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Original article

# Past Contributions and Present Challenges of Sunflower Breeding in Argentina

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**Abstract**

Sunflower is grown in Argentina across a large and heterogeneous target population of environments. From the beginning of sunflower breeding activities in 1931 until the present day, the evolution of planted area, pathogen populations, market demands, and management practices posed challenges to the local breeding community. In the first part of this review, we have divided the national sunflower production history into three periods to analyze the past contributions of local breeding to the local and global sunflower industries. Special emphasis is placed on the role played by the National Institute of Agriculture Technology. The first period was characterized by the development of open pollination varieties which became the germplasm foundation on which the Argentine sunflower hybrid industry was later developed. From 1975 onwards, the genetic gains achieved by sunflower breeding programs have strongly contributed to the increase in farmers' yields (second and third periods). Production per unit area was sustained during the phase of displacement of the crop to more marginal environments pushed by the explosive growth of soybeans (third period). In the second part of this study, we used a holistic approach to analyze the present challenges of sunflower breeding in Argentina, addressing (1) the complexity of the target genotype-environment system, (2) the genetic resources available to the breeding programs, (3) the clarity of the breeding objectives and strategy, and (4) the resource capability to implement, evaluate and manage the necessary breeding strategies.

**Keywords:** Sunflower breeding, Hybrid development, Genetic gain, Argentina.

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## INTRODUCTION

Sunflower (*Helianthus annuus* L.) is grown in Argentina between latitudes 26ºS (Chaco) and 39ºS (southern Buenos Aires) across a large and heterogeneous target population of environments (TPE). These include subtropical (Northern) and temperate (Central and Southern) climates and a wide range of soil types, water regimes, pest and disease conditions, and management practices. Over the last 50 years, the national planted area fluctuated between 1.2 and 4.2 million hectares (summer seasons 1974-1975 and 1998-1999, respectively), strongly driven by the price of sunflower oil relative to other agriculture commodities and the dynamics of the soybean planted area. Currently, sunflower is the second oilseed and the fourth grain crop in terms of both planted area and total country production (Subsecretaría de Agricultura, 2023). Besides being a very relevant and distinctive component of the national agro-industrial sector, sunflower is also a key player in many regional economies, contributing to the sustainability of rural communities in vast regions of the country.

The cultivation of sunflower in Argentina started by the end of the 19$^{th}$ century, when European immigrants introduced seeds of open pollinated varieties (OPV) from Russia and multiplied them at small scale in different regions of the national territory. Most sunflower seeds introduced and grown during the first decades of the 20$^{th}$ century corresponded to the OPV known as Giant of Russia or Mammoth Russian. This heterogeneous population showed strong variability for relevant agronomic traits (Bertero de Romano and Vázquez, 2003; Castaño, 2018). With the aim of uniformizing cycle and plant type of this cultivar, a population improvement program began at La Previsión Research Station (province of Buenos Aires) in 1931; this milestone being considered the starting point of sunflower breeding in Argentina. From those early days to the present, the dynamics of the sunflower planted area, the evolution of the pathogen populations, the changing market demands, and the development of advanced crop management practices imposed continuous challenges to the local (public and private) breeding community.

## PAST BREEDING CONTRIBUTIONS

The 6 periods into which the history of sunflower production in Argentina was divided (ASAGIR, 2017; Castaño, 2018) provide a suitable framework to review the past contributions of local breeding to the regional and global sunflower production systems. For the analysis of breeding activities, the first 4 periods (i.e., “pre-industrial”, from the introduction of the crop until 1929; “the great expansion”, 1930-1949; “crisis”, 1950-1959; and “recovery”, 1960-1974) could be grouped into one phase (called first period in this paper), in which genetic improvement efforts focused on the introduction and local development of OPVs. The discovery of nuclear (Leclercq, 1966) and cytoplasmic male sterility (Leclercq, 1969) and fertility restoration (Kinman, 1970) systems allowed the development and commercial production of sunflower single-cross and three-way hybrids. These were massively grown during the following (second and third in this paper) periods, corresponding to the "dissemination of hybrids" (1975-1999) and "relocation" (2000-present).

During the first period and extending up to 1990, private companies and public institutions obtained and registered 25 OPVs in Argentina. Although yields achieved by farmers in the decades in which OPVs were grown remained stuck around 750 kg $ha^{-1}$ (López Pereira et al., 1999; Fig. 1), population breeding activities resulted in the creation of a broad base of locally adapted sunflower germplasm, which became instrumental for the success of the subsequent development of inbred lines and commercial hybrids (Fig. 1; González et al, 2015). Bertero de Romano and Vázquez (2003) have reported the originating stations, authors, methods of obtention, pedigrees, years of release, and main characteristics of the 25 OPVs created in Argentina. Using this information, we will limit the scope of this review to highlighting the key milestones achieved by breeders during this period.

In 1938, E. Klein released Selección Klein, the first Argentine sunflower OPV. It was developed from a local population and was shorter, earlier, and more uniform than those grown by farmers at that time. Soon after, V. Brunnini and B. Scheloto released La Previsión 8 and La Previsión 9 in 1939 and 1941, respectively, both derived from Giant of Russia. These and other breeders such as Massaux, Forrajeras Bonaerenses, Northrup King, La Forestal, the Ministry of Agrarian Affairs of the Province of Buenos Aires, and the National Institute of Agriculture Technology (INTA) continued developing OPVs until 1990. This was the year of release of Antilcó, the last Argentine oilseed OPV, developed mainly for marginal conditions and released 20 years after the first commercial hybrid (Bertero de Romano and Vázquez, 2003; Castaño, 2018).

