Essay

Contributions of the National Institute of Forestry, Agricultural and Livestock Research to genetic improvement of vegetables

Enrique González-Pérez[1§]
Moisés Ramírez-Meraz[2]
Jaime Canul-Ku[3]
Román Flores-López[4]
Luis Martin Macías-Valdez[5]

[1]Bajío Experimental Field-INIFAP. Celaya-San Miguel de Allende Highway km 6.5, Colonia Roque, Celaya, Guanajuato, Mexico. CP. 38110. [2]Las Huastecas Experimental Field-INIFAP. Tampico-Mante Highway km 55, Cuauhtémoc, Tamaulipas, Mexico. CP. 89610. (ramirez.moises@inifap.gob.mx). [3]Zacatepec Experimental Field-INIFAP. Zacatepec-Galeana Highway km 0.5, Zacatepec, Morelos, Mexico. CP. 62780. (canul.jaime@inifap.gob.mx). [4]Metepec Experimental Site-INIFAP. Highway Toluca-Zitacuaro km 4.5, Zinacantepec, State of Mexico, Mexico. CP. 51350. (flores.roman@inifap.gob.mx). [5]Pabellón Experimental Field-INIFAP. Aguascalientes-Zacatecas Highway km 32.5, Pabellón de Arteaga, Aguascalientes, Mexico. CP. 20660. (macias.luis@inifap.gob.mx).

[§]Corresponding author: gonzalez.enrique@inifap.gob.mx.

Abstract

Mexico is a center of origin and diversification of horticultural species. Through the genetic diversity that is possessed, several improved materials have been developed, in which, the National Institute of Forestry, Agricultural and Livestock Research has been a very important pillar, being this, one of its main activities. In the genetic improvement program of vegetables, different relevant genotechnical strategies are applied to increase bulb, fruit and tuber yield, such as the selection of clones in garlic, individual selection or hybridization in onion, pedigree or formation of pure lines by self-fecundation in chili; recurrent selection or hybridization in tomato, clonal selection in potato, family selection of maternal half siblings in husk tomato, with which experimental lines, clones, hybrids and varieties have been generated. As a result of those investigations, 19 varieties of garlic, 10 of onion, 21 of chili, 29 of potato and 2 of husk tomato have been released in the 35 years of INIFAP. Varieties that have been adopted by producers in the different agroecological regions of Mexico. However, despite the efforts that plant breeders make to continue with the generation of improved materials, it has not been possible to impact on a market dominated by transnational companies; therefore, necessary to implement INIFAP positioning strategies and invest in conservation and breeding of germplasm that possesses, which in future will result in obtaining better genetic materials that contribute to the benefit of human health.

Keywords: conservation, genetic variability, germplasm, varieties, vegetables.

Reception date: April 2021
Acceptance date: June 2021

In Mexico, genetic improvement in vegetables has been limited to few plant species, mainly to crops of greater culinary interest, with constant demand in the national and international market and due to the vast genetic diversity existing in species such as garlic (*Allium sativum* L.), onion (*Allium cepa* L.), chili (*Capsicum annum* L.), tomato (*Solanum lycopersicum* L.), potato (*Solanum tuberosum* L.) and husk tomato (*Physallis ixocarpa* Brot.), whose economic importance lies on their exports. In 2019, the average yield (t ha^{-1}) was 12.24 in garlic, 29.78 in onion, 34.74 in chili, 63 in tomato, 30.12 in potato and 19.18 in husk tomato (SIAP, 2020).

Yields that are directly related to the genetic structure of populations. Mexico is the center of origin of chili and husk tomato and of genetic diversity of crops such as garlic, tomato, onion and potato, so it has native or Creole germplasm (Rivera, 2001; Pérez *et al*., 2005; Ramírez-Meraz *et al*., 2015; Tavitas and Hernández, 2017; González-Chavira *et al*., 2019) to generate materials with high yield potential, wide adaptation to the different producing regions, the genetic resources of these five species are widely distributed in Mexico.

In garlic, two types are known, *Allium sativum* L. var. *Sativum* (softnecks; false soft stem or without floral stem) and *Alliun sativum* L. var. *Ophioscordon* (hardnecks; false hard stem or with floral stem), from which most of the materials grown in El Bajío region (Guanajuato and Querétaro), who produce purple garlic, the central area (Aguascalientes), with white garlic and the north-central area (Zacatecas and Durango) with jaspeado garlic, have been generated. Although it is also produced in a smaller area in other states such as Guerrero, where producers sow Creole genotypes (Pérez *et al*., 2005).

