in the trials at each location, with the exception of Mali, also due to limited availability of seed. In addition, each NARS partner was given the option of including at least two more varieties in their multi-location trials. Selected varieties included 'HA 3060' (Hazera Genetics Ltd.), 'HMX 4810' (Harris Moran Seed Company), 'Lety F1' (De Ruiter Seeds Group B.V.), 'Ponchita' (Enza Zaden Benelux B.V.), 'Realeza' (De Ruiter Seeds Group B.V.) and 'Thoriya' (De Ruiter Seeds Group B.V.). The trials began in November 2007.

Multi-location trials were conducted with similar protocols to those used in the advanced trials. However, they were conducted on rented plots on commercial farms (rather than at NARS stations) and in at least two of the major tomato production areas (preferably in different agroecological zones) of each of the seven participating countries. The trials had two goals: to confirm the performance of the selected varieties in the less forgiving environment of farmers' fields and to publicize the varieties to producers in many regions throughout West Africa. These trials offered an opportunity to evaluate germplasm within the context of actual vegetable production areas and according to the customs of the farmers in the region, rather than in the more controlled environment of an agricultural research station, providing a more realistic view of the potential performance in a production setting. These multi-location trials also served as the bridge between germplasm evaluation and variety distribution. Situated among the fields of commercial tomato producers, these trials served as demonstration plots for these new materials, helping to spread the word about modern varieties and diminishing some of the risk associated with adoption of the new varieties by allowing farmers to learn from others [40]. The trials demonstrated that the selected tomato cultivars could perform significantly better than 'Roma VF' both on agricultural research stations and on farmers' fields. In all locations, all selected cultivars had lower symptom severity scores than 'Roma VF,' and in Benin and Mali, tested cultivars had very low symptom severities or even remained symptomless [38]. Farmers who witnessed the trials were uniformly enthusiastic about the new varieties, and many expressed interest in gaining access to seeds. In all trial locations, visiting farmers expressed interest in all the trialed varieties, except for one. 'Atak' (Enza Zaden Benelux B.V.), 'Bybal' (De Ruiter Seeds Group B.V.), 'Lety F1' (De Ruiter Seeds Group B.V.) and 'Yosra' (Enza Zaden Benelux B.V.) were mentioned frequently by farmers. 'GemPride' (Seminis Inc.) was not preferred by farmers because it produced softer fruit under these conditions; they preferred hard fruit for durability during shipping.

In both the advanced trials and the multi-location trials, the top four varieties selected had lower average ToLCD symptom severities and higher average yields than 'Roma VF,' demonstrating lower levels of ToLCD susceptibility and greater yield potential across countries (Table 2). It is notable that average ToLCD symptom severity on 'Roma VF' did not change significantly between year 2 and year 3, implying that there was no change in overall ToLCD pressure (Table 2). However, the cultivars under evaluation, 'Atak,' 'Bybal,' 'GemPride' and 'Yosra,' did show approximately twofold increases in ToLCD symptom severity and twofold decreases in yield in the switch from the advanced trials to the multi-location trials. This is likely a reflection of the change in environment. While the advanced trials were conducted on research stations with relatively controlled environments and relatively advanced management practices, the multi-location trials were conducted on farms with uncharacterized soils and unknown local disease pressures. While the change to a less-controlled environment had a significant impact on the performance of the selected cultivars, it had an even greater impact on the performance of 'Roma VF,' which saw a fourfold decrease in yield for the same transition. While performance varied from one environment to the next, the selected ToLCD-resistant varieties consistently outperformed the regionally popular ToLCD susceptible variety. This is crucial in the heterogeneous, often degraded environments of West Africa where farmers have limited access to inputs and therefore limited control over their environments. By offering consistently higher yield potential in all environments, the selected varieties promise farmers more predictable returns and thus more consistent livelihoods.

