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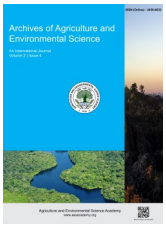

REVIEW ARTICLE

Insights into the germplasm conservation and utilization: Implications for sustainable agriculture and future crop improvement

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ABSTRACT

Plant genetic resources are critical for maintaining global biodiversity and ensuring food security. However, these resources face threats from factors such as habitat loss and climate change, with approximately 22% of plant species estimated to be at risk of extinction. To address this issue, both natural and biotechnological methods are being developed to preserve plant genetic resources, with germplasm being a key component. Germplasm contains the complete genetic information of a plant and can be stored for extended periods and replicated as required. The objective of this study is to emphasize the importance of preserving germplasm of endangered or near-extinct plant species through in situ and ex situ conservation methods. In situ conservation involves conserving species in their natural environment, while ex situ conservation includes using gene-seed banks and tissue culture to store genetic resources. These methods are crucial for maintaining genetic diversity and preventing the loss of valuable plant resources. The study highlights the various ex situ conservation methods, including cryopreservation, pollen and DNA banks, farmer's fields, botanic gardens, genetic reserves, and slow-growing cultures, which are essential for preserving germplasm. Gene banks worldwide currently hold over 7.4 million accessions of crop genetic resources, demonstrating the value of germplasm conservation efforts. Additionally, understanding the phenotypic and genetic characterization of related species is crucial for identifying endangered or vulnerable species that can diversify into new varieties or subspecies. In conclusion, prioritizing germplasm conservation efforts is crucial for meeting future demands while preserving endangered or vulnerable species. This will ensure that plant genetic resources remain available for future generations and that agricultural innovation can effectively address global food security challenges.

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INTRODUCTION

Germplasm, also known as a living genetic resource, refers to the genetic material passed down to the progeny through the germ cells (Marshall, 2016). In breeding programs, developers use the complete sets of genes, which are the primary components, to create new strain lines with desirable characteristics including higher yield, disease resistance, and improved quality (Priyanka *et al.*, 2021). Genetic material from sexually or asexually reproducing plants can be used in breed development programs and other varieties of variety creation. Genetic stocks, landraces, breeding lines, and other derivatives of wild and domesticated species, as well as exotic and native species, are all examples of germplasm (Ramya *et al.*, 2014). In order to improve the breed, combat various threats to reproduction, and stop the loss of a species' genetic diversity, genetic material is

collected and preserved around the world (Marshall, 2016). PGRFA (Plant Genetic Resources for Food and Agriculture) has assembled about 7000 species and designated them as important, but only 30 species are the ones on which the emphasis is focused (Offord and Gardens, 2017). The International Board for Plant Genetic Resources (IBPGR) was established in 1974 to oversee a global network of gene banks, coordinate international efforts in exploration and acquisition, and manage genetic resources (Engels and Ebert, 2021). Since the 1950s, the Food and Agriculture Organization (FAO) has been actively involved in the development of germplasm conservation plans (Offord & Gardens, 2017), in collaboration with a number of institutions, to preserve genetic diversity using a range of techniques (Engels and Ebert, 2021). This is because the future needs and requirements cannot be predicted, and it is crucial to preserve as much germplasm as possible to ensure a diverse and sustainable genetic resource pool to meet future demands (Engles *et al.*, 1995). The method of germplasm preservation varies depending on the type of plant, with asexual reproduction plants being maintained through field maintenance, cryopreservation, tissue culture, and cold storage (Imarhiagbe *et al.*, 2016). Additionally, seed banks, gene banks, nurseries, and other institutions can preserve genetic resources (Marshall, 2016). In order to detect genetic erosion in landraces, the first gene bank was founded in the 1920s (Engels and Ebert, 2021). Habitat degradation, unplanned grazing, unplanned human settlement, forest destruction, global warming, and the replacement of native species with improved varieties are the main causes of the ongoing depletion of genetic resources in natural habitats (Ramya *et al.*, 2014). The conservation of vulnerable and endangered species is a focus of germplasm conservation. Exploration, collection, preservation, evaluation, documentation, and distribution are crucial tasks related to germplasm conservation (Priyanka *et al.*, 2021). Conservation of living genetic resources is one way to achieve sustainable agriculture development, and there is a correlation between sustainable agriculture and germplasm conservation (Ramya *et al.*, 2014).