Most OPVs registered during this period were derived from reselection or crosses and further selection of local and introduced varieties (mainly from the former USSR), and synthetic populations of domesticated *Helianthus annuus*. The breeding programs of INTA were the exceptions to this rule, as they systematically utilized wild *Helianthus* species to incorporate relevant agronomic and defensive traits through interspecific crosses (Bertero de Romano and Vázquez, 2003; Castaño, 2018; González et al., 2015).

Sunflower breeding activities conducted by INTA commenced in 1939 and 1950 at the research stations of Pergamino and Manfredi, respectively (González et al., 2015). The breeding efforts of these programs were mostly focused on uniformity, duration of the ontogenetic cycle, self-compatibility, tolerance to shattering, drought tolerance, disease resistance (mainly rust and downy mildew) and grain-oil concentration. In Table 1 we list few examples of OPVs developed by INTA which were massively adopted by farmers and, most importantly, contributed with relevant adaptive traits to further development of commercial germplasm (Bertero de Romano y Vázquez, 2003):

**Table 1:** Examples of relevant open pollination varieties developed by INTA.

| Originating Station | Code | Year of release | Wild species in the background | Key traits |
|---|---|---|---|---|
| Manfredi | Manfredi INTA | 1960 | *H. annuus ssp. annuus* | Rust resistance |
| Manfredi | Impira INTA | 1962 | *H. argophyllus* | Rust resistance; tolerance to drought, Sclerotinia and downy mildew |
| Manfredi | Cordobés INTA | 1965 | *H. annuus ssp. annuus* | Rust resistance; tolerance to drought, Albugo and Alternaria |
| Pergamino | Guayacán INTA | 1964 | *H. annuus* | Rust resistance |
| Pergamino | Ñandubay INTA | 1964 | *H. debilis ssp. cucumerifoliu*s | |
| Pergamino | Pehuén INTA | 1969 | No wild background | Rust resistance; high grain-oil concentration |

The lead contributors to the germplasm developed by INTA were: Manfredi station: H. Bauer, J. Báez, T. Mácola, C. Areco and D. Álvarez; Pergamino station: A. Luciano, M. Davreux, P. Ludueña, A. Bertero de Romano and C. Farizo.

The first sunflower hybrid released in Argentina was Dekalb G 104. It was created by J. Semienchuck, registered in 1970, and developed using nuclear male sterility linked to an anthocyanin pigmentation phenotypic marker (Semienchuck, 1974). Four years later, the first hybrids developed with cytoplasmic male sterility, Cargill S 200 and Contiflor, created by O. Monge Navarro and A. Vázquez, respectively, were released to the market (Castaño, 2018). The massive replacement of OPVs with hybrid cultivars starting in 1975 resulted in breaking points in both the rates of farmers' yield increase (Fig. 1) and genetic gain for grain yield (López Pereira et al., 1999). At this point in time, several private seed companies not listed among the OPV developers were already actively conducting local sunflower breeding efforts. During the second and third periods (1975-1999 and 2000-present, respectively), the high rates of yield gain in the farmers' fields (Fig. 1 and 2) and genetic progress achieved across all sunflower growing regions (Sadras et al., 2000; de la Vega et al., 2007b; de la Vega and Chapman, 2010; Tassara and Bock, 2016) allowed the development of a sustainable sunflower value chain in Argentina.