Characterization of begomoviruses associated with ToLCD in West Africa and screening tomato varieties for resistance with a vector-independent method (agroinoculation)

Protocols were developed to detect and identify begomoviruses and betasatellites associated with ToLCD in field-collected leaf tissue samples, and to screen tomato varieties for resistance to the predominant begomoviruses identified with the vector-independent agroinoculation method. Samples of tomato leaves with symptoms of begomovirus infection (e.g., stunting, erect and distorted growth and leaf curl and yellow leaf curl) were collected during a survey of West African countries (Benin, Burkina Faso, Ghana, Niger and Togo) conducted in February 2007 and by NARS collaborators from these

Table 2 Average performance across countries of the top four varieties included in the multi-location trials

Variety name	2006–2007—AT[a]		2007–2008—MLT[a]		Change	
	SS	Yield	SS	Yield	SS (%)	Yield (%)
'Atak'	0.85	33.56	1.82	16.58	+113	−51
'Bybal'	0.86	30.07	1.65	14.54	+91	−52
'GemPride'	1.06	32.19	1.70	12.48	+60	−61
'Yosra'	1.25	34.46	1.51	16.12	+21	−53
'Roma VF'	3.34	28.75	3.29	6.90	−2	−76

Cultivars were analyzed in the advanced trial (AT) of year 2 (2006–2007) and the multi-location trial (MLT) of year 3 (2007–2008). Changes in symptom severity (SS) scores and total yields are indicated. 'Roma VF' is included as the susceptible check. Yield was measured in tons per hectare (t/ha)

ToLCD symptom severity scale where 0 = no symptoms, 1 = mild leaf curling, 2 = leaf curling, light green to yellow discoloration and vein purpling; 3 = stunting, distorted growth and strong upward leaf curling and vein swelling and purpling; and 4 = severe stunting and distorted growth, upward leaf curling and vein purpling, as established in Lapidot and Friedmann [39]. Plants were evaluated at flowering, fruiting, and first harvest

[a] Advanced trails (AT) were conducted on NARS research stations; multi-location trials (MLT) were conducted on farmers' fields

countries in 2007–2008. Leaf disks from these samples were squashed onto nylon membranes, which were brought to UC Davis and analyzed for the presence of begomovirus DNA by squash blot (SB) hybridization with a general begomovirus probe [41]. Samples positive for begomovirus infection were further analyzed by SB-PCR (polymerase chain reaction) and DNA sequencing to identify the specific begomovirus(es) and betasatellites involved [19]. This involved using a combination of degenerate and species-specific primers, followed by sequencing of PCR-amplified fragments [19, 42]. Taken together, these studies revealed three locally evolved monopartite begomoviruses cause ToLCD in these West African countries: *Tomato leaf curl Mali virus* (ToLCMLV), *Tomato yellow leaf curl Mali virus* (TYLCMLV) and *Pepper yellow vein virus* (PepYVMLV, also known as Tomato yellow leaf crumple virus). An unusually severe symptom phenotype was shown to be due to a mixed infection of TYLCMLV and Cotton leaf curl Gezira betasatellite. A subsequent study revealed an additional monopartite begomovirus associated with ToLCD in Ghana and Togo, *Tomato leaf curl Ghana virus*, and two additional betasatellites (Tomato leaf curl Togo betasatellite and Tomato leaf curl Ghana betasatellite) [4, 43].

In general, the majority of samples collected during the survey of West African countries and provided by the NARS partners were positive for begomovirus infection, whereas betasatellites were detected in a relatively small number of plants (~5–10%). Based on SB-PCR tests with specific primers for TYLCMLV, ToLCMLV and PepYVMLV and sequencing of selected PCR-amplified fragments, all three viruses were commonly detected in tomato plants with ToLCD symptoms. The relative prevalence of these viruses in different countries varied (Table 3). All three viruses were detected in four countries (Burkina Faso, Ghana, Mali and Togo), two viruses were detected in two countries (Benin and Senegal), whereas only PepYVMLV was detected in Niger. In some countries, especially Ghana and Togo, evidence of other begomoviruses associated with ToLCD was found (i.e., some samples that were PCR-positive with degenerate primers were negative with the virus-specific primers). Subsequent studies have confirmed this additional genetic diversity in begomoviruses causing ToLCD in West Africa [4, 43, 44]. Because of the important role of these three viruses in ToLCD in West Africa, a disease resistance breeding program for ToLCD in West Africa should involve all three viruses; in contrast, betasatellites do not need to be included because of their low incidence and nonessential role in ToLCD in West Africa.