Since it is impossible to produce new germplasm quickly, the main goal of germplasm conservation is to lessen genetic erosion for future use in the development of new breeds or species. The concern over conserving the target genetic material is still present even when collection strategies or action plans for germplasm conservation are successful (Engles *et al.*, 1995). A wide range of industries for food and non-food utilization, including ornamental species, wood and fuel species, and medicinal species of plants, are governed by germplasm conservation. These implications include plant breeding and ecosystem restoration for horticulture, agroforestry, and farm animals (Priyanka *et al.*, 2021). Advance breeding materials, plants that have been developed by plant breeders (Marshall, 2016), Improved germplasm, plant material that exhibits one or more desirable characteristics (Engelmann, 2006), Landrace, those strain improved by the grower themselves without using any modern techniques of breeding (Jaradat, 2016), and others are different types of germplasm on the advancement in the agroecosystem. Weedy relatives are non-domesticated strains that have a common ancestor with crop varieties, are highly resistant, and are used in breeding programs (Hammer and Teklu, 2008), as well as genetic stocks, which are strains with a genetic abnormality that breeders use for a particular purpose (Marshall, 2016). The most undervalued aspect of germplasm preservation is the use of genetic resources for crop improvement. Between the actual use of the germplasm and the collection's availability in the gene banks, there is a very big gap. If the knowledge required by crop improvement scientists is not easily accessible, germplasm resources won't be utilized. The very goal of building huge germplasm collections is to better crops, not to frequently utilize fewer, closely related parents and their descendants. The overall idea of germplasm conservation, as well as its present state and potential future directions, are all addressed in this paper. This paper describes the implications, constraints, and structure of germplasm conservation that can support the distinctive affinity of the logical research field.

Status of germplasm conservation

There are roughly 1750 conventional seed banks worldwide, and the majority of these work to safeguard the genetic resources of cultivated plants and their wild relatives (Liu, 2020). Science has identified about 345,777 species of vascular plants, of which 332,857 are seed plants and 22% to 37% of them are threatened with extinction (Weisenberger and Keir, 2014). Although the Global Strategy for Plant Conservation (GSPC) acknowledged the significance of ex-situ conservation in achieving GSPC target 1, 8, and 9 (Krishnan, 2014), in-situ conservation is typically thought to be the best. Only 10% or fewer wild plants have secured taxa, and collections account for 64% of those (Andorf *et al.*, 2019). Since they are already used for quality enhancement, resistance development, tolerance to abiotic conditions accounting for drought, waterlogging, heat, and cold, as well as to improve crop species breeding efficiency, various crop wild varieties have been stored (Khoury *et al.*, 2015). Because they are useful in industries like fragrances, the pharmaceutical industry, essential oil production in agriculture, and cosmetics, a number of species of medicinal and aromatic plants have received a lot of attention in terms of conservation and development. For instance, in response to market demand, mint production lines with high yields were developed (Brezeanu *et al.*, 2015). The conserved genetic resources are examined, described, used, and altered to produce hybrids in order to comprehend their capabilities, methodology, etc. for upcoming or ongoing development processes (Andorf *et al.*, 2019). With the help of data science and the development of new breeding techniques using genomic details, genomic editing, genotyping, and gene sequencing technologies are advancing quickly and having an impact on numerous crop improvement programs (Andorf *et al.*, 2019; Weisenberger and Keir, 2014). In order to conserve more SCI than the ex-situ method, the in-situ method has been more widely used in seed banks. The ability to be stored for a long time is present in about 75% of SCI seeds (Weisenberger and Keir, 2014).

A proper assessment of the available genetic resources must be made because there is an excessive risk of germplasm erosion. Furthermore, to address the need for genetic resource conservation, both ex-situ and in-situ methods should be used (Krishnan, 2014). According to reports, the global threat to vascular plants is estimated to be 12.5% (34,000 species). Red list of status of germplasm prepared by International Union for Conservation of Nature (IUCN) for 2019–2020 is given in Table 1.

Method of germplasm conservation

Different ex-situ and in-situ conservation strategies must be used to protect living genetic resources for the benefit of the future, as demonstrated in Figure 1 (Kant *et al.*, 2016). Similar to conservational germplasm programs, there is a systematic flow of tasks that must be completed for any conservation program. For the past ten years, programs for ex-situ and in-situ conservation have been used to safeguard genetic material (Ibars and Estrelles, 2012; Ramya *et al.*, 2014).