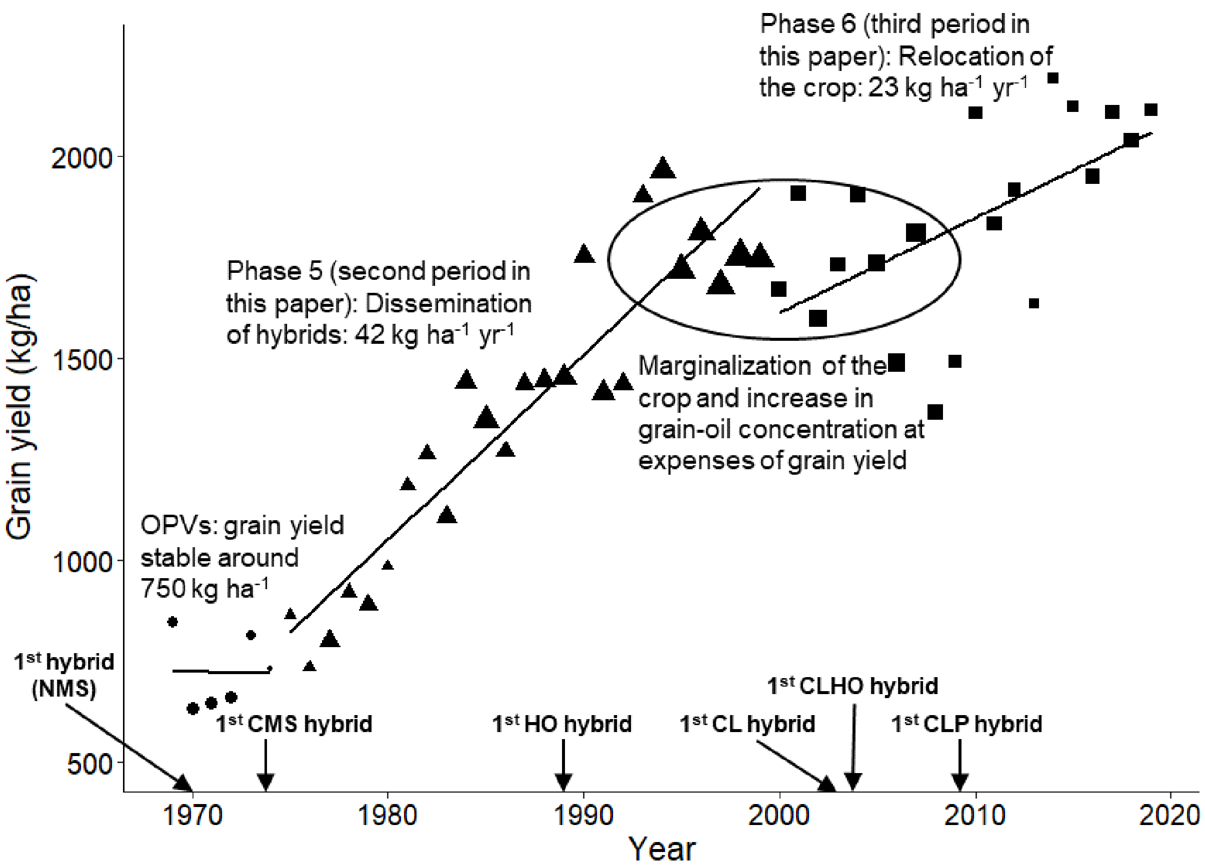


**Figure 1:** Evolution of sunflower grain yield in Argentina from 1970 to the present (data from Subsecretary of Agriculture of Argentina). Three phases of sunflower history (ASAGIR, 2017; Castaño, 2018) are identified. The size of the symbols is proportional to the total national planted area of each year. Key milestones for sunflower breeding in Argentina (technology releases) are indicated on the x axis.

Genetic gains can be estimated either by (1) comparing an historic set of cultivars with uniform management at the end of the period under study or (2) from retrospective analysis of multi-environment trial data collected by breeding programs over years (de la Vega et al., 2007a). Applying the first approach to a set of cultivars developed by Syngenta between 1984 and 2005, Tassara and Bock (2016) reported rates of genetic gains for grain yield of 25.5 kg ha$^{-1}$ year$^{-1}$, 63.6 kg ha$^{-1}$ year$^{-1}$, 49.6 kg ha$^{-1}$ year$^{-1}$ and 29.1 kg ha$^{-1}$ year$^{-1}$ for conventional, herbicide resistant (HR), high oleic (HO), and HR-HO hybrids, respectively. In a similar study, 43 commercial hybrids developed by Advanta Seeds between 1983 and 2021 and tested in the Central and Southern sunflower regions of Argentina allowed to estimate rates of genetic gain for oil-corrected grain yield of 32 kg ha$^{-1}$ year$^{-1}$ and 102 kg ha$^{-1}$ year$^{-1}$ for conventional and HR hybrids, respectively (R. Reid, personal communication). Following the second approach, utilizing linear mixed model analyses to account for the imbalance of historical trial datasets, and including hybrids of all relevant companies in the market, a rate of genetic gain for grain yield of 16.1 kg ha$^{-1}$ yr$^{-1}$ was reported for the period 1982-2005 in the Central region (de la Vega et al, 2007b), and rates of genetic gain for oil yield of 6.7 kg ha$^{-1}$ yr$^{-1}$, 10.5 kg ha$^{-1}$ yr$^{-1}$ and 6.2 kg ha$^{-1}$ yr$^{-1}$ were reported for the period 1982-2007 in the Northern, Central and Southern regions, respectively (de la Vega and Chapman, 2010).

The genetic gains achieved by sunflower breeding programs have strongly contributed to the observed increase in farmers' yields from 1975 (Fig. 1; second period) and sustained the production per unit area during the phase of displacement of the crop to more marginal environments (Fig. 1; third period). The increase in yield was observed across all sunflower growing regions of the country (Fig. 2). During the second period and the beginning of the third one, sunflower breeding has progressed to merge the best combinations of two original hybrid groups. These are: group 1: intermediate-late to late maturity hybrids of white-striped seed, low grain-oil concentration, and high relative grain yield, mostly developed from locally bred OPVs; and group 2: intermediate-early to early-maturity hybrids of black seed, high grain-oil concentration, and low relative grain yield, largely derived from Eastern European and US germplasm. The breeding process towards this goal resulted in a narrower range of maturities and higher oil yield resulting from the combination of high grain yield and high grain-oil concentration (de la Vega et al., 2007b; de la Vega and Chapman, 2010).