Full-length infectious clones were generated for TYLCMLV, ToLCMLV and PepYVV. Agroinoculation systems were generated for each virus by inserting multimeric copies of the genome into the Ti plasmid of *Agrobacterium tumefaciens*. Upon introduction of an *A. tumefaciens* strain carrying a begomovirus multimeric clone into a tomato plant, e.g., into the stem just beneath the shoot apex with a hypodermic syringe, the viral DNA is delivered directly into the nuclei of wounded cells, where it initiates the infection cycle without needing to have been introduced by the whitefly vector [45]. This method is extremely efficient (infection rates are typically ~100%) and reproducible. Using agroinoculation systems generated for TYLCMLV, ToLCMLV and PepYVMLV, tomato varieties were screened for resistance in a controlled environment chamber at UC Davis. A total of 41 tomato varieties, including the 11 that performed best in the multi-country variety trials and susceptible control 'Roma VF,' were individually screened with each of the three viruses with this vector-independent method (Table 4). The response of the varieties was classified as susceptible (disease ratings of 3–4 and detection of a high level of viral DNA by semiquantitative PCR), moderately resistant (rating of 2 and detection of a high to medium level of viral DNA), resistant (rating of 0–1 and detection of high to medium level of viral DNA by PCR) and highly resistant (rating of 0 and detection of a low level or no viral DNA by PCR). For all the varieties and each of the viruses, replicates of 5–10 plants were agroinoculated and the experiment was repeated three times. The response of the varieties to the three viruses was similar. Therefore, a general response for all viruses tested is presented. 'Roma VF' showed the expected susceptible response in all of the nine experiments (three replications for each of the three viruses), indicating that the agroinoculation technique was successful. In general, most of the tested varieties showed some level of resistance: 20%

Table 3 Detection of tomato-infecting begomoviruses in West African countries in 2007–2008 based on squash blot-PCR assays

	Tomato-infecting begomovirus		
Country	Tomato yellow leaf curl Mali virus	Tomato leaf curl Mali virus	Pepper yellow vein virus
Benin	X	X	
Burkina Faso	X	X	X
Ghana	X	X	X
Mali	X	X	X
Niger			X
Senegal		X	X
Togo	X	X	X

Squash blot-PCR assays were conducted as described in Zhou et al. [19]. The number of samples tested per country ranged from 38 to 95

Table 4 Response of selected tomato varieties to the three predominant West African tomato-infecting begomoviruses (tomato yellow leaf curl Mali virus, tomato leaf curl Mali virus, and pepper yellow vein virus, tomato yellow leaf crumple virus)

Susceptible[a]	Moderate resistant	Resistant	Highly resistant
'Roma VF' (Tropicasem)	'*HA 3060*'[b] (Hazera Genetics Ltd.)	'*Atak*'[b] (Enza Zaden Benelux B.V.)	'CLN 2545B' (AVRDC)
	'CLN2123A' (AVRDC)	'*Bybal*'[b] (DeRuiter Seeds Group B.V.)	'*GemPride*'[b] (Seminis Inc.)
	'CLN2545A' (AVRDC)	'Cheyenne E448' (Syngenta AG)	'Nirouz TH99806' (Syngenta AG)
	'*Industry DR 10403*'[b] (DeRuiter Seeds Group B.V.)	'Favi 9' (Hebrew University of Jerusalem)	'*Realeza*'[b] (De Ruiter Seeds Group B.V.)
	'F1 3019 Galina' (Tropicasem)	'HMX 4810' (Harris Moran Seed Company Inc.)	'Yassamen TH 99802' (Syngenta AG)
		'*Lety F1*'[b] (DeRuiter Seeds Group B.V.)	'*Yosra*'[b] (Enza Zaden Benelux B.V.)
		'*Chenoa*'[b] (Enza Zaden Benelux B.V.)	'TY 75' (Takii & Co., Ltd.)
		'Cheyenne E448' (Syngenta AG)	
		'Favi 9' (Hebrew University of Jerusalem)	
		'*Ponchita*'[b] (Enza Zaden Benelux B.V.)	
		'*Thoriya*'[b] (DeRuiter Seeds Group B.V.)	

Varieties in italics were ranked in the top 11 of the variety trials

Viruses were delivered by agroinoculation of ~3- to 4-week-old plants followed by a second inoculation seven days later

[a] Plants were visually rated for disease symptoms 21 days after the first inoculation according a 0–4 scale with 0 = no symptoms, 1 = slight upcurling of leaves, 2 = upcurling and vein purpling, 3 = stunting and upcurling and vein purpling, and 4 = severe stunting and distorted growth and curling and vein purpling; the presence of viral infection was determined by PCR with virus-specific primers. Response to the viruses was as follows: susceptible, rating of 3 or 4 and PCR-positive with a strong signal (DNA band); moderate resistant, rating of 2 and PCR-positive with a strong signal; resistant, rating of 0–1 and PCR-positive with a moderate–strong signal; and highly resistant, rating of 0 and PCR-negative or positive with a weak signal