In-situ method of conservation

In-situ conservation, which takes place in a plant's natural habitat or ecosystem, is one method for preserving genetic material (Engelmann, 2006). The growth of varieties continues in their natural habitat, involving gene pools and co-evolution, making in -situ conservation a dynamic method (Ibars and Estrelles, 2012; Ramya *et al.*, 2014). To protect and keep track of natural populations, in-situ conservation suggests reducing or maintaining a particular level of factors that cause a species to go extinct (Gulati, 2018; Ramya *et al.*, 2014). Along with this method of conservation, the ecosystem in agricultural fields is also being preserved (Delgado-paredes *et al.*, 2021). Natural selection is permitted, which leads to the ongoing evolution of conserved species (Engelmann, 2006; Kant *et al.*, 2016). Protected areas, wilderness areas, farm conservation, natural reserves, and protected wildlife are all included in it (Ramya *et al.*, 2014). The idea of preserving crop wild descendants in their natural habitats was first proposed in the 1970s, and it started to gain traction in the late 1980s as inadequate protection for these irreplaceable resources for agriculture became apparent (Marfil *et al.*, 2015). Due to their vulnerability to natural habitat, a number of ecological members are significantly declining; in these circumstances, in-situ contributes to habitat protection by halting the population decline (Engelmann, 2006; Ibars and Estrelles, 2012). Local communities and all pertinent organizations should support its implementation because in-situ conservation by locals using their expertise is the best way to preserve and restore biodiversity (Graddy, 2013; Ibars and Estrelles, 2012). In-situ conservation is expensive, necessitates a sizable area for preservation, is unable to protect every species in an ecosystem, and runs the risk of environmental contaminants and natural disasters deteriorating the germplasm (Ramya *et al.*, 2014; Rubenstein *et al.*, 2005).

Table 1. Red list of status of germplasm prepared by International Union for Conservation of Nature (IUCN) for 2019–2020.

Category	Species
Data deficient	4090
Least concern	24,810
Near threatened	3181
Lower risk: Conservation dependent	157
Vulnerable	8459
Endangered	8593
Critically endangered	4674
Extinct in the wild	42
Extinct	122

Source: (Priyanka *et al.*, 2021).

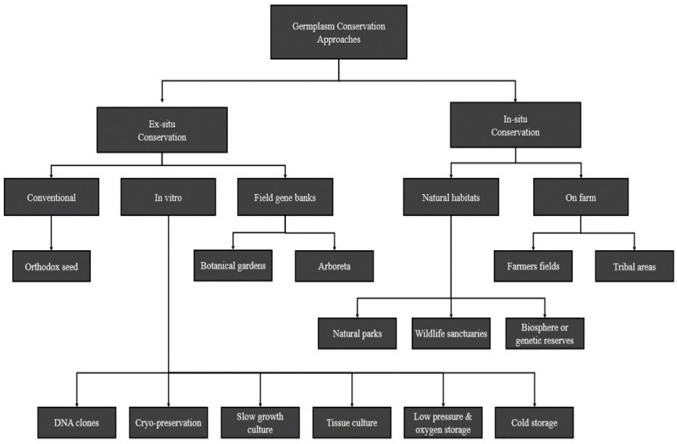

Figure 1. *Schematic representation of germplasm conservation approaches, encompassing ex situ and in situ conservation methods.*

Ex-situ method of conservation

Ex-situ conservation involves preserving genetic material outside of its natural habitat (Marfil *et al.*, 2015; Offord and Gardens, 2017) or relocating endangered species from their natural habitat to a new location (Borokini, 2013) in order to preserve them. Cryopreservation falls under the ex-situ conservation method, while the preservation of seeds in fields, field gene banks, and seed banks falls under in-vitro storage, which uses the technical method (Priyanka *et al.*, 2021; Ramya *et al.*, 2014). Seed storage is the most practical method for long-term germplasm preservation (Gulati, 2018; Merritt *et al.*, 2014). The best course of action is to conserve wild and domesticated plant species using the in-vitro method (biotechnological method) (Delgado-paredes *et al.*, 2021; Offord and Gardens, 2017). Ex-situ conservation strategy improvement and global crop diversity management are key goals of the Global Crop Diversity Trust (GCDT) organization (Priyanka *et al.*, 2021). Regular viability tests and prompt crop recovery are necessary to maintain the crop's usefulness, depending on the biology of the crop (Offord and Gardens, 2017; Priyanka *et al.*, 2021). Ex-situ conservation is gradually implemented to safeguard populations that are at risk of disappearing, being replaced, or declining (Gulati, 2018). Ex-situ conservation boosts long-term security and safeguards the genetic integrity of populations and individuals (Ibars and Estrelles, 2012; Rajasekharan and Sahijram, 2015). Ex-situ conservation is done in living gene banks, which are traditionally referred to as in-vitro and in-vivo banks (Bhatia, 2015; Borokini, 2013). These banks include

Table 2. Advantages and disadvantages of ex-situ versus in-situ conservation.

