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GENETIC RESOURCES AND BREEDING STRATEGIES FOR SUSTAINABLE IMPROVEMENT OF EGGPLANT (*SOLANUM MELONGENA* L.) A REVIEW

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Abstract

The broad yet underutilized genetic diversity of eggplant (Solanum melongena L.) provides a crucial foundation for breeding strategies aimed at enhancing yield, resilience, and adaptability. In light of accelerating climate change and mounting biotic and abiotic stresses, the development of improved cultivars necessitates a strategic and effective deployment of these genetic resources. This review synthesizes current knowledge on eggplant genetic diversity and its practical integration into breeding programs, with emphasis on germplasm evaluation, trait-based selection, stress tolerance, and yield and quality improvement. Particular attention is given to conventional and hybrid breeding approaches, the role of phenotypic diversity in cultivar adaptation, and the linkage between genetic variation and nutritional or functional traits. By consolidating recent advances and breeding outcomes, this review highlights pathways for strengthening eggplant improvement programs and supports the development of resilient cultivars suited to sustainable agricultural systems.

Key words*: eggplant, germplasm evaluation, genetic resources, quality improvement, breeding strategies, sustainable improvement.*

INTRODUCTION

Eggplant (*Solanum melongena* L.) production is expected to be highly vulnerable to the accelerating impacts of climate change, which increasingly threaten global agricultural sustainability and food security (del Pozo et al., 2019; Habib-ur-Rahman et al., 2022). Rising temperatures, altered precipitation regimes, and the growing frequency and intensity of extreme climatic events are reshaping agroecosystem stability and crop performance. In particular, recurrent and prolonged drought episodes represent a critical constraint for water-stress–sensitive crops such as eggplant, disrupting physiological processes, impairing biomass accumulation, and ultimately compromising yield stability and fruit quality (Plazas et al., 2022).

Eggplant ranks among the most economically and nutritionally important solanaceous vegetable crops cultivated worldwide (Yu et al., 2026). It constitutes a dietary staple for numerous populations, particularly across Africa, the Middle East, Southeast Asia, and subtropical regions including India, Bangladesh, and Central America (Chapman, 2019). In addition, its cultivation extends to warm temperate zones such as the Mediterranean basin and the southern United States (Mat et al., 2020). As a high-value horticultural crop, eggplant harbors extensive and largely underexploited genetic diversity, representing a substantial reservoir for crop improvement. Addressing contemporary production constraints and enhancing resilience to climate change will require a paradigm shift toward advanced, strategically integrated breeding approaches capable of delivering qualitative genetic gains (Gramazio, 2023).

This study was designed as a comprehensive literature-based analysis aimed at systematically evaluating the global body of scientific evidence related to the research topic. Relevant publications were identified through structured searches of major academic databases, including Google Scholar, Web of Science, PubMed, ScienceDirect, MDPI, Frontiers, and ResearchGate, among others.

Only peer-reviewed articles published in reputable scientific journals within recent years were considered to ensure methodological rigor and relevance. An initial pool of more than 300

publications was screened according to predefined inclusion criteria, including scientific quality, topical relevance, and data transparency. In addition, secondary statistical data were retrieved from FAOSTAT (Food and Agriculture Organization of the United Nations). These datasets were systematically processed, statistically analyzed, and interpreted to support and contextualize the findings derived from the literature review.

This paper intends to highlight the importance of genetic diversity in eggplants (*Solanum melongena*) and how it can be effectively used in breeding programs to obtain varieties with high productivity, increased tolerance to biotic and abiotic stresses, and greater adaptability to conditions generated by climate change, in order to develop high-performing and sustainable cultivars for modern agricultural systems.

RESULTS AND DISCUSSIONS

Solanum melongena (eggplant), *Solanum aethiopicum* (scarlet eggplant) and *Solanum macrocarpon* (gboma eggplant) represent the three principal cultivated eggplant species distributed across Europe, Asia, and Africa. These taxa exhibit substantial phenotypic diversity, primarily distinguished by fruit skin color, shape, size, and weight. However, environmental influences, onset of fruiting, and biochemical composition further contribute to the development of morphological variability and diversification among cultivated forms (Mishra et al., 2024).