In onion, the intensive introduction of hybrids to Mexico began in 1968, with varieties of the types white, granex, yellow, yellow granex, red globe and red, since its introduction, the onion has undergone changes in its genetic constitution, which has allowed the generation of genetic variability in Creole materials, which over time have shown genetic differences with their predecessors because of the effect of the environment (Güemes and Inoue, 2001).

In Mexico, four types of onions are known: white, red, yellow, and scallion, in which transnational companies have captured the market. Thus, the most sown commercial onion hybrids are imported, among them Cirrus, Carta Blanca, and Cal 214 stand out (Personal communication with producers). In a smaller proportion, varieties of Creole origin are grown, such as Elena, Santa Teresa, La Chona, Santa Cruz, Copándaro, Cojumatlán and Estrella Roja (ATAG, 2015).

In the case of chili, 30 species of the *genus Capsicum* are known, five of which are domesticated: *C. annuum*, *C. frutescens*, *C. chinense*, *C. pubescens* and *C. baccatum*. The most cultivated species is *C. annuum*, followed by *C. frutescens* (Wang and Bosland, 2006). Mexico is considered the main center of origin and diversity and has the greatest genetic variability of the species *C. annuum* (jalapeños, guajillos, serranos anchos, pasillas, de árbol, etc.); also has other important species such as *C. chinense* (habanero), *C. pubescens* (perón chili or manzano) and *C. frutescens*, of which only wild and semi-domesticated materials (chilpayas or tabasco chili) are available (Ramírez *et al*., 2015).

In tomato, Mexico is a center of domestication and diversification (Peralta and Spooner, 2007). It has wide genetic diversity (Blanca *et al*., 2012) of both domesticated and wild species (Alvarez-Hernández *et al*., 2009; Chávez-Servía *et al*., 2011), as well as mutant, recombinant, and exotic materials. The species identified in Mexico and with which genetic improvement has been worked are: *S. lycopersicum*, *S. hirsutum*, *S. peruvianum*, *S. glandulosum* and *S. pimpinellifolium* (Tavitas and Hernández, 2017; 2019). Being the related species of *S. lycopersicum*, *S. habrochaites* and *S. pimpinellifolium* the only ones in which crosses have been made (Hernández-Bautista *et al*., 2014; Marín-Montes *et al*., 2020).

In potato, there are currently more than four thousand varieties worldwide, with a great diversity in terms of shape, color, flavor, resistance to pests and diseases and they present different levels of adaptation to climatic conditions. Genetic resources are preserved as collections of clones, tubers (*in vivo*), cultures *in vitro* and in liquid nitrogen, while the botanical seed of wild species is preserved under controlled conditions, such as in the International Potato Center (CIP) which has more than 6 thousand accessions of Creole varieties, wild and improved materials generated by CIP and other national programs.

In husk tomato more than 70 species of *Physalis* have been reported, of which the most cultivated species is *Physalis ixocarpa* Brot. (*Physalis philadelphica* Lam.), with eight recognized breeds and from which commercial materials have been derived (Peña *et al*., 2014). This improvement is based on genetic diversity whose sources of germplasm are wild, breeds or primitive cultivars, ancient varieties, material that has undergone an improvement process, but has not been released and germplasm of introduced species that have evolved to the Creole level.

During the 35 years of existence of the National Institute of Forestry, Agricultural and Livestock Research (INIFAP), researchers of the genetic improvement program of vegetables from various Experimental Fields have been working on the process of genetic improvement of several horticultural species implementing many genotechnical methods, such as individual selection of bulbs and plants, clonal selection of spontaneous mutants or plants for garlic (Lampasona *et al*., 2003), individual selection, combined mass selection, family selection of half siblings and hybridization in onion (Güemes *et al*., 2010); individual selection, mass selection, mass-stratified selection, pedigree, single seed descent method, formation of pure lines by self-fecundation (SSD) for hybrid formation and the use of haploidy in chili (Tut *et al*., 2013; Ramírez *et al*., 2018a; Santiago-López *et al*., 2018a; Santiago-López *et al*., 2018b; Santiago-López *et al*., 2020); recurrent selection, intra and interspecific hybridization and genomic selection for tomato (Marín-Montes *et al*., 2019; Hernández-Bautista *et al*., 2020), classical genetic improvement, hybridization and clonal selection in potato (Rivera, 2001), stratified visual mass selection, family selection of maternal half siblings and plant-to-plant crosses for husk tomato (Peña *et al*., 2002; Santiaguillo *et al*., 2004), relevant improvement methods for the increase in the yield of bulb, fruit and tuber.