[b] This variety ranked in the top 11 in the trials

were moderately resistant, 34% were resistant and 24% were highly resistant (Table 4). This indicates that most of the materials provided for this trial did have some resistance to these viruses. Moreover, as most of the resistance in these materials had been identified based on screening against TYLCV, this appears to be a reliable indicator that a material will be resistant to the monopartite begomoviruses causing ToLCD in West Africa. This is also consistent with the observation that the same genes (e.g., *Ty-1*, *Ty-2* and *Ty-3*) confer resistance to most Old World monopartite tomato-infecting begomoviruses. Importantly, the 11 preferred materials selected in the multi-country trials based on disease resistance and horticultural traits also showed responses of moderate resistant ('Industry DR 10403' and 'HA 3060'), resistant ('Atak,' 'Bybal,' 'HMX 4810,' 'Lety F1,' 'Ponchita' and 'Thoriya') or highly resistant ('GemPride,' 'Realeza' and 'Yosra'). This revealed an agreement between the results of the resistance screening in the field in West Africa and under controlled conditions at UC Davis and provided further support for a begomovirus etiology for ToLCD is West Africa. Finally, this is a good example of how a vector-independent disease resistance screening method can be developed with the tools of biotechnology, and how the results can provide practical information to help manage an applied problem, e.g., an outbreak of a serious disease.

Biotechnology played an important role in characterizing the tomato-infecting begomovirus complex and betasatellites associated with ToLCD symptoms in West Africa. However, many of these protocols could not be conducted in West Africa due to a lack of equipment and expertise. To initiate the development of a self-sustaining biotechnology research program in West Africa, considerable efforts were invested to transfer molecular biology research capacity to the project's West African NARS partners. A week-long intensive molecular biology and genetics training workshop was held in Bamako, Mali, in August 2007 for over 20 participants from the seven partner countries.

Post-trial seed availability

The multi-location trials conducted in the last year of the project (year 3) allowed for the identification of varieties that performed best in each location. Results of the vector-independent screening confirmed the resistance in these varieties to the predominant viruses involved with the ToLCD. Upon completion of the project, variety performance reports were provided to all the seed donors. Given many of these companies and institutions had yet to enter the West African market, the development of distribution capacity from the ground up will be required. This is not a trivial task, as the commercial seed distribution sector in West Africa is severely underdeveloped [46]. Seed distributed through commercial outlets needs to be adapted to the region, including resistance to important pests and pathogens. Varieties such as the commonly available 'Roma VF' are becoming increasingly undesirable as disease pressures intensify. NARS partners provided updated information on seed availability and the incidence of ToLCD (Table 5). Two varieties from the trials are widely available including 'GemPride' (Seminis Inc., now *Monsanto*) and 'Nadira' (Tropicasem). Monsanto is currently selling 'GemPride' in Ghana and Senegal, and also recently starting selling the TYLCV-resistant variety 'VL-642' in West Africa [47]. 'Lety F1,' another Monsanto variety included in these trials, is not a commercial variety in West Africa [47]. The Tropicasem variety 'Nadira' is widely available in many, if not all of the countries included in this project.

In Benin, collaborators from INRAB (Institut National des Recherches Agricoles du Benin) indicated that 'TLCV15' (AVRDC) and 'Nadira' (Tropicasem) are currently sold in the region. 'LetyF1' (De Ruiter Seed Group B.V., now *Monsanto*) was sold in pre-extension trials, but collaborators found that it was rejected by farmers due to fruit size. As noted above, Monsanto is currently not selling 'Lety F1' in West Africa; therefore, available 'Lety F1' seed in the region would be the result of on-farm multiplications rather than the hybrid included in the trials. The most popular varieties in the region are all susceptible to ToLCD. These include 'Tropimech,' 'Petomech,' 'Caraibo,' 'Mongal F1,' as well as three local varieties, 'Tounvi,' 'Akikon' and 'Kekefo.' Once popular variety 'Roma VF' has been abandoned, it is very susceptible to ToLCD. In Southern Benin, growers sometimes grow 'Nadira' (Tropicasem), which was included in the trials, but it is not well adapted to Southern Benin. Additionally, farmers reported to INRAB that the 'Nadira' seed is very expensive. 'TLCV 15' (AVRDC) is grown in limited locations in urban and peri-urban areas of Cotonou and Ouidah. The variety is popular with producers, consistent with experimental results obtained at the INRAB research station. 'TLCV 15' is the only variety of the trials that INRAB multiplied for sale and registered in the national catalog of vegetable species. There are many tomato varieties that are available in Benin; however, there are few high-quality improved varieties available because the seed distribution chain is not well organized. Due to a lack of improved tomato seed, many farmers grow local varieties of pepper and onion. The only well-known seed distributor in Benin is Benin Semences (formerly Tropicasem/Technisem). During the rainy season from August to November in the South, and August to October and December to February in the North, there is an over production of tomatoes. A new tomato-processing facility has been established in Southern Benin, making year-round production stability even more important.