Eggplant breeding programs have historically focused on elucidating the genetic architecture of adaptive traits, particularly through the exploitation of wild relatives as reservoirs of beneficial alleles (Oladosu et al., 2021). Despite their recognized value, the utilization of wild germplasm has been constrained by limited genomic resources, including incomplete genome sequence information, which hampers efficient introgression strategies (Gramazio et al., 2018). This limitation is particularly significant given that resistance to biotic and abiotic stresses is frequently derived from wild species (Dempewolf et al., 2017).

In recent years, substantial progress has been achieved through the development of multiple mapping populations derived from interspecific crosses between cultivated eggplant and its wild relatives (Kaushik et al., 2016). These efforts have enabled the successful introgression of resistance traits, including Fusarium wilt resistance from *Solanum aethiopicum* (Toppino et al., 2008) and Verticillium wilt resistance from *Solanum linnaeanum* into cultivated eggplant backgrounds (Liu et al., 2015).

Current Insights into the Origin and Domestication of Eggplant

The genus *Solanum*, comprising 13 major clades, represents one of the most taxonomically and morphologically diverse lineages among angiosperms. Eggplant is assigned to the *Leptostemonum* clade (Knapp et al., 2013), commonly referred to as the "*Solanum spinosum*" group due to the presence of prominent epidermal spines on stems and leaves (Vorontsova et al., 2013).

Although eggplant is widely regarded as a vegetable crop of Asian origin, most of its wild relatives are distributed across Africa (Weese & Bohs, 2010). Archaeobotanical evidence indicates a long history of eggplant cultivation in both India and China, suggesting that the exploitation of wild progenitors may have begun in India prior to its introduction into China. In addition, an independent center of domestication has been proposed in the Philippines (Meyer et al., 2012). It has been hypothesized that certain local landraces may represent some of the earliest domesticated forms.

Subsequent molecular analyses have provided further insights into the domestication history of eggplant. Meyer et al. (2012) demonstrated that eggplant underwent multiple domestication events. More recent evidence indicates that domestication occurred independently on several occasions from *Solanum insanum*, a wild species naturally distributed throughout tropical Asia, from Madagascar to the Philippines (Knapp et al., 2013). Nevertheless, despite advances in phylogenetic and genomic research, important questions concerning the domestication process remain unresolved. (Taher et al., 2017).

The identification and taxonomic delimitation of wild relatives of eggplant remain challenging due to the extensive diversity within the genus. However, the integration of recent genetic and phenotypic datasets, along with the

classification of primary, secondary, and tertiary gene pools and improved knowledge of domestication pathways and wild progenitors, has substantially enhanced the potential for utilizing these resources in breeding programs (Taher et al., 2017).

Archaeological findings further corroborate the historical significance of eggplant. Fuks et al. (2020) reported the presence of mineralized plant remains, including seeds of *Solanum melongena*, recovered from excavations of an 8th–9th century CE Abbasid market in Jerusalem, providing material evidence of its cultivation and trade during the early medieval period.

Eggplant in the Global Agri-Food Economy

Eggplant (*Solanum melongena* L.) is a horticultural crop of considerable global economic relevance. Approximately 94% of worldwide production is concentrated in the subtropical regions of Asia, where its widespread cultivation and culinary prominence have earned it the designation "queen of vegetables" (Caruso et al., 2017).

According to preliminary statistics and recent reports derived from the FAOSTAT database of the Food and Agriculture Organization of the United Nations (FAO), global eggplant production reached record levels in recent years. Production totaled 58.70 million metric tons in 2021, followed by a 1.0% increase in 2022 compared with the previous year, further consolidating eggplant's status as a major crop, particularly within Asian agricultural systems (FAO, 2023).

As illustrated in Figure 1, China remains the leading producer, with 39.244 million tons, followed by India with 12.792 million tons and Egypt with 1.859 million tons.

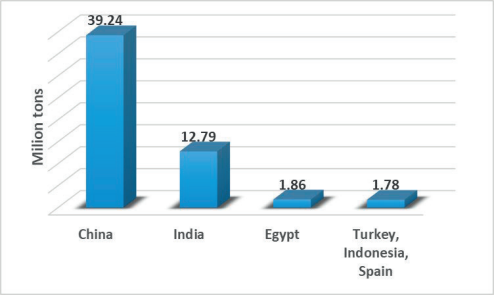

Figure 1. Top producers of eggplant

Among the subsequent major producers, Turkey (817.59 thousand tons), Indonesia (699.89 thousand tons), and Spain (260.41 thousand tons) rank prominently in global production statistics (Al-Salmi et al., 2025).