Genetic improvement in garlic, onion, chili, tomato, potato, and husk tomato at INIFAP

The genetic improvement area of vegetables of economic importance in Mexico is mainly dominated by transnational companies, such as in the case of tomato, onion, potato, and husk tomato, but in species such as garlic and chili, Mexico is competitive. This is reflected in the largest area cultivated with foreign varieties in the different production systems of the country.

Garlic. In Mexico, the genetic improvement of garlic began in the autumn-winter cycle (A-W) 1978-1979 at the Agricultural Experimental Field Bajío belonging to the former National Institute of Agricultural Research (INIA), currently INIFAP. Work began with an individual clonal selection process in the Chilean variety of garlic (used for export) using as the main criterion the selection of bulbs with fewer teeth compared to the average of the original variety, as well as the bulb size, vigor, and plant health.

After six consecutive selection cycles, the top six clones were identified by individual selection and two compounds by mass selection. Clones that, when evaluated, responded favorably, showing fewer teeth per bulb and increase in weight. In 1986, a mass selection was released as a variety under the name Chileno Compuesto 1 and in 1987 individual selections under the names Chileno Vikingo 1, Chileno Vikingo 2 and Chileno Apaseo with yields of 16.5 t ha^{-1} were released. The same criterion was used for the Taiwan-type garlic (introduced in 1978), which after six cycles selections with 10 to 14 teeth per bulb and average yield of 41 t ha^{-1} were obtained. Selections from which the varieties: Tacátzcuaro, Tingüindín, Tocumbo, Texcoco, Huerteño, Chapingo-94, INIFAP 94 and Celayense were released (Heredia and Heredia, 2000).

In Zacatecas, the Barretero variety was released, obtained from germplasm from Chaparrosa region, municipality of Villa de Cos, Zacatecas (Reveles-Hernández *et al*., 2014) and the variety CEZAC 6, originated from bulbs from Korea, which by means of individual selection a genotype of Jaspeado type was obtained, provisionally identified as Korean and as Jaspeado Calera Orión (Table 1) (Reveles-Hernández *et al*., 2011). In Aguascalientes, the Orion variety of pearl type garlic was released, obtained from the clone CAL-RN-11-1-1-2-4 (highly productive material) (Macías *et al*., 2010b) and by individual selection the pearl-type San Marqueño variety was obtained from the clone C-37-1/8 and Orión (Table 1) (Macías *et al*., 2010a).

Table 1. Improved vegetable materials released* by INIFAP in the last decade.

Species	Category	Type	Denomination
Garlic	Variety	Jaspeado	Barretero and CEZAC 6
	Variety	Pearl	San Marqueño and Orión
	Variety	California	Diamante
Onion	Variety	White	Blanca Morelos
Chili	Variety	Habanero	Jaguar, Mayapan and Calakmul
	Variety	Ancho poblano	AP-VR
	Variety	Ancho mulato	AM-VR
	Variety	Guajillo	Don Luis
	Hybrid	Serrano	HS-44
	Hybrid	Ancho	HAP14F
	Hybrid	Ancho	HAM14F
	Hybrid	Guajillo	HAMG14E

Potato	Variety	White	Ramona, Nieder, Bayonera, Modesta, Milagros, Granate, Cuarzo, Cristal, Plata, Nevada, Frisca, Adelita, Paz, Antila, Real 14 and Micaela
	Variety	Red	Rubí and Citlali
	Variety	Pink	Ameyali
Husk tomato	Variety	Purple	INI-181

*= National Catalogue of Plant Varieties (CNVV).

Onion. The intensive introduction of hybrids to Mexico began in 1968 with the materials White Álamo F_1 and White Granex. In the same year, the first improvement works for hybrid formation began at the former INIA, now INIFAP. Works consisting of the evaluation of foreign onion materials during the A-W cycle at CAEB in Celaya, Gto. Subsequently, genetic improvement works focused mainly on obtaining materials resistant to premature flowering and in the increase of yield, as a result, in 1976 the Santa Cruz cultivar, recommended for the spring-summer cycle (S-S), was released and in 1984 the Géminis variety for the A-W cycle was released in Guanajuato (Heredia, 1985).