S.No.	Ex-situ conservation		In-situ conservation		References
	Advantages	Disadvantages	Advantages	Disadvantages	
1	Generally, costs are concentrated.	Certain types of germplasm are difficult to preserve.	Genetic resources are put to good use to create a valued product.	Expenses are borne by the farmers (for land-races)	Graddy, 2013; Hammer and Teklu, 2008; Joshi *et al.*, 2018; Rubenstein *et al.*, 2005
2	Can store a huge number of different germplasms	Regeneration might be costlier, and tedious.	Evolutionary processes are still going on.	Farm output may suffer.	Gulati, 2018; Offord and Gardens, 2017
3	More breeders will be able to access germplasm.	The risk of genetic "drift" can compromise the collection's integrity.	Certain farmers' requirements may be better met.	The land is required.	Ramya *et al.*, 2014; Rubenstein *et al.*, 2005
4	High-security storage that is resistant to the majority of natural catastrophes	Collectors often struggle to effectively monitor, document, and analyze their samples.	Some germplasm, such as animals or crops that reproduce vegetatively, is more efficient.	Farmer selections may not retain the diversity that is desired.	Gulati, 2018; Hammer and Teklu, 2008

Table 3. Base, active and working collections in seed bank along with their storage conditions.

S. No.	Storage	Base collections	Active collections	Working collections	References
1	Period	Long term (~50 or more years)	Medium-term (8-10 years)	Short term (3-5 years)	Engelmann, 2006; Moreno *et al.*, 2013; Ramya *et al.*, 2014
2	Temperature	-18 or -20°C	0 °C	5-10 °C	Liu, 2020
3	Moisture	5±1 %	0.08	8-10%	Offord and Gardens, 2017
4	Utilization	Used for regeneration purposes	Implemented in breeding programs	Utility in crop improvement programs	Ramya *et al.*, 2014

horticultural centers, kitchen gardens, botanical gardens, and field gene banks at research stations. In contrast to in-vivo gene banks, where the germplasm is preserved using conventional methods like seeds and reproductive organs, in-vitro gene banks preserve the germplasm using novel methods like cell and tissue culture approaches (Bhatia, 2015; Marfil *et al.*, 2015; Mousavi *et al.*, 2017). Over the years, gene banks have been established in a number of countries, and the number of accessions preserved in roughly 1400 gene banks has now surpassed six million; however, it is known that there are more than 1,750 different gene banks (Borokini, 2013; Offord and Gardens, 2017). Gene banks guarantee the efficient use of genetic resources in farms, breeding programs, or research facilities in addition to protecting them (Borokini, 2013). The advantages and disadvantages of ex-situ and In-situ conservation is given in Table 2.

Seed banks: It is the most popular and practical method for conserving germplasm worldwide (Offord and Gardens, 2017; Ramya *et al.*, 2014). To increase viability, seeds are dried to reduce moisture content before being stored in a sealed container at a subzero temperature in a freezer or cold store (Borokini, 2013; Offord and Gardens, 2017). According to time and use, the seed bank collections are divided into base, active, and working collections. According to Harrington's rule of thumb, a seed's lifespan doubles for every 1% decrease in moisture content (Offord and Gardens, 2017). Food and Agriculture Organization (FAO) claims that 90% of the 6 million enlistees who were ex-situ preserved worldwide were done so using this technique (Borokini, 2013). The main advantage of seed storage is that it makes ideal conditions and lessens the need for rejuvenation, allowing the conservation of a sizeable population and reducing genetic erosion (Borokini, 2013; Offord and Gardens, 2017). By using this method, only orthodox seeds can be stored; recalcitrant, intermediate, and vegetatively propagating seeds cannot be stored (Ramya *et al.*, 2014). The type of collections and their storage conditions is given in Table 3.

Field gene banks: Field gene banks are ex situ collections of predominantly agricultural or forestry species. For some species, field gene banks—small populations of plants maintained in protected areas—might be an essential conservation technique. These are frequently a part of living exhibit collections at botanical gardens. Intentional gene flow by cross-fertilization with wild populations or with institutions harboring related species may be necessary to maintain the genetic diversity of the field gene bank throughout years of cultivation. To maximize the conservation potential of field gene banks, institutional partnerships and meticulous georeferenced data keeping and sharing are required. The ICRAF platform alone has 11,000 enlistees from 60 industrially important tree and nut seeds, mostly from Africa and Asia, representing field gene banks from 44 countries across six different continents (Ibars and Estrelles, 2012; Priyanka *et al.*, 2021). Collection from one area and replanting into another are both methods of conserving genetic material in field gene banks (Borokini, 2013; Offord and Gardens, 2017). Genetic resources are typically grown in nurseries at various intensities depending on the species (Priyanka *et al.*, 2021). Field gene bank preservation is challenging because appropriate samples must be taken to preserve germplasm, additional space

Table 4. Relative advantages and disadvantages of conservation method.