In Ghana, ToLCD causes significant losses during the dry and fresh market season. There is a lack of improved tomato varieties on the market. In fact, a number of areas still grow landraces rather than improved varieties [44]. Local collaborators reported that 'GemPride' from Monsanto and 'Nadira' from Tropicasem are sold in Ghana; however, the most popular varieties are 'Pectomech,' 'Pectofake,' 'Power Rano,' 'Burkina' and 'Ada Lorry Tyre,' local landraces susceptible to ToLCD. A lack of improved tomato varieties has caused farmers to grow other vegetable crops, most commonly chili pepper. Currently, most to all tomato production is fresh market because the cost of production is too high for the processing companies to survive. Due to this underproduction, Ghana imports tons of processed tomato from Italy, China and the USA. Surveys of tomato farmers in Ghana found that cost of seed, management practices and familiarity with the variety, and shelf life due to skin thickness were extremely important [7]. This supports the importance of local variety trialing, as well as our results which indicated a preference for varieties that stand up well to shipping. In June 2015, a workshop was held in West African Center for Crop Improvement (WACCI) called *Workshop on Tomato Value Chain in Ghana*, which included tomato producers as well as representation from the Tomato Traders and Transporters Association [48]. The workshop brought together participants from WACCI, the Syngenta Foundation for Sustainable Agriculture (SFSA), the Australian International Food Security Research Centre (AIFSRC/ACIAR), Crawford Fund (CF), the University of Queensland (UQ), and local stakeholders in the tomato industry. Whitefly-transmitted viruses such as those that cause ToLCD were cited at this meeting as among the most important pathogens in the region.

In contrast to the persistence of landraces in Ghana, production of tomato is highly commercialized in Burkina Faso where producers focus on hybrids [44]. For example, La Société de Transformation des Fruits et Légumes de Loumbila (STFL), a tomato-processing facility outside Ouagadougou contracts tomato farmers to produce for its processing facility. In early 2014, the new processing facility had recently completed field testing for tomatoes with the collaborators for this project, INERA, Institut d'Etudes Environnementales et de Recherches Agricoles. They tested 15 varieties of tomato selecting five, including 'GemPride' and 'Nadira.'

In Mali, our collaborators from IER (Institute d'Economie Rurale) indicated that the most popular tomato varieties are all susceptible to ToLCD: 'Roma VF,' 'UC-82' and 'Rossol VF.' The Tropicasem variety 'Nadira'

Table 5 2016 incidence of ToLCD and availability of ToLCD-resistant varieties in participating countries