In 1985, the improvement program at CEBAJ of INIFAP was initiated, with the aim of generating varieties that would meet characteristics of size, shape, and yield for export in A-W plantings, which allowed the release of the varieties Elena, Santa Teresa, and Estrella Roja in 1989 (Heredia, 1989). On the other hand, in the Experimental Field Zacatepec, from 1996 to 2001, using collections from Copándaro and by family selection of half siblings, the variety Blanca Morelos was release (Table 1), which is the only one with breeder’s title valid until 2027 (Güemes *et al*., 2010; Ayala *et al*., 2010).

From 2000 to 2012, INIFAP did not work on the genetic improvement of onion, which caused the loss of the germplasm preserved in genetic improvement programs. Currently, CEBAJ has a collection of 120 accessions of white, purple and yellow onion, on which, since 2012, work has been carried out for the generation of varieties and hybrids of intermediate days, through the cross of materials with high content of dry matter and functional compounds, which allowed the obtaining of 12 advanced lines, which have been under evaluation since 2018, and of which in 2019 three promising materials were evaluated, and characterization in commercial batches, for possible release as hybrids. To date, INIFAP has released 10 varieties.

Chili. In Mexico, research in chili began at the Institute of Agricultural Research (IIA) and the Office of Special Studies (OEE) in the 50’s. The latter started a program of genetic improvement in 1952, which in 1956 moved to the Experimental Field El Horno. With the merger of IIA and OEE, INIA was formed in 1961, where the process of genetic improvement continued in different locations: CEBAJ for ancho and mulato chili; CE Pabellon for pasilla and guajillo; CE Las Huastecas for serrano; CE Cotaxtla for jalapeños and the Experimental Field Zona Henequenera for habaneros.

From this initial effort, the first varieties of ancho chili (Esmeralda, Verdeño, Flor de Pabellón and Mulato V2), of pasilla (Pabellón and Apaseo), of guajillo (Loreto, La Blanca and Gran Mirasol) were generated, as well as serrano chili with the variety Tampiqueño-74, that covered 90% of the national area of serrano chili in the 70’s (Pozo, 1981). In the same period, the germplasm bank of chili was formed at CEBAJ, with more than two thousand accessions from the different breed groups of *Capsicum* (Pozo, 1981).

With this genetic variability during the 35 years of the existence of INIFAP, 21 chili materials have been released: two varieties and three hybrids of serrano chili, three varieties and two hybrids of habanero, three varieties of jalapeño, two varieties and two hybrids of ancho chili, two varieties and one hybrid of guajillo and a variety of puya chili. Of which Coloso, Centauro, Don Benito, Jaguar, Mayapan, AP-VR, AM-VR and Don Luis (Table 1) are the genetic materials with the greatest economic impact in Mexico.

Tomato. The genetic improvement of tomato in Mexico has not been attended by government institutions, and just partly by public research centers. Only transnational companies have formally attended it (Salgado-Meraz *et al*., 2018). INIFAP has germplasm banks of tomato, of which its research staff have limited themselves to regenerating and, in the best of cases, characterizing. The INIFAP genetic collection of tomato comes from different parts of Mexico and the world, consisting of 231 accessions constituted by the species *S. lycopersicum*, *S. hirsutum*, *S. peruvianum*, *S. glandulosum* and *S. pimpinellifolium* (Tavitas and Hernández, 2017, 2019), sheltered in Zacatepec, Morelos and 129 accessions preserved in Celaya, Guanajuato (Molina and Córdova, 2006).

Of these, only 54% are characterized. In 1989, a genetic improvement program began at the Experimental Field Zacatepec (CEZ) to generate varieties resistant to chino del tomate. As a result, four tolerant F_7 lines were obtained, without releasing any variety (SNICS, 2020). From 2016 to 2019, genetic improvement works were developed in tomato collections carried out through projects supported by fiscal resource resulting in a collection of 25 accessions, which are being used to develop materials of saladette, heirloom or rough and grape type, of the latter there is an advanced line that is in the process of morphological and phenotypic characterization for its possible release as a variety. However, with all this genetic richness the formation of advanced lines and experimental hybrids is minimal (Hernández-Leal *et al*., 2013, 2019; Parra-Gómez *et al*., 2016) and consequently to date, INIFAP has not released improved materials.