Nutritional and Functional Traits as Targets for Genetic Improvement

Eggplant (*Solanum melongena* L.) represents not only a crop of agronomic importance but also a valuable source of nutritional and bioactive compounds, making its health-related attributes a key consideration in breeding programs aimed at sustainable improvement. The fruit is characterized by low caloric content and appreciable levels of vitamins, minerals, and diverse phytochemicals, including phenolic compounds and flavonoids (Taher et al., 2017; Al-Salmi et al., 2025). These nutritious qualities make eggplant a crucial part of diets focused on health and justify its inclusion among priority crops for quality-oriented genetic enhancement.

Wild relatives within the *Solanum* genus constitute an important reservoir of bioactive metabolites, particularly saponins and steroidal alkaloids, which have demonstrated significant pharmaceutical potential (Oladosu et al., 2021). The exploitation of these genetic resources provides opportunities to broaden the phytochemical profile of cultivated eggplant through introgression breeding and pre-breeding strategies. Comprehensive phytochemical analyses have identified numerous functional compounds in eggplant fruits and leaves, including aspartic acid, tropane alkaloids, flavonoids, lanosterol, gramisterol, steroidal alkaloids, glycoalkaloids, histidine, nasunin, oxalic acid, solasodine, ascorbic acid, and tryptophan (Naeem et al., 2019). The enhancement and stabilization of such traits through molecular breeding and selection approaches may contribute to the development of nutritionally superior cultivars.

In addition to their nutritional value, eggplant-derived compounds exhibit documented bioactivities relevant to human health. Extracts have been shown to exert stronger cytotoxic effects on cancer cells than on normal cells (Afshari et al., 2016), while chlorogenic acid demonstrates anticarcinogenic activity by inducing apoptosis in leukemia and lung cancer cell lines (Tajik et al., 2017). Antimicrobial

activity against pathogens such as *Escherichia coli, Staphylococcus aureus, Bacillus subtilis*, *Vibrio cholerae*, *Pseudomonas* spp., and *Bacillus cereus* has also been reported (Ahmed et al., 2016). These functional properties highlight the potential of breeding strategies aimed at increasing specific phenolic compounds and secondary metabolites without compromising agronomic performance.

Furthermore, the contribution of eggplant to cardiovascular health, together with its content of vitamins, carbohydrates, and proteins, reinforces its value as a functional food (Eyid Abbas et al., 2021). The integration of nutritional quality traits into breeding objectives aligns with contemporary approaches to sustainable crop improvement, where yield stability, stress tolerance, and enhanced health-promoting properties are addressed simultaneously. Collectively, the nutritional and pharmacological attributes of eggplant emphasize the strategic importance of conserving and utilizing genetic resources to develop cultivars that meet both agronomic and public health goals.

Functional Metabolites in Eggplant: Implications for Breeding Strategies

Eggplant synthesizes a diverse array of primary and secondary metabolites, as summarized in Table 1. These phytochemicals represent a significant source of bioactive molecules with applications in both conventional and modern medicine, contributing to the prevention and management of various human diseases.

Among these compounds, chlorogenic acid (5-*O*-caffeoylquinic acid; CGA), predominantly localized in the fruit peel, is one of the major phenolic constituents of eggplant. CGA has been reported to exhibit anti-obesity, anti-inflammatory, anti-diabetic, and cardioprotective activities, underscoring its relevance for functional food development and nutraceutical applications (Plazas et al., 2013). In this context, the integration of metabolomic approaches into plant breeding programs has gained increasing importance, as it enables the identification, quantification, and selection of desirable phytochemical traits in cultivated germplasm (Oladosu et al., 2021).

Table 1. Metabolites produced by eggplant

Type	Description	Role	Literature
Primary metabolites	vitamins, lipids, proteins, and carbohydrates	play a direct role in regulating plant growth and essential physiological functions	Mistry et al., 2016
Secondary metabolites	phenols, glycoalkaloids (solasodine), carotenoids, anthocyanins, and antioxidants	are essential for maintaining physiological homeostasis and conferring protection against biotic and abiotic stressors.	Naeem et al., 2019

Growing consumer demand for health-promoting foods has increased interest in specific secondary metabolites. Mansurat et al. (2023) report that health-conscious consumers prioritize phenolic content, glycoalkaloids, carotenoids, and antioxidant capacity (Table 2). Therefore, the characterization and enhancement of these bioactive compounds have become key objectives in modern eggplant breeding strategies.