S. No.	Method	Advantages	Disadvantages	Research needed	References
1	Field gene bank	Simple access to characterization, evaluation, and application. Does not necessitate the use of highly trained personnel infrastructure. Requirements are straightforward.	Space constraints are exacerbated by the requirement to maintain a safe separation distance between trees, which is especially important for tall trees that outcross regularly. Extensive labor; the high likelihood of labeling errors. Exposure to both biotic and abiotic variables.	A minimum number of trees is required to sustain genetic diversity. Plot approaches that have been filed for suitable characterization and assessment. Cost of maintaining a crop field gene bank.	Dulloo *et al.*, 2005; Engelmann, 2006; Hammer and Teklu, 2008; Jaradat, 2016; Kulkarni *et al.*, 2015; Offord and Gardens, 2017; Ramya *et al.*, 2014
2	In vitro collecting and culture of zygotic embryos	Protocols that have been established. Facilitates the interchange of germplasm for botanical research.	Only suitable for short-term storage. Infrastructure requirements are unusually high. High upkeep costs. Users have little access to it.	Optimization of an in vitro culture procedure is being tested.	Engelmann, 2006; Imarhiagbe *et al.*, 2016
3	On-farm conservation	Environmental changes and dynamic conservation. Local communities and stakeholders may now participate more easily. Overall, save a lot more genetic variety. Agronomic crops are well-suited to this variety. Germplasm transfer is difficult.	Natural and man-made calamities, such as fire, cyclones, vandalism, land-use change, deforestation, and so forth, make them vulnerable. Materials are scarce and difficult to come by. Appropriate Management regimes are not well known. Active oversight and monitoring are required. There is a lot of genetic variation.	There is a scarcity of data on the state of genetic diversity. Farmers' know-how must be documented in a systematic way. Several concerns including the socioeconomics of farming, IK, and community engagement in on-farm conservation are discussed. More effort is needed in agricultural conservation techniques.	Dulloo *et al.*, 2005; Offord and Gardens, 2017; Priyanka *et al.*, 2021
4	Cryopreservation	Long-term safe storage is possible. Low-cost, easy-to-maintain. Embryo protocol has been created. Not a lot of effort is required.	It necessitates the use of expert labor. Infrastructure requires a lot of money to start with.	More research is needed to improve the cryopreservation procedure.	Engelmann, 2006; Hammer and Teklu, 2008; Marshall, 2016; Priyanka *et al.*, 2021; Rajasekharan and Sahijram, 2015
5	Seed banks	Reduce the need for regeneration. Conservation of huge population. Reduce genetic erosion.	Recalcitrant seed, immediate, and vegetative propagating seed cannot be stored.	More studies to know the moisture and seed life relation.	Offord and Gardens, 2017; Ramya *et al.*, 2014

is needed, trained staff is expensive, and natural variability is vulnerable (Ramya *et al.*, 2014). Historically, recalcitrant and vegetative species have been safeguarded and preserved using field gene banks (Offord and Gardens, 2017; Priyanka *et al.*, 2021). Insects, diseases, and natural disasters have a high likelihood of destroying genetic material in the field bank (Marfil *et al.*, 2015; Ramya *et al.*, 2014; Takrama *et al.*, 2012).

Botanical garden: An institution may have a collection of botanical plants for preservation, education, and scientific purposes (Borokini, 2013; Marfil *et al.*, 2015). The botanical garden contains a large collection of economically significant plants, wild relatives, aromatic, and forest species. Numerous others have since served as research hubs for plant taxonomy and horticulture since the first botanical garden was founded in Pisa, Italy, in the 17th century (Priyanka *et al.*, 2021; Rajasekharan and Sahijram, 2015). There are up to 80,000 species represented by more than 6 million living accessions in 2500 botanic gardens around the world (Borokini, 2013). Traditional services are still provided by modern botanical gardens, along with a conservation program (Marfil *et al.*, 2015; Offord and Gardens, 2017). In order to preserve the inter-specific diversity of the flora, botanical gardens typically maintain a large number of species with few accessions per species (Borokini, 2013).