During the third period, the rate of hybrid registration increased, reaching a peak of 20 to 30 hybrids per year between 2013 and 2015 (Fig. 3a). From the end of the second period and during the third one, the sunflower research programs of Argentina released to the market end-user oil quality and herbicide resistance technologies that improved the competitiveness of the crop. The first HO, Clearfield®, and Clearfield® HO hybrids were registered in 1988, 2003 and 2004, respectively. The Clearfield® Plus herbicide technology was developed in Argentina by Nidera (Sala et al., 2012). The first Clearfield® Plus hybrid (Paraíso 1000 CL Plus) was registered in 2009 (technology milestones are indicated in Fig. 1).

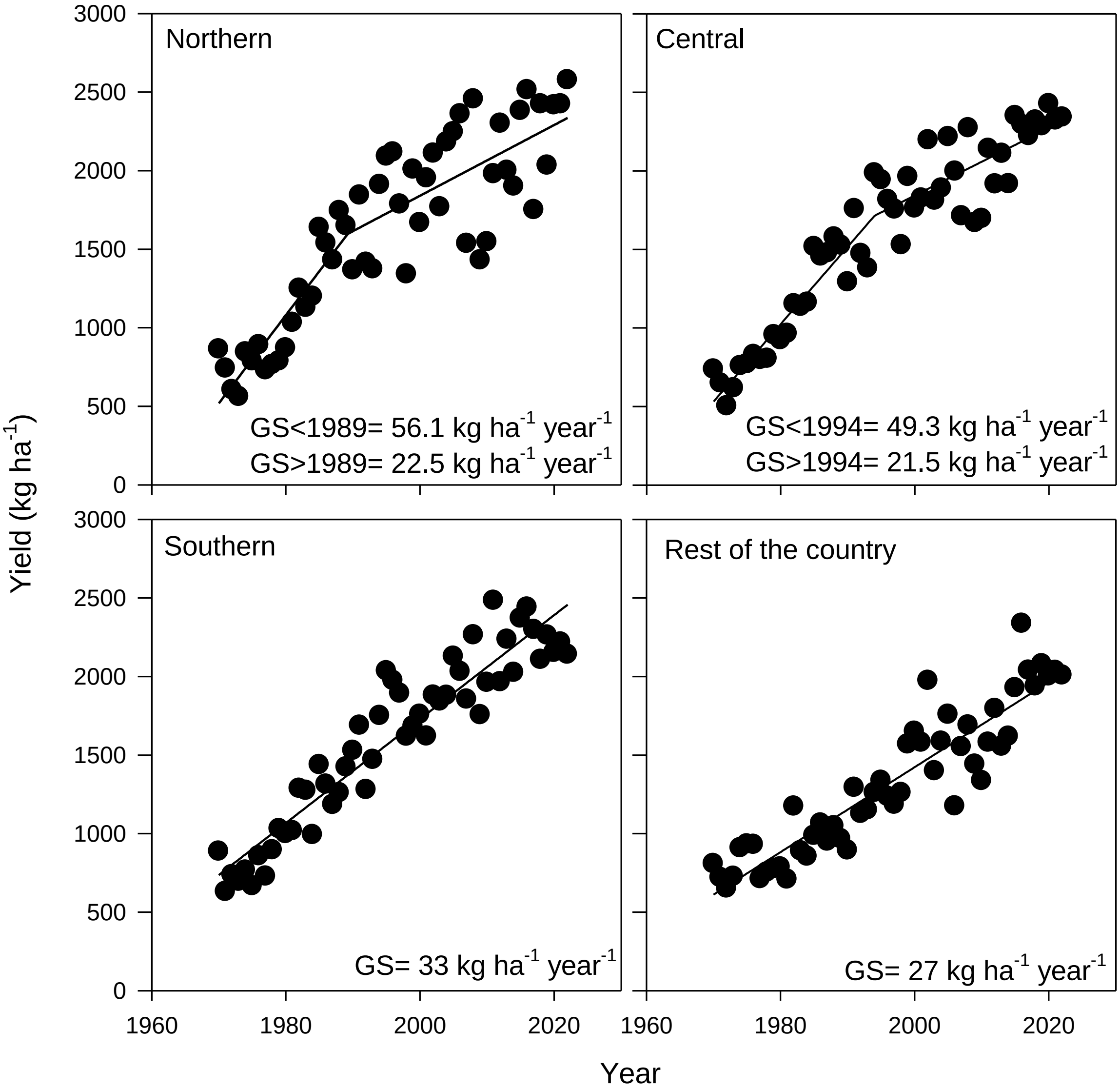


**Figure 2:** Evolution of sunflower grain yield in different growing regions of Argentina from 1970 to the present (Subsecretaría de Agricultura, 2023). Regionalization according to Castaño (2018).

With the beginning of the "dissemination of hybrids" period in the mid-1970s, the breeding programs of INTA refocused most of their efforts towards the development of inbred lines for hybrid creation and population improvement. Both OPVs and inbred lines created by INTA were made available to local and international breeders. The main traits targeted by these programs were disease resistance (mainly Verticillium wilt, rust, and downy mildew), grain weight and quality, grain-oil quality and concentration, and tolerance to bird damage (González et al., 2015). Below we provide a few examples of germplasm accessions obtained by INTA or by other institutions but derived from INTA cultivars, which became known sources of relevant agronomic traits (grouped by trait; González et al., 2015). This list is not expected to be exhaustive; it is rather an illustrative sample of genotypes that helped enhance many germplasm bases around the globe. Please visit the references in this paper for more detailed information.