Table 2. Secondary metabolites from eggplant

Type	Description	Literature
Phenols	Eggplant (*Solanum melongena*) possesses the highest phenolic content within the Solanaceae family, establishing it as a primary dietary source.	Helmja et al., 2007
	Intravarietal variation in phenolic profiles among local cultivars provides critical insights for the development of targeted breeding programs.	Oladosu et al., 2021
	Polyphenolic composition in eggplant is strongly influenced by cultivar genotype, environmental conditions, agronomic practices, developmental stage, and specific fruit tissues. Seasonal fluctuations markedly affect phenolic levels, reporting a pronounced decline from spring to summer, suggesting that elevated temperatures inhibit phenolic biosynthesis.	Mansurat et al., 2023
	Seasonal fluctuations markedly affect phenolic levels, reporting a pronounced decline from spring to summer, suggesting that elevated temperatures inhibit phenolic biosynthesis.	García-Salas, et al., 2014
	Eggplants are enriched with a diverse spectrum of phenolic compounds, including anthocyanins, rutin, naringin, naringenin, syringic acid, caffeic acid, chlorogenic acid, p-coumaric acid, and sinapic acid.	Mansurat et al., 2023
	Dark purple cultivars exhibit superior antioxidant capacity compared with white and green variants, despite the latter occasionally presenting higher total phenolic content.	Mansurat et al., 2023
Carotenoids	Carotenoid accumulation in eggplant is modulated by multiple factors, including post-harvest handling, environmental stress, developmental stage, and culinary processing, as these compounds are dietary essentials that cannot be synthesized endogenously in humans.	Sánchez-Maldonado et al., 2016; Linnewiel-Hermoni et al., 2015
	Storage at 0 °C effectively preserves carotenoid content, with the highest levels observed at early stages of fruit maturity, followed by a gradual decline throughout ripening.	Zaro et al., 2014
	Dietary intake of carotenoid-rich foods is strongly correlated with a reduced risk of certain malignancies.	Linnewiel-Hermoni et al., 2015
	Consuming carotenoid-rich diets, including eggplant, contributes to the prevention of vitamin A deficiency, particularly in pediatric populations.	Kamga et al., 2013; Mishiba et al., 2020
Glycoalkaloids	Glycoalkaloids play a critical role in enhancing plant defense mechanisms against pests and pathogens.	Zaro et al., 2014
	Eggplant-derived glycoalkaloids exhibit notable anticarcinogenic properties.	Shen et al., 2017
	The principal steroidal glycoalkaloids in eggplant, α-solanine and α-solamargine, exert anticancer activity by reducing cancer cell proliferation across multiple malignancies, including basal cell carcinoma, osteosarcoma, lung, liver, leukemia, and gastric cancers.	Gürbüz et al., 2018 & Shen et al., 2017
Antioxidant compounds	Eggplant ranks among the top ten antioxidant-rich vegetables out of 120 evaluated species.	Nisha et al., 2009
	Total antioxidant content ranges from 2664 to 8247 mmol Trolox/kg, influenced by cultivar, fruit size and shape, skin pigmentation, and post-harvest storage conditions.	Gürbüz et al., 2018

Morpho-Physiological Assessment of Eggplant Germplasm for Breeding and Conservation

Eggplant (*Solanum melongena* L.) exhibits considerable diversity in fruit shape, color, and productivity (Figure 2) (Yurlisa et al., 2019).



Figure 2. Representative variety of eggplant fruit

Due to its greater economic importance compared with the native African species *Solanum aethiopicum* L. and *Solanum macrocarpon* L., *S. melongena* has been the primary focus of genetic and breeding research on diversity and interspecific crossability (Daunay et al., 2019).