Potato. The potato research program in Mexico began in 1949 at the OEE, sponsored by the Rockefeller Foundation, predecessor of INIA, who conducted studies on late blight and selected clones with resistance to this disease (Niederhauser, 1954), which gave rise in 1958 to the Eréndira variety. Subsequently, the varieties Anita, Berthita, Conchita, Dorita, Elenita, Florita, Gabriela, Greta, Hilda, Juanita, Murca, Atzimba and Montsama were released, highly resistant to late blight, but in some cases with poor visual quality and of long cycle, characteristics typical of the agroecological conditions of Mexico’s ranges.

Epidemiological studies on late blight and its relationship with native wild species such as *S. Demisum*, general and specific combining ability of genotypes and population variability (Zúñiga-López *et al*., 2000), the characterization of Oomycete breeds and the mechanisms of resistance to it (Rubio *et al*., 2005) have been used as basis for the obtaining of varieties. As well as studies on the purple top complex or zebra chip (Díaz-Valasis *et al*., 2014) and the genetic variability of potato in relation to the resistance to haplotypes of *Candidatus* Liberibacter *solanacearum* (Hernández-Dehesa, 2018).

As a result of these investigations, of the 58 materials registered in Mexico in the National Catalogue of Plant Varieties (CNVV) (SNICS, 2020), INIFAP has contributed 29 varieties, in addition to the 13 released in the 50's and 60's that are not in CNVV. In 2014 the varieties Nevada, Plata, Rubí, Granate, Cuarzo and Cristal were released. From 2015 to 2020, the varieties Citlali, Frica, Adelita, Paz, Antila, Micaela, Real 14 and Ameyali (Table 1). INIFAP's potato program has provided genotypes with long-lasting resistance to late blight that have been used in improvement programs and even some genotypes have been released as varieties in other Central American countries.

Currently, there are two banks of germplasm, one *in vivo* with more than 5 000 accessions and another *in vitro* which has 480 genotypes that have materials with resistance to late blight, purple top or zebra chip, golden nematode, bacteria, precocious, with industrial quality, tolerance of high temperatures and wide adaptability (20 to 3 400 m) (López, 1988). From both banks the breeders identify progenitors with desired qualities in the new progenies, select outstanding genotypes with the improvement scheme and evaluate in the field material free of viruses and other diseases so that the selected genotypes express their full performance potential.

Husk tomato. Genetic improvement works on husk tomato began in 1972 in CEZ of INIFAP, from the evaluation of a collection of 49 Creole populations in the State of Morelos.

In the following four years, the top 11 populations were evaluated and in the last year four high-yield lines were identified and selected, one of which was released as 'Rendidora' (Saray *et al*., 1978) and from which varieties registered in the CNVV have been generated that have unfortunately been released by other instances.

From 1980 to 2012 no genetic improvement was carried out in husk tomato at INIFAP, which led to the loss of much of the genetic diversity. Situation for which, during this period, producers grew Creole materials that they reproduced many years ago (Magaña *et al*., 2011) and Creole selections from foreign companies. As of 2014, the genetic improvement program of this species was reactivated, with the intention of taking advantage of the small number of germplasm collections of INIFAP and the collections carried out from 2014 to 2017.

Currently, CEBAJ has 400 accessions collected in producing regions from Guerrero, State of Mexico, Morelos, Puebla, and Tlaxcala, which, since 2014, have been used to generate genetic variability. Experimental lines with desirable characteristics by the producers have been derived from these accessions, which are being evaluated and of which five are in evaluation stages of homologous cycle (González-Chavira *et al*., 2019). One of them released in 2020 as a variety under the name INI-181 (Table 1) for cultivation in central Mexico.

Perspectives and challenges of genetic improvement of horticultural species in Mexico

Horticultural crops in Mexico maintain their growth prospects in the short, medium and long term. Their main strength lies on the fact that Mexico has a great genetic diversity in many of the horticultural species that keep a constant demand by the population and whose profit margins are lucrative. Their cultivation demands considerable investments, with the seed being an expensive input and the prices obtained by the producer are affected by the periodic concentration registered in supply during the year, so they use native or Creole genetic resources.