Arboreta: A collection of living plants is called an arboretum. The main goals of these collections' maintenance are study, the preservation of genetic material, and instruction. The term "arboreta" refers to trees that are preserved for research or educational purposes (Borokini, 2013). The difference between an arboretum and a botanical garden is that the former may contain all plant species, whereas the latter only displays trees (Borokini, 2013; Priyanka *et al.*, 2021). When it comes to cataloging its collections, eliminating duplication, and fostering collaboration, Arboreta lacks centralized coordination (Borokini, 2013; Offord and Gardens, 2017).

Cryopreservation: One common technique for preserving important collections is cryopreservation. Cell division, growth, and other biological processes are completely stopped at a base temperature of liquid nitrogen (-196 ^{0}C), which is what is done to the living animal and plant cells (Borokini, 2013; Gulati, 2018; Ibars and Estrelles, 2012). This method relies on dehydrating the tissues either physically or osmotically to remove all freezable water before rapidly freezing them (Ramya *et al.*, 2014). Numerous studies have shown that spores of various species survive longer at low temperatures than at higher temperatures (Ibars and Estrelles, 2012). Spores can be kept in liquid nitrogen (-196 °C), vapor nitrogen (-150 °C), deep freezers (-80 °C), solid carbon dioxide (-79 °C), or -79 °C (in this method) (Bhatia, 2015). there are some cryopreservation techniques available for vitrification, encapsulation-dehydration, fast freezing, and slow cooling (Borokini, 2013). Plant material can be preserved using the liquid nitrogen storage method, including embryos, meristems, calluses, suspension cells, mature seeds, gametes, and protoplast cultures (Borokini, 2013; Gulati, 2018). One method of cryopreservation involves using a cryoprotectant compound to crystallize intracellular fluid, while a second method entails encasing samples in an alginate gel and then dehydrating them (Gulati, 2018; Ibars and Estrelles, 2012). Several substances, including mannose, propylene, glucose, glycerol, acetamide, sucrose, praline, ethylene, dimethyl sulfoxide, and others, are used as cryoprotectants (Bhatia, 2015; Gulati, 2018). Despite the immense diversity of germplasm found in the tropics, cryopreservation techniques are rarely investigated (Gulati, 2018). Few attempts to use cryopreservation techniques on tropical and subtropical fruit species have been made, with the exception of Musa spp. and Citrus spp. (Bhatia, 2015).

Cold storage: By using a slow-growth technique at low, non-freezing temperatures between 1 and 9 °C, germplasm can be preserved (Bhatia, 2015; Priyanka *et al.*, 2021). The main benefit of this strategy is that it protects the plant from cryogenic damage by restricting rather than completely stopping plant development (Bhatia, 2015). Certain crops, tubers, rhizomes, and bulbs that can be preserved at 0 to 15 °C at high humidity for several months or up to one year using this procedure are stored for a brief period of time (Marshall, 2016). Making the plant available for research or distribution by keeping in-vitro collection in cold storage increases security (Priyanka *et al.*, 2021). This method is simple, affordable, and results in germplasm with a higher survival rate (Bhatia, 2015). Numerous exceptional cases have been reported, including the preservation of virus-free strawberries for about six years at 10 °C and the preservation of some grape plants for nearly 15 years in cold storage (9 °C) through yearly replanting in fresh medium (Bhatia, 2015; Priyanka *et al.*, 2021).

Slow growth culture: Slow-growth culture techniques enable the preservation of clonal plants under aseptic conditions for a number of months to years (depending on the species), necessitating the infrequent subsequent transfers of the cultures. Slow growth culture is method for conserving and regenerating germplasm (Marshall, 2016). Slow growth strategies have been developed in order to preserve species over the medium term (Ramya *et al.*, 2014). It limits the conditions for growth so that culture cannot develop and spread in a typical environment (Bhatia, 2015; Marshall, 2016). This technique slows growth to lessen the need for tissue culture plants to be rejuvenated. It is a potential substitute for cryopreservation because it is less expensive, contamination from gene changes is minimal, and it is simpler to carry out (Priyanka *et al.*, 2021). Culture development is influenced by a number of variables, including temperature, nutrition restriction, growth regulation, and osmotic concentration (Bhatia, 2015; Marshall, 2016; Priyanka *et al.*, 2021). The amount of oxygen in the air, the propagating vessel used, and the amount of light needed for cultures are additional considerations (Marshall, 2016; Priyanka *et al.*, 2021).