At the germplasm access level, gene banks provide detailed information on phenotypic traits, including plant growth habits, branching patterns, leaf, flower, and fruit morphology, plant height, as well as flowering and fruiting periods (Barchi et al., 2019). Morpho-physiological evaluation and characterization of

available germplasm for target traits represent a fundamental component of eggplant breeding programs (Musa et al., 2020). These morpho-physiological traits facilitate rapid and accurate discrimination of phenotypic variation, which is typically highly heritable and moderately influenced by environmental conditions (Kumar et al., 2008).

In response, organizations such as the European Cooperative Program for Plant Genetic Resources (ECPGR), Bioversity International, and the International Union for the Protection of New Varieties of Plants (UPOV) have developed standardized descriptors and methodologies for eggplant characterization (Prohens et al., 2012; Hurtado et al., 2012).

Morpho-physiological assessments, which are essential for the sustainable management of genetic resources, are classified into two categories:

- Primary characterization: involves the quantification of readily observable traits at multiple growth stages, including the vegetative phase, inflorescence descriptors, maturity stage, and germination/seedling phase.
- Secondary morphological characterization: encompasses additional complex agronomic traits, such as biochemical composition, yield potential, fruit set, and resistance to pests and diseases (Musa et al., 2020).

These assessments provide the foundation for effective utilization and conservation of eggplant genetic resources in breeding programs.

Breeding Approaches for Sustainable Eggplant Improvement

With advances in breeding technologies and artificial selection, eggplants are increasingly cultivated for enhanced yield and fruit quality. However, as varietal uniformity improves, the genetic diversity of cultivated germplasm is progressively narrowing (Mohanty et al., 2023). Wild relatives, representing native populations, remain a critical reservoir of genetic variation, harboring genes conferring resilience to biotic and abiotic stresses that have been naturally selected over millennia, making them valuable for improving cultivated varieties (Yu et al., 2026).

Eggplant breeding has historically focused on enhancing productivity and improving resistance to diseases and pests while optimizing fruit quality (Daunay et al., 2007). Over time, domestication and selection have undergone multiple stages of refinement, resulting in modern cultivars that significantly outperform local landraces in terms of yield and overall agronomic performance (Mishra et al., 2024). Despite the crop's global cultivation, relatively limited effort has been directed toward exploiting local germplasm for hybrid development compared with other solanaceous crops such as tomato and potato (Mistry et al., 2016).

Current eggplant cultivars have largely been developed using the genetic resources of cultivated *S. melongena*, which have facilitated the creation of improved selections, breeding lines, and F1 hybrids (Solberg et al., 2022; Gramazio et al., 2023). Intensive breeding programs in regions of extensive cultivation, including China, India, Bangladesh, Western Europe, Turkey, and Japan, have yielded numerous open-pollinated and F1 hybrids exhibiting distinct phenotypic traits (Sękara et al., 2007). However, the reliance on cultivated germplasm has narrowed the genetic base of elite breeding lines; for instance, Muñoz-Falcón et al. (2009) reported that contemporary F1 hybrids of black eggplant share a common genetic origin and display reduced diversity.

The potential of wild *Solanum* species in breeding programs has been largely underutilized, primarily due to interspecific incompatibilities that often manifest as hybrid sterility (Laura et al., 2025; Bletsos et al., 2004). Nonetheless, biotechnological approaches, including genetic transformation, protoplast fusion, somatic hybridization, and haploidization, have enabled the transfer of desirable agronomic traits from wild relatives into cultivated backgrounds (Oladosu et al., 2021). Interspecific hybridization remains a critical strategy for broadening the genetic base of farmed eggplants and developing novel cultivars with enhanced stress tolerance, with some hybrids also exhibiting heterosis (Laura et al., 2025).

Somatic hybridization has been investigated as a tool to overcome cross-incompatibility barriers and integrate agronomically valuable traits from wild species into *S. melongena*. While successful in producing hybrids with desired characteristics, sterility and the tetraploid nature

of somatic hybrids often limit their practical application in breeding programs (Iwamoto et al., 2007; Rizza et al., 2002; Rotino et al., 2005). Marker-assisted selection (MAS) has emerged as a powerful tool to accelerate breeding cycles and enhance selection efficiency, thereby reducing the time required for crop improvement (Chen et al., 2024; Yu et al., 2026).