The alternative is the use of materials improved by INIFAP, adapted to the different agroclimatic regions of Mexico and with of lower cost compared to the materials offered by transnational companies, which would bring direct benefits to producers and INIFAP. The possibility that producers, from the states where vegetables are grown and marketed, adopt the improved genetic materials of INIFAP can be achieved by implementing promotion and diffusion strategies that provide the conditions for our varieties to raise their regional and therefore national acceptance averages. A challenge that is not easy to face, because currently around 95% of the seed of horticultural species of economic importance that are marketed in Mexico are of foreign origin.

It is a priority to resume research levels for the development of new varieties of garlic, onion, chili, tomato, potato, husk tomato and other species with increasing demand for national and even international consumption. Besides a greater quality control in the seeds of released varieties already used by producers, to avoid the loss of the country's biodiversity and reduce the costs of obtaining seeds of varieties from national origin.

The impulse and financial support of INIFAP to the genetic improvement of vegetables will allow in the near future the obtaining and release of materials with characteristics desirable by producers and that are competitive. Because of this, the conservation and use of germplasm possessed by INIFAP is a priority. The germplasm sheltered in the different experimental fields, where genetic improvement is carried out, is from different agroecological regions located in states such as the State of Mexico, Guanajuato, Oaxaca, Puebla, San Luis Potosí, Sinaloa, Tamaulipas, Tlaxcala and Yucatán. Core collections, with which the traditional genetic improvement is still working, that has led to the obtaining of advanced lines derived from the elite material and the release of varieties.

Effort that has been insufficient and has limited INIFAP's competitiveness towards transnationals in the horticultural sector, so the challenge is to initiate a systematized program of genetic improvement by applying different genotechnical strategies. For this, it must be innovated with genomic selection tools (Cappetta *et al*., 2020; Hernández-Bautista *et al*., 2020) combined with traditional improvement, hybridization, selection, backcrosses, introgresion etc.

With the primary objective of generating improved materials adapted to the different production systems of Mexico. Considering biotic and abiotic restrictive factors affected by climate change. In the short term, it is important to continue the maintenance of germplasm banks, the generation and release of new horticultural varieties resistant to pests and diseases as a component for sustainable production. As well as the seed production of varieties generated at INIFAP that meet in a timely manner the changing demand of users.

In this sense, the registration of new materials is projected, such as the variety of serranillo chili or soledad CHISER-522 for the Gulf of Mexico region, the serrano chili hybrid HS-52, the variety of jalapeño rayado chili Crótalus developed especially to produce chipotle, and the chile de árbol variety CdA- 58 to meet the demand of producers of the country (Ramírez *et al*., 2016; Ramírez *et* *al*., 2018b). Additionally, the program of mass seed production of the hybrids HMG14E (guajillo chili), HAM14F (ancho mulato) and HAP14F (ancho poblano) of recent generation will start (Santiago-López *et al*., 2018a; Santiago-López *et al*., 2018b; Santiago-López *et al*., 2020). In husk tomato, the release of the INI-64 variety is expected, which is a purple tomato recommended for the central part of Mexico.

In the medium term, technologies such as cryopreservation should be incorporated into germplasm banks, continuation with traditional and assisted genetic improvement, generation of varieties with resistance to diseases, incorporation of characteristics for tolerance of different temperatures, industrial quality, nutraceutical and for different culinary and gourmet uses.

Continue the generation of sustainable production technologies and establish seed increase programs of varieties that meet the requirements of the entire production chain: producer (yield, resistance to adverse factors, adaptation), marketer (quality in appearance, shelf life), processor (industrial yield) and consumer (shapes, colors, smells, and flavors) (Ramírez *et al*., 2018b).

In the long term, the maintenance of germplasm banks and the generation of varieties must be continuous and of high priority, so it is important to have government and institutional support to meet the changing demands of producers and the productive sector. Having as a premise the conservation of genetic resources and the generation of materials that adapt to the changes that the climate constantly undergoes as result of human activities.

Conclusions

INIFAP needs to revalue its germplasm diversity. It should focus on the conservation of germplasm and generation of materials demanded by the producer and therefore the consumer. To achieve this, it is necessary to refresh the outstanding germplasm existing in germplasm banks, continue collecting and propose frontier strategies in genetic improvement in the near future.

Acknowledgements

The authors thank the National Institute of Forestry, Agricultural and Livestock Research (INIFAP) for the facilities provided for making this contribution.

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