*2.1. Tolerance to Sclerotinia head rot*: RK 416, IL ALB2/5261, IL 5383, IL 51084/5429, IL 7-1-1 (Filippi et al., 2017)

*2.2.* Resistance to downy mildew: HA 60 (*Pl1*), HA R4 (*Pl16*), HA R5 (*Pl13*)

*2.3. Resistance to rust*: HA R1, HA R2 (*R5*), HA R3 (*R4*), HA R4, HA R5, HA 369

*2.4. Resistance to Verticillium wilt*: HA R1, HA R2, HA 369, Estanzuela 75

*2.5. Drought tolerance*: R426-1, R435, R431 (Moreno, 2010), HA R4 (Lambrides et al., 2004)

*2.6. Tolerance to bird damage*: BRS-1, BRS-2, BRS-3

## OBJECTIVES OF SUNFLOWER BREEDING IN ARGENTINA

The main objective of sunflower breeding is to increase oil yield (Fick and Miller, 1997) across all environmental conditions that are present in a program's TPE. To achieve this goal, it is necessary to increase both grain yield per unit area and grain-oil concentration (determined by husk-to-kernel ratio and kernel-oil concentration; Zuil et al., 2016). Further it is necessary to ensure all agronomic and defensive attributes that confer adaptation to the local growing conditions are present in a way that allows yield potential to be expressed in the farmers' fields as much as possible. The most agronomically relevant traits for the sunflower production system of Argentina include duration of the ontogenetic cycle (earliness *per se* and response to photoperiod), plant height, plant architecture, anatomy and position of the capitulum that maximizes grain number, reduces achene temperature during grain filling (Ploschuk and Hall, 1995) and reduces bird damage (Zuil and Colombo, 2012), self-compatibility, tolerance to root and stalk lodging (Sposaro et al., 2010), stay green (de la Vega et al., 2011), tolerance to drought and high temperatures (Rondanini et al., 2006), tolerance to high plant population densities (López Pereira et al., 2022), herbicide resistance (Miller and Al-Khatib, 2002 and 2004, Sala and Bulos, 2012), tolerance/resistance to fungal and bacterial diseases (Bertero de Romano, 1986; Vear, 2017), insect tolerance (in particular *Melanogromyza cunctanoides* Blanchard) and resistance to broomrape (Fernández-Martínez et al., 2015); the last trait being relevant only because many Argentine breeding programs develop germplasm for Europe.

Other sunflower breeding goals in Argentina include end-use quality traits (e.g., conventional oil type, HO, ultra HO, high palmitic, high stearic, reduced sats; Martínez-Force and Garcés Mancheño, 2004), grain type (e.g., oilseed, dehulling type, bird food; Fick and Miller, 1997) and producibility of parental inbred lines (e.g., seed number, seed dimensions and test weight in female inbred lines and recessive branching and high pollen production in male lines).

## Challenges of sunflower breeding in Argentina

To deliver a genetic gain that guarantees the long-term sustainability of sunflower in Argentina, breeding programs must overcome some challenges that are unique to this complex production system. In this analysis, we will review these challenges following the approach proposed by Cooper et al. (1999). We will consider (1) complexity of the target genotype-environment system; (2) genetic resources available to the breeding programs to achieve their objectives; (3) clarity of the breeding objectives, capacity of the adopted breeding strategy to achieve the necessary genetic modifications and selection strategy; and (4) physical and human resource capability to implement, evaluate and manage the necessary breeding strategies.

*Complexity of the target genotype-environment system*: The sunflower production system of Argentina is geographically large, very heterogeneous in terms of the environmental factors affecting absolute and relative yields (Chapman and de la Vega, 2002), and shows strong gaps between attainable and achieved yields (Hall et al, 2013). In this context, local breeding programs must deal with the effect of strong genotype × environment (G×E) interactions, which complicate the identification of superior genotypes and could impose a restriction to genetic progress. This challenge is even greater for breeding programs targeting other markets, such as Europe, North America, or tropical sunflower producer countries.

The observed magnitude of the predictable genotype × subregion interactions suggested that subdividing the TPE into mega-environments (ME) or adaptation zones (North subtropical and South-Center temperate) and selecting for specific and broad adaptations between and within MEs, respectively, would have a higher relative merit than selecting for wide adaptation to the undivided TPE (de la Vega and Chapman, 2006). Retrospective analyses of genetic gain have shown that selection for specific adaptation to the Central region did not have a correlated response in the Northern or in the Southern regions (de la Vega and Chapman, 2010), which would confirm the value of the subdivision strategy. However, it must be considered that the outcomes of these studies are highly dependent on the tested germplasm. Empirical observations allow us to hypothesize that breeding programs have progressed in the development of broad adaptation during the last decade, so these conclusions could not be totally valid nowadays.

Even subdividing the sunflower TPE of Argentina and selecting for specific adaptation to the Northern, Central and Southern (or Northern and Central-Southern) MEs, the ratios of G×E interaction to G effects within subregion (0.3 to 3.6) still complicate genotype selection decisions for breeders and farmers. For example, it was estimated that more than 10 testing locations conducted over at least 4 years are needed to reach a hybrid-mean repeatability above 0.80 in the Northern region (de la Vega and Chapman, 2006). With the aim of providing sunflower farmers with an objective decision tool for hybrid election based on accurate characterizations of yield performance (stability and adaptability) and disease tolerance profile, the National Network of Sunflower Hybrid Testing (known as RNG from its Spanish initials) was created in 2001. This effort was a joint initiative of INTA and the Argentine Sunflower Association (known as ASAGIR from its Spanish initials).