Some wild species exhibit superior tolerance to abiotic stress compared with cultivated forms. For example, García-Fortea et al. (2019) demonstrated that *Solanum elaeagnifolium* possesses a more extensive root system than *S. melongena*, conferring improved drought tolerance. Despite such promising traits, introgression from wild species remains challenging (Adithya et al., 2025). Conventional breeding approaches are time-consuming and labor-intensive, often limiting their effectiveness in generating cultivars with enhanced pest and abiotic stress resistance (Alam et al., 2021). Consequently, most breeding initiatives continue to rely heavily on cultivated *S. melongena* germplasm, despite significant advances in breeding strategies (Gramazio et al., 2023).

Compared with other major vegetable crops such as tomato, eggplant lags in both genetic improvement and the effective utilization of allied species' genetic resources, highlighting the need for innovative strategies to expand the genetic base and accelerate sustainable improvement (Schouten et al., 2019).

Worldwide Collection and Preservation of Eggplant Genetic Resources.

According to the latest Global Strategy for the Conservation and Utilization of Eggplants, a total of 110 germplasm banks and collections worldwide maintain 19,020 accessions of cultivated eggplants and related species (Solberg et al., 2022). The most extensive collections are held by several key institutions, including the National Plant Genetic Resources Office in India, the World Vegetable Center in Taiwan, which conserves 3,036 accessions, the National Gene Bank for Plant Germplasm Resources in China (1,601 accessions), the INRAE Gene Bank in France (2,388 accessions), and the NARO Gene Bank in Japan (1,501 accessions) (Salinier et al., 2022; Solberg et al., 2022).

Pest and Disease Constraints in Eggplant Breeding

A major challenge in contemporary eggplant breeding is the development of cultivars exhibiting enhanced resistance or tolerance to prevalent pests and diseases, which can result in yield losses of up to 100% (Kole et al., 2020; Vezzulli et al., 2022). The high genetic complexity among *Solanum* species complicates the identification of beneficial local variants and the improvement of cultivated lines with enhanced productivity and biotic stress resistance. Advances in biotechnological tools and methods have facilitated the genetic enhancement and ideotype development of eggplant (Mishra et al., 2024).

Although cultivated eggplants are susceptible to a range of bacterial and fungal pathogens, many wild relatives possess natural resistance, underscoring the importance of elucidating the genetic basis of disease resistance for breeding programs (Oladosu et al., 2021). Among diseases, bacterial wilt caused by *Ralstonia solanacearum* is particularly detrimental, especially in tropical regions, often necessitating the use of resistant rootstocks to sustain production (Lebeau et al., 2013; Barik et al., 2020; Namisy et al., 2019). Other economically significant diseases affecting eggplant include *Verticillium* and *Fusarium* wilts, as well as damage caused by root-knot nematodes (*Meloidogyne* spp.) (Vezzulli et al., 2022).

Pests represent another primary biotic constraint in commercial eggplant production. Major insect pests include mites, whiteflies, aphids, and the hadda beetle (*Henosepilachna vigintioctopunctata* Fabricius), while nematodes - particularly root-knot nematodes - pose serious challenges in both greenhouse and open-field cultivation (Nayak et al., 2021; Caliskan et al., 2023). The genetic basis of nematode resistance in eggplant remains poorly understood, highlighting an important gap for future breeding efforts aimed at sustainable pest management (Caliskan et al., 2023).

CONCLUSIONS

Eggplants contain essential primary metabolites for growth and secondary metabolites with significant nutritional, pharmaceutical, and stress-resilience roles. Evidence of their activity

against cancer cells and pathogenic bacteria highlights their health-promoting potential, emphasizing the need to integrate metabolomic approaches in breeding programs.

The conservation and strategic use of genetic resources, particularly wild species, remain critical for developing high-yielding, stress-tolerant, and locally adapted varieties. Modern breeding tools, including interspecific hybridization, somatic hybridization, marker-assisted selection, and genetic transformation, can overcome cross-compatibility barriers and expand the genetic base of cultivated eggplants. Enhancing resistance to pests and diseases is essential for sustainable production, reducing reliance on chemical controls and securing the global food supply. International initiatives such as the Global Crop Diversity Trust's climate adaptation programs illustrate the value of global collaboration in improving conservation and utilization of eggplant germplasm (Dempewolf et al., 2014; Eastwood et al., 2022; Gramazio, 2023). Continued coordinated efforts are required to fully realize the potential of these genetic resources in sustainable eggplant agriculture.

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