Country	Current incidence of ToLCD and in-country seed supply	Commercially available ToLCD-resistant varieties	Comments on tomato varieties that are currently cultivated
Benin	ToLCD causes significant losses during the dry and fresh tomato season in the north and south of the country	'Nadira' 'TLCV15'	'LetyF1' (De Ruiter Seed, now *Monsanto*) was distributed in pre-extension field trials but was rejected due to fruit size 'Nadira' (Tropicasem) is grown in the South but is not well adapted to that region, some of the big tomato producers unsuccessfully experimented with it (trials were done in the North). This variety has not become very popular with growers due to the seed price 'TLCV15' (AVRDC) is popular with growers who have worked with INRAB. This is the only variety which INRAB multiplied for sale, and the only variety which INRAB registered for the national vegetable seed catalog
Niger	ToLCD is currently a problem in the region Niger Semence (formerly Tropicasem/Technisem/Sahéliasem, Agrimex) are the distributors in the country. Due to a lack of improved tomato varieties, farmers grow local varieties of pepper and onion	'Nadira' 'Mongal'	'Nadira' and 'Mongal' (Tropicasem) are recommended for cultivation in the rainy season and are on sale in Ag retailers 'RomaVF' (Tropicasem) is currently on sale and is popular; this was the susceptible check in the field trials and in the agroinoculation test
Mali	ToLCD is still a problem in the region	'Nadira' 'OPB 149' 'OPB155'	'Roma VF,' 'UC-82,' 'Rossol VF' are the most popular varieties, but they are susceptible to ToLCD. 'Nadira' is not the most popular variety, but farmers who know its tolerance to ToLCD prefer it to the susceptible varieties Recently, open-pollinated cultivars 'OPB 149' and 'OPB155' have been released to farmers in Kati, Baguineda and Niono. These varieties were developed and distributed to farmers by Institute d'Economie Rurale (IER) in collaboration with the IPM Innovation Lab. These varieties have been found to produce good yield under ToLCD pressure and have been well received by farmers Popular with the local farmers, but currently unavailable in country are: 'Atak' (Enza Zaden Benelux B.V., now *Enza Zaden*), 'Bybal' (Enza Zaden Benelux B.V., now *Enza Zaden*), 'Cheyenne E448' (Syngenta AG, now *Syngenta*), 'HA 3060' (Hazera Genetics, now *Hazera*), 'H8804' (Heinzseed) and 'Shasta' (Harris Moran Seed Company Inc, now *Harris Moran*)
Ghana	In Ghana, ToLCD causes significant losses during the dry and fresh market season Both local (Manoma) and international seed distributors (Agrimex and Technisem) distribute seed	'Nadira' 'GemPride'	The most popular varieties are: 'Pectofake,' 'Petromech,' 'Ada Lorry Tyre,' 'Power Rano,' 'Burkina' and 'Ada Lorry Tyre,' local landraces susceptible to ToLCD
Senegal	There is a lack of open-pollinated (OP) varieties adapted to wet conditions and resistant to diseases such as ToLCD	'GemPride' 'Nadira'	'GemPride' (Seminis, now *Monsanto*), 'Nadira' and 'Yaqui' (Tropicasem) are very popular 'HMX 4810' (Harris Moran Seed Company, now *Harris Moran*) was very popular with farmers, but seed supply was a bottle neck
Burkina Faso	There is currently a shortage of tomato; ToLCD is still a major problem	'Nadira' 'GemPride'	'Nadira' (Tropicasem) and 'GemPride' (Seminis, now *Monsanto*) have been selected by contract farmers for a tomato-processing facility called STFL (La Société de transformation des fruits et légumes) located in Loumbila
Togo	In areas where improved tomato varieties are not available or too expensive, farmers grow other vegetables such as onion, eggplant and okra		'TLCV15' (AVRDC) was popular with farmers. Current information regarding cultivation is unknown

is available; however, this variety is not the most popular, but farmers who know its tolerance to ToLCD prefer it. After the trials, farmers who had conducted trials or visited trials were asking for 'Atak' and 'Bybal' (Enza Zaden Benelux B.V., now *Enza Zaden*), 'Cheyenne E448' (Syngenta AG, now *Syngenta*), and 'HA 3060' (Hazera Genetics Ltd., now *Hazera*); however, none of these varieties are currently available for commercial sale in the region. A similar situation exists for the early maturing hybrids 'Shasta' (Harris Moran, previously Campbell) and 'H8804' (Heinzseed) introduced to Baguineda as part of IPM-CRSP (now IPM Innovation Lab). Currently, there are not major shortages of tomato; however, if tomato-processing plants became operational, this may cause a shortage. Recently developed open-pollinated cultivars 'OPB 149' and 'OPB155' produce good yields under ToLCD pressure. These varieties were developed and distributed to farmers in Kati, Baguineda and Niono by IER in collaboration with IPM Innovation Lab.

Collaborators in Senegal report that Monsanto variety 'GemPride' is very popular with farmers. The Harris Moran variety 'HMX 4810' was also very popular, but again, seed distribution was a bottleneck. 'Nadira' is also very popular. NARS collaborators from INRAN (Institute National de Recherche Agronomique du Niger) indicated that of all the ToLCD-resistant varieties that were included in the trials, only 'Nadira' was available. 'Nadira' is recommended for cultivation in the rainy season and is readily available from local agricultural retailers. 'RomaVF' is currently on sale and is still very popular. In Togo, AVRDC variety 'TYLCV 15' had been extremely popular with farmers, but current seed availability was uncertain at the time of this publication.