Low pressure and low oxygen storage: Low-pressure storage

(LPS) and low-oxygen storage (LOS) have been created as alternatives to cryopreservation and cold storage for germplasm preservation. The atmospheric pressure surrounding the plant material is decreased in low pressure storage, which tends to slow down the growth of organized or unstructured tissues in vitro. When there is low oxygen storage, ambient pressure (260 mm Hg) is kept constant by the addition of inert gases. By lowering the oxygen content and air pressure in plant material, this method reduces the availability of oxygen and the production of carbon dioxide, which inhibits growth and dimension by lowering photosynthetic activity (Bhatia, 2015). Low pressure lessens pathogenic activity and prevents spore germination, aiding in the preservation of germplasm (Priyanka *et al.*, 2021). The growth of plant tissue slows down when the partial oxygen pressure drops by 50mm Hg, extending the shelf life of the species (Bhatia, 2015; Priyanka *et al.*, 2021).

DNA banking: DNA banking is a quick, easy, and long-term method of genetic information preservation. It is becoming more vital for the management and research of genetic resources, especially for plant species. DNA banks can now preserve DNA, RNA, cDNA, and genes at a low cost, making it a useful backup against crop diversity loss. Although it cannot replace traditional conservation techniques, DNA storage shows potential due to its small sample size and DNA stability in cold storage. However, DNA banks have limitations since complete plants cannot be rebuilt directly, and original genotypes cannot be recovered. By cloning DNA segments onto a suitable vector, germplasm can be preserved for a variety of uses, including the study of genetic traits, preservation, taxonomy, and many others (Borokini, 2013; Marshall, 2016; Offord and Gardens, 2017). However, it is an expensive and time-consuming process. The targeted samples' DNA, which has valuable reserves for research, is used to create the extract required for the molecular marker (Borokini, 2013). The relative advantages and disadvantages of conservation methods is given in Table 4.

Method of genetic characterization

In a broad definition, genetic characterization refers to any variation in an accession's appearance or makeup brought on by modifying factors, specific genes, or DNA fragments (Vicente *et al.*, 2005). It explains a trait or quality of an individual. The breeding community can look into genotypic and phenotypic variation using this practical method (Nadeem *et al.*, 2020). Breeders can improve crop varieties with the help of genetic characterization, recognition, and evaluation of crop germplasm (Sitther *et al.*, 2014; Wu *et al.*, 2014). The crop improvement process chooses as a parent those crop lines with more impressive combining ability and traits with a higher tolerance to drought, acidic soil, diseases, and pest resistance (Wen *et al.*, 2012). Characterization's main objective is to learn more about genetic variation, genetic erosion, and the population structure of germplasm (Sitther *et al.*, 2014; Wu *et al.*, 2014).

Morphological characterization: The phenotypic description of a plant depends greatly on its morphological characteristics, which are heavily influenced by consumer preferences, the socioeconomic environment, and evolutionary theory (Kandel and Shrestha, 2018). Morphological characterization is essential for choosing, identifying, and categorizing various germplasm or inbred lines (Kulkarni *et al.*, 2015; Mashilo *et al.*, 2017). When describing and classifying germplasm, which is used as the parent lines in a breeding program, the first choice is to use molecular characteristics (Khadivi *et al.*, 2018). Selecting the best breeding strategy for creating promising inbred lines involves characterizing and examining the heritable components of various quantitative characters. The ability to identify crop species depends on leaf characteristics like leaf shape, color, size, and angle, which are also related to each crop species' potential for production (Kulkarni *et al.*, 2015; Marfil *et al.*, 2015; Vicente *et al.*, 2005). Characterizing the agro-morphologically significant quantitative characters is the main objective of morphological characterization of various crop germplasm accessions (Tesfaye and Mengistu, 2017). Understanding how genotypes, environment, and their interaction affect crop phenotypic performance and reveal how various crops have adapted to various environmental circumstances (Nadeem *et al.*, 2020; Vicente *et al.*, 2005). One of the most common methods used by researchers to identify novel variants that can be used to create improved cultivars with a high yield, improved quality, and resistance to biotic and abiotic stress has historically been morphological characterization of genetic resources (Mashilo *et al.*, 2017; Nadeem *et al.*, 2020).

Quality characterizations: Taste, scent, softness, expansion potential, cooking qualities, etc. are quality traits of crop accession (Kandel and Shrestha, 2018). In order to classify crops according to their quality, to best use donors with specific traits for crop improvement activities, and to maintain the unique characteristics of various crops, germplasm is necessary (Bisne and Sarawgi, 2008; Kumar *et al.*, 2016).