ASAGIR was created in the 1980s and strongly revitalized in 2000, as a response of the sunflower value chain community to the displacement of the crop in Argentina. For four decades, ASAGIR has promoted and implemented multiple actions to improve the competitiveness of sunflowers in the context of the global and national oil complexes. Among other actions aimed at achieving this goal, ASAGIR has organized international and national sunflower conferences and symposia, promoted knowledge exchange, supported research (Castaño, 2018) and coordinated the supervision and publication of the trials conducted by the RNG. It is important to notice that INTA conducted sunflower trials before the creation of the RNG, but ASAGIR became a guarantor of the quality of the published results since 2001.

The RNG evaluates the performance of hybrids obtained by private and public breeding programs through a national INTA-ASAGIR agreement. The main goals of the RNG are field phenotyping (cycle, grain yield, grain-oil concentration, oil fatty-acid profile for HO hybrids, plant height, root and stalk lodging, disease scores, etc.) and the creation of a public-access database, which allows different actors in the value chain to conduct studies for multiple traits utilizing data collected across environments. Disease screening through artificial inoculation in controlled or managed environments that favor the pathogen development is also part of the scope of this network (Troglia, 2003). All results obtained by the RNG are published on the INTA and ASAGIR webpages. The methods utilized for statistical analyses (performance, stability, patterns of adaptation) include (1) univariate analysis (GLM or ANOVA) and mean comparison tests (LSD), (2) grain and oil yield as a function of the CV (Abbate et al., 2010); (3) stability according to Shukla (1972) (adapted by Masiero and Castellano, 1991); and (4) linearly adjusted environmental indexes (Finlay and Wilkinson, 1963, Santos et al., 2013, Czyruk et al., 2020).

On average, the RNG evaluates 40-70 commercial and precommercial hybrids every year across 27-30 sites distributed all over the sunflower growing regions, which are expected to provide a representative sample of the TPE. The strong increase in hybrid registration observed for the period 2005-2015 resulted in the testing of more than 100 hybrids per year during these years (Fig. 3b). The RNG made an important contribution to technology adoption by farmers. For example, soon after the downy mildew epiphytotic suffered in 2001 in the south of the province of Buenos Aires, several hybrids showing resistance to the races 710, 730 and 770 were evaluated in this testing net. The information generated by those experiments allowed a fast and informed hybrid replacement by farmers. A similar situation was observed when a new downy mildew epiphytotic affected the Northern region (Bazzallo et al., 2016). Since the summer season 2005-2006, the RNG conducts experiments to evaluate the Clearfield® technology and to characterize its potential to control weeds in different growing conditions. This has contributed to the adoption of imidazolinone herbicide resistance by most sunflower farmers in Argentina.

The seasonal and spatial evolution of pathogens, the displacement (marginalization) of the growing area and the changes in crop management practices also contribute to the complexity of the Argentine sunflower production system. It has been observed that yields of individual sunflower hybrids decline over time (de la Vega et al., 2007a); which could be partially explained by the changes in the composition of the TPE resulting from the above-mentioned factors. The changes in racial composition, geographical distribution, and severity of pathogens in the last decades were particularly evident for downy mildew (Spring, 2019), Verticillium wilt (Clemente et al., 2017) and Phomopsis stem canker (Zambelli et al., 2021). The displacement of sunflower to less favorable environments, which occurred between the second and third historical periods, could have also resulted in a significant change in the environmental composition of the sunflower TPE due to both (1) the increase in the proportion of marginal conditions relative to favorable ones, and (2) the decrease of the planted area of the Central region relative to the Northern and the Southern regions (Castaño, 2018).