West African tomato exports and processing

An examination of tomato exports showed a steady increase in fresh tomatoes exports from Senegal and Burkina Faso from 2003 to 2012 (Table 6). An increase in fresh tomato exports was not observed for the other five countries in this project during this time period, or for any other type of tomato product. Despite this increase in fresh tomato exports in Senegal and Burkina Faso, imported tomato paste dramatically increased starting in the early 2000s and has continued to increase in the region [49]. In Ghana, there was an increase in canned tomato exports in 2006, but this dramatically decreased in 2007 and has continued to fall in an equally dramatic manner. This was most likely due to the common practice of bulking (typically imported) paste and repackaging prior to selling it [50]. In 2003, a factory was established in northern Ghana by Trusty Foods Ltd, an Italian company, to supply West Africa with tomato paste [12]. However, this company primarily imports the paste and repackages it at the factory; just 7% of its product come from tomatoes grown in Ghana [13]. The Ghana export strategy allows the company to benefit from lower tariffs on products from the region [50]. Given the dramatic fall in exports from Ghana in 2008, it is possible that this loophole has been closed. Nigeria is one of the major importers of tomato paste from Ghana, and it may have introduced barriers that resulted in the decline [50].

For tomato, improved seed sold in the region is either inconsistently available in the marketplace, is not adapted to climatic and disease constraints, or the seed has been repeatedly multiplied on-farm causing the loss of key traits such as disease resistance. Mechanization in any form, including irrigation pumps and tractors, is exceedingly rare and only available on larger, export-oriented farms or in contract farming where processors develop contracts with farmers [12, 13]. Imported canned tomatoes have become increasingly available due to reduced import tariffs and an absence of import quotas [13]. The low price of imported tomato paste and the relatively high cost of locally produced tomatoes make production costs too high for processing companies to make a profit in the region [13]. For example, in 1992 import quotas were abolished in Ghana and tariffs were reduced to 20% [13]. These factors undoubtedly contributed to the closure of tomato-processing plants in the country, and subsequent reluctance to reopen as the prevalence and low cost of foreign tomato paste make it very difficult for local processing companies to break even [13]. In order to compete with foreign paste from China, growers would need to harvest approximately 30 tons per hectare; however, yields have been estimated well below ten tons per hectare, and agricultural input costs are too high to be competitive [13]. Poor quality has also been cited by processors as a restraint to purchasing locally [12]. Fresh tomatoes are typically sold locally for higher prices, or can be sold around the country or internationally to Cote D'Ivoire, Togo, or Burkina Faso [12]. Improved seed will increase yield and quality, which are essential to becoming competitive in the processed tomato market.

Conclusions

The establishment of a West African germplasm trialing network and the introduction of modern high-yielding virus-resistant hybrid tomato varieties address the larger goal of improving livelihoods in West Africa. The continued incidence of ToLCD in the region may cause seed companies to start selling their resistant varieties in the region, particularly given that the additional requirements of ECOWAS seed certification have been completed [27–30]. Theoretically, increased and stabilized tomato yields and improved produce quality will attract

Table 6 Export trade data of tomato from each of the seven countries to the rest of the world in metric tons (MTs), 2003–2012

Sum of volume (MTs)	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Grand total
Tomato, fresh or chilled	5759	5304	6513	23,451	24,561	18,279	15,677	15,695	20,669	22,655	158,563
Senegal	3723	4660	5626	9877	9632	10,810	8163	10,300	11,740	12,649	87,180
Burkina Faso	962	588	501	13,553	14,233	7179	7309	5188	8725	10,000	68,237
Ghana	106	38	350	15	694	287	192	69	109		1861
Togo	957	9	8	3	1	2	6	4	0	0	992
Mali		0	1			1	6	134	0	6	148
Niger	10	5	20	1	0	0	2		96	0	134
Benin	0	3	6	1						0	10
Other (tomatoes, whole or in pieces)	5117	3280	6605	34,160	18,842	4839	6371	1546	1787	8526	91,073
Ghana	2548	1780	2864	29,938	14,687	3184	2512	497	1454	1432	60,895
Togo	2253	1350	3616	3631	3323	1560	3507	802	67	3720	23,829
Senegal	84	77	117	175	249	92	175	158	200	2368	3696
Burkina Faso	62	48	7	316	581	3	7		20	891	1935
Benin	170	25	1	88		0	3	0	17	115	419
Niger				12	2		163			0	178
Mali	0					0	4	88	29		121
Tomato ketchup and other tomato sauces	1	16	57	43	20	50	1336	12	29	38	1604
Togo	1	4	15	39		21	1140		0	0	1220
Senegal		7	15		19	15	190	1	29	27	304
Mali		5	25	5							35
Ghana	1	0	1	0	1	7	6	1	0	8	24
Burkina Faso				0				11			11
Niger						7					7
Benin										3	3
Tomatoes, whole or in pieces	23	0	16	2	4	11	0	1	7	40	106
Senegal	21		16		4	6			2	1	50
Ghana				0		5	0	1	2	37	46
Burkina Faso			0	2					2	1	5
Togo	1			0	0				1	0	3
Mali										1	1
Benin	1	0									1
Niger				0							0
Grand total	10,901	8601	13,191	57,656	43,428	23,179	23,385	17,254	22,492	31,261	251,346