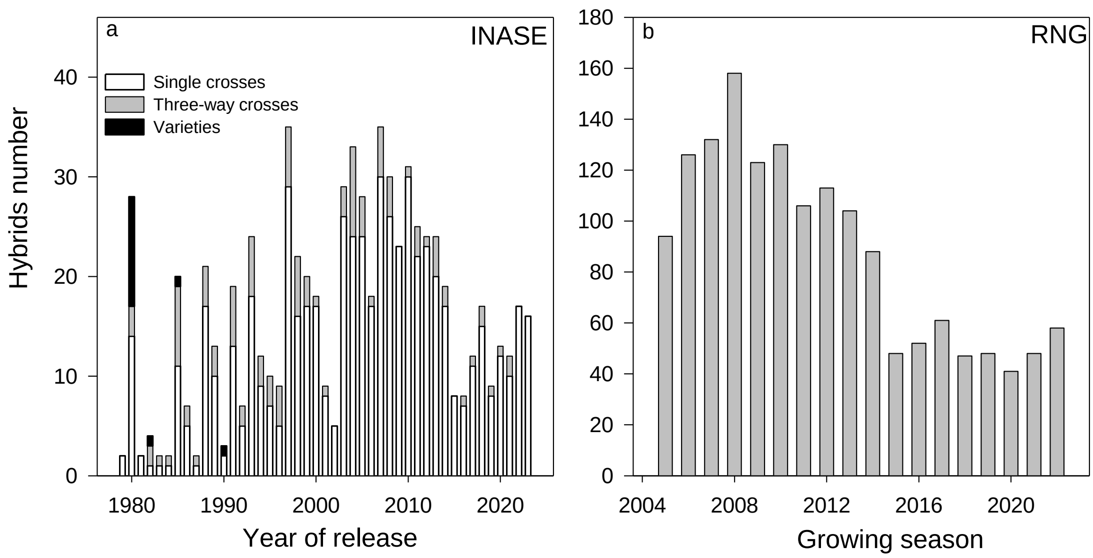


**Figure 3:** Number of hybrids registered in the National Register of Cultivars of the National Seeds Institute (INASE from its Spanish initials) from 1979 (a) and hybrids tested by the RNG from 2005 to the present (b).

Finally, the need for breeders to combine many agronomic, defensive, and end-user quality traits, in many cases determined by multiple genes and which expression is modified by the genetic background, could slow down genetic progress for yield potential, broad adaptation and tolerance to abiotic stresses.

*Genetic resources available to the breeding programs to achieve their objectives*: In the beginning of sunflower hybrid development in Argentina, private breeding programs relied on different sources of germplasm to create inbred lines, including locally developed OPVs (INTA, INRA, Seed companies), introduced OPVs (mostly from the former USSR and Eastern Europe), public inbred lines developed by INTA, USDA, INRA and Central and Eastern European national agriculture institutes, and germplasm developed by the same companies in other parts of the world. On top of these, wild *Helianthus* species were also used in breeding by private companies, mainly as sources of resistance to diseases, parasitic plants, and herbicides (e.g., Seiler and Jan, 2014).

Over the last 40 years, the sunflower genetic bases of private companies have evolved and have been enriched as a result of the multiple mergers and acquisitions that occurred in the seed industry. Over the same period, many of the public institutions that used to develop sunflower public germplasm have reduced or simply discontinued their breeding efforts. The global distribution of the sunflower crop, with more than 70% of the planted area concentrated in Europe (https://www.fao.org/faostat/en/#home) and mainly in the countries around the Black Sea, determines that a very large proportion of the global private breeding effort is based in that geography. Although Argentina and Europe present strong differences in terms of their sunflower genotypic discrimination effects, European germplasm constitutes a rich source of attributes of agronomic value for Argentine breeding programs.

*Clarity of the breeding objectives, capacity of the adopted breeding strategy to achieve the necessary genetic modifications and selection strategy*: As for any other allogamous species, sunflower breeding methods could be divided into (1) development, selection, and coding of inbred lines showing high general combining ability (GCA) for yield and (2) creation (using the available coded elite lines), phenotyping and selection of hybrids, exploiting both general and specific combining abilities. All scientific progress achieved in the improvement of these methods aimed at either increasing the precision, i.e., heritability or repeatability, or decreasing the duration of the processes, or both. The ultimate goal is always to increase genetic gain per unit of invested resource.

Regarding the development of inbred lines (both new genetic platforms and conversions), although there is still no reliable method to produce sunflower double haploids on a commercial program scale, many technologies have been adapted by Argentine breeding programs to create a greater number of lines fixed for multiple traits of interest in less time. These include, among others, accelerated forward breeding (up to 4-5 cycles per year mediated by horticulturization -fully controlled growing conditions-, artificial photoperiod enlargement and embryo rescue), *in vitro* screening for herbicide resistance (Breccia et al., 2011), artificial inoculation of diseases and parasitic plants, selection assisted by molecular markers, and whole-genome predictions. The capabilities of the strategies adopted by each program to sequentially stack defensive, agronomic, and end-user quality traits, combining forward breeding and trait introgression, without losing sight of genetic progress for yield, determine the success of each program in responding to the market demands and contributing to the sustainability of the production system.

Breeding for disease resistance has always been central in the development of Argentine sunflower germplasm. The rates of genetic gain for yield under farming conditions observed in this geography can be partially explained by the genetic progress achieved in terms of disease resistance profile of the hybrids released over years (e.g., de la Vega et al, 2007a). The first documented disease observations in Argentina correspond to the so called "black plague" ("peste negra" in Spanish) at that time, consisting of the premature death of plants after flowering. From 1942 to 1949, these symptoms were considered caused by bacteria and viruses (Muntañola, 1948; Traversi, 1949; Luciano and Davreaux, 1967). In 1958, *Sclerotium bataticola* Taub was isolated from diseased plants (Godoy and Bruni, 1960). Finally, the "black plague" was reported as caused by *Sclerotium bataticola* Taub, *Phoma oleracea* var. Helianthi tuberosi Sacc, *Helminthosporium helianthi* Hans and *Verticillium dahliae* Kleb (Bruni, 1965a and 1965b).

Verticillium wilt caused by *Verticillium dahliae* Kleb. is present in 50% of the soils of the Central and Southern sunflower growing regions. Several races have been identified for this pathogen, four of them being prevalent in main production areas (Bertero de Romano and Vázquez, 1982; Clemente et al., 2017). Major QTLs conferring resistance to these races have been identified and introgressed into the core germplasm of commercial breeding programs. Because of this, it can be considered that Verticillium wilt is currently adequately controlled in Argentina. The data obtained from the RNG, for example, indicate that 60% of the hybrids tested in the last 5 years are resistant or moderately resistant to the prevalent races (Bertero de Romano and Vázquez, 1998; Galella et al. al., 2004).