Data obtained from UN Comtrade

investment in the infrastructures necessary to make the tomato industry in West Africa a serious player in the local or even global market. A major goal of this project was to forge connections between the West African seed industry, global and regional seed companies and public plant breeding institutions to develop outstanding varieties, which is extremely important in the region [48, 51].

The trialing network established by this project provides a model for a thorough and efficient means of evaluating breeding materials and for applying biotechnology tools to address a major production constraint (ToLCD). Having access to the trialing network will streamline the breeding process and hasten the establishment of breeding capacity in the region. The participatory nature of the trialing network, with direct farmer input and involvement, promises to make varietal selection more accurate and appropriate for local farmer preferences. This trialing network provides an easily accessible strategy for international seed companies to enter the marketplace via the trialing network and connect into distribution channels for the dissemination of selected varieties to farmers. In Burkina Faso, trial data from this collaboration were used by a local cannery to inform variety selection for contract growers. The future of the vegetable industry in West Africa depends heavily on the introduction of new high-yielding, disease-resistant varieties that will allow the region to compete successfully in globalized markets. The newly established variety trialing network takes one step in that direction by enabling West African governments to evaluate the pool of available germplasm and select the most optimal varieties for the region. It is our hope that this capacity will serve as the foundation for poverty reduction as a host of complementary industries develop to translate better yields of vegetable crops into better livelihoods for producers and consumers. Improved tomato production in West Africa might benefit not only farmers, whose livelihoods would increase due to increased sales, but also those employed in downstream industries including regional or local canning or drying operations, truck drivers, exporters and merchants. Studies of the downstream effects of the adoption of high-yielding rice varieties during the Green Revolution in India found that higher earnings in the agricultural sector led to greater off-farm expenditures, resulting in widespread economic growth [52].

Abbreviations

AVRDC: The World Vegetable Center; CIRAD: French Agricultural Research Centre for International Development; ICRISAT: International Crops Research Institute for the Semi-Arid Tropics; ITRA: Institut Togolais de Recherche Agronomique; INRAB: Institut National des Recherches Agricoles du Bénin; CRI: Crop Research Institute; INRAN: Institut National de la Recherche Agronomique du Niger; CDH/ISRA: Centre pour le Développement de l'Horticulture/Institut Sénégalais de Recherches Agricoles; IER: Institut d'Economie Rurale; INERA: Institut de l'Environnement et de Recherches Agricoles de Burkina Faso; ABSPII: Agricultural Biotechnology Support Program II; SSA: Sudano-Sahelian zone of West Africa; ToLCD: tomato leaf curl disease; IPM: integrated pest management; USAID: United States Agency for International Development; IPM-CRSP: Integrated Pest Management Collaborative Research Support Program; NARS: National agricultural research services; ECOWAS: Economic Community of West African States; WACPSV: West African Catalogue of Plant Species and Varieties; TYLCV: tomato yellow leaf curl virus; ToLCMLV: tomato leaf curl Mali virus; TYLCMLV: tomato yellow leaf curl Mali virus; PepVYV: pepper vein yellows virus; WACCI: West African Center for Crop Improvement; SFSA: Syngenta Foundation for Sustainable Agriculture; AIFSRC/ACIAR: Australian International Food Security Research Centre; CF: Crawford Fund; UQ: University of Queensland; STFL: La Société de transformation des fruits et légumes de Loumbila; t/ha: tons per hectare; MLT: multi-location trial; AT: advanced trial.

Authors' contributions

MMJ, RLG, KP, JF-G conceived of the study, participated in its design and coordination, and wrote and edited the manuscript. KP, JF-G, IKA, VL, AAA, AM, OB, BH, FA-K, AAM, MN, LCO, LO, KTG, FS, RLG, MMJ participated in the design and/or execution of the variety trials in Africa, as well as compiling the post-trial tomato seed availability and tomato-processing information. RG, TK and MRR conceived and completed the begomovirus characterization work. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Ethical approval and consent to participate

This study did not require any ethical approval. All participants in this study provided their consent.

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