Head rot caused by *Sclerotinia sclerotiorum* Lib. De Bary is present across the Central and Southern regions. It has produced severe epiphytotics in the Southern region of Buenos Aires. During the epiphytotic of the summer season 1987-1988, only 4% of the commercial cultivars grown in the Southern region had moderate tolerance to head rot. In 2012-2013, this proportion had increased up to 49% (Quiróz, 2014). Artificial inoculation experiments conducted by the RNG show that progress in this area has been maintained over time to the present day.

Downy mildew (*Plasmopara halstedii* (Farl.) Berl. & De Toni) is one of the most important sunflower diseases worldwide, showing annual fluctuations in prevalence and incidence and possessing a high capacity to generate new races or pathotypes. So far, 10 races have been determined in Argentina: 300, 330, 710, 730, 770, 710601, 713600, 770620, 777730, 770220, 774734 and 730920 (Vázquez and Bertero de Romano, 2006; Bazzallo et al., 2016, Huguet, 2021, Piubello et al., 2024). Since 2017, 58 hybrids have been registered in the National Registry of Cultivars (INASE) and 62%

have resistance to some of these races. The introgression of resistance genes into these races was done from public lines obtained from populations developed in the United States and Argentina, including *Pl5, Pl6, Pl7, Pl8, Pl15, Pl17, Pl18* and *PlArg* (Bazzallo et al, 2016).

Phomopsis stem canker and head rot caused by the *Phomopsis*/*Diaporthe helianthi* Muntañola-Cvetkovic complex was observed for the first time in Argentina in 2005, but it was not until 2014 that its explosive dissemination began in Western Buenos Aires. In the province of La Pampa, Ghironi et al. (2018) estimated grain yield losses up to 44% and grain-oil concentration reductions between 4% and 22%. Although resistance to stem canker was not a priority breeding goal in Argentina until 2014-2015 and most of the locally developed germplasm showed high susceptibility to this disease complex, sunflower breeding programs of Argentina responded quickly to this unexpected challenge, releasing hybrids with an adequate level of tolerance.

Finally, sunflower rust caused by *Puccina helinthi* Schw. can produce severe yield losses in Argentina, especially in the Northern region. Juncos and Bertero de Romano (1985) estimated losses between 10% and 30%, depending on the year and the severity of the attack. The pathogenic population of this disease in Argentina was firstly described by Antonelli (1969 and 1985). The races present today in Argentina are 700, 704, 740, 744 and 760, while the genes which confer resistance and were incorporated into some commercial hybrids are *R4* and *Pu6* (Moreno et al., 2012). In the last two decades, the cropping systems of the Northern region have experienced a noteworthy evolution. With the aims of accommodating a second crop in the rotation, escaping heat stress, and harvesting at a high scoop price, sunflower planting dates were brought forward. As a result of this management (i.e., environmental) change, we have observed a decrease in the frequency and severity of rust attacks.

Regarding hybrid creation, phenotyping and selection, several methods have been adapted and implemented in Argentina. These include hybrid creation assisted by whole-genome prediction; optimization of the distribution of testing locations to provide a representative sample of the environment types present in the TPE; design and analysis of experiments to accommodate the effects of spatial variation (Montiel et al., 2017), the imbalance of the multi-environment trial datasets, and the G×E interactions present in the target genotype-environment system (de la Vega and Chapman, 2006); optimization of the number of sites, years and replicates to minimize the cost per unit of response to selection (de la Vega and Chapman, 2006); mechanization of all activities from seed counting to harvest; precise phenotyping with drones; and screening trials in semi-controlled environments for abiotic and biotic stresses.

*Physical and human resource capability to implement, evaluate and manage the necessary breeding strategies*: As it is observed in other countries, the investment in sunflower breeding in Argentina is relatively low when compared to crops like corn and soybeans. This imposes certain restrictions on the three main factors determining the success of a plant breeding program, namely (1) the value of the germplasm base, (2) the adequate understanding of the TPE in terms of genotypic discrimination and (3) the breeding methods implemented. As described in *4.2*, the relatively low number of sunflower breeding programs worldwide could result in limited genetic variability available to the local programs. The lack of resources to conduct extensive trial networks, collect precise phenotypic and environmental data, and analyze them through advanced methods, could limit the understanding of the TPE and, consequently, the accuracy of selection decisions. Lack of resources could also limit the application of next-generation methods for phenotyping and genotyping, necessary to adequately compete with other crops.

## CONCLUSION

Despite the limitations that could have been imposed by the strong environmental heterogeneity, the evolutionary dynamics of pathogens, the displacement of the planted area, the changes in management systems, the multiple attributes that must be stacked in a commercial product, the reduced development and release of public germplasm in other geographies, and a certain scarcity of resources compared to other crops, Argentine breeding programs have managed to respond to the challenges of a changing production system and consistently released superior hybrids that guaranteed the sustainability of the sunflower value chain. In addition to this, commercial lines and hybrids were created for other sunflower regions of the world and globally leveraged technologies, such as Clearfield Plus® and AIR herbicide resistances (Sala et al., 2012), were developed.

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