Agronomical characterization: Agronomical traits like 50% flowering, stem length, time to maturity, weight of 1000 gram grain, length of grain, etc. are assessed for accessions of various crops (Kandel and Shrestha, 2018; Pachauri *et al.*, 2017). Descriptive statistics, phenotypic variation, principal component analysis, and cluster analysis are used to gather genetic information (Trentacoste, 2011). Agronomic characterization, which additionally provides pertinent information about the genetic linkages and specific features of agronomic significance, facilitates the systematic application of germplasm collections in a crop improvement initiative (Maquia *et al.*, 2013). Numerous crop cultivars are identified, described, and assessed using agronomic characteristics (Trentacoste, 2011).

Molecular and biochemical characterization: The useful data from the phenotypic and molecular profiles completes the molecular characterization. Numerous traits exhibit striking genetic variation among genotypes (Ciancolini *et al.*, 2012; Mashilo

et al., 2017). Genotypic characterization is aided by statistical techniques such as principal component analysis and cluster investigation (Khadivi *et al.*, 2018). Molecular characterization of germplasm is carried out using non-DNA markers that reveal the list of genes and gene products that are very helpful for breeding strategies (Kagimbo *et al.*, 2018; Weckwerth *et al.*, 2020). In order to promote genetic diversity, the widest genotypes are used to create crop species with improved quality and better yield (Mashilo *et al.*, 2017). Some of the molecular markers used in the molecular characterization of specific crop germplasm include amplified fragment length polymorphisms (AFLPs), randomly amplified polymorphic DNAs (RAPDs), restriction fragment length polymorphisms (RFLPs), single nucleotide polymorphisms (SNPs), and simple sequence repeats (SSRs/microsatellites) (Adu *et al.*, 2019; Kandel and Shrestha, 2018; Maquia *et al.*, 2013; Takrama *et al.*, 2012; Woldesenbet *et al.*, 2015). Due to their higher polymorphism and co-dominant inheritance, SSR and SNP markers are frequently used to assess genetic diversity. Additionally, it has a high throughput at a lower cost (Adu *et al.*, 2019; Marconi *et al.*, 2018; Moreno *et al.*, 2013; Wu *et al.*, 2014). Since DNA markers are unaffected by exogenous conditions, they are preferred over biochemical and morphologically based biomarkers. Additionally, it increases breeding potential, which is beneficial for a breeding program that works (Adu *et al.*, 2019). The use of molecular markers to produce selection variation or facilitate the selection process is common (Kandel and Shrestha, 2018; Takrama *et al.*, 2012). It is crucial to evaluate the diversity of ancestors and cultivars descended from them (Begum *et al.*, 2019; Kandel and Shrestha, 2018). It is possible to identify crop breeding patterns, individual breeding effectiveness, and the frequency of gene transfer within and between populations of the same or related species. Molecular characterization can be used to estimate the size of diminishing germplasm (Kandel and Shrestha, 2018; Vicente *et al.*, 2005). A functional add-on method that produces more accurate information on phylogenetic relationships without regard to genotype or environment is molecular marker-based characterization (Maquia *et al.*, 2013).

Agro-morphological characterization: The availability of information on germplasm is necessary for plant breeding activities due to the agro-morphological characterization (Ferreira *et al.*, 2011; Pachauri *et al.*, 2017). The method for characterizing crops agro-morphologically is Principal Component Analysis (PCA) (Pachauri *et al.*, 2017). The diversity and germplasm of crops are characterized and assessed using various agro-morphological markers (Kandel and Shrestha, 2018). The agro-morphological parameters are used to determine the production potential, suitability, and capacity to overcome biotic and abiotic stress (Kumar *et al.*, 2016). Agro-morphological diversity aids in the formulation of an effective preservation and utilization plan for successful crop improvement and variety recognition (Kandel and Shrestha, 2018; Kumar *et al.*, 2016).

Utilization of germplasm conservations

Human intervention has caused the genetic contrast to disappear by enlarging preferred genes and completely exterminating the less desired, endangering the survival of the historical genetic material (Priyanka *et al.*, 2021). Germplasm aids in preserving information about the plant's wild species, extinct species, and other ancestors. The green revolution saw a well-known instance of unmediated germplasm exchange. The Green Revolution is credited with improving agriculture in developed countries and displacing hundreds of thousands of people who abstained from food (Smith *et al.*, 2021). Obtaining the fresh specimens from the collector, cultivating them for seed expansion, characterization, initial assessment, and subsequent appraisal are just a few of the many steps involved in the application of germplasm collection (Maji *et al.*, 2012). Due to a number of advantages, wild plant genetic resources and species are now sought after for conservation, including the maintenance of biological diversity. A global database of plant genetic resources and agricultural gene pools classifies a high preference for protection and variety (Migicovsky *et al.*, 2019). Woody perennial crops rarely reproduce successfully because of their high heterozygousness. Some even produce seeds that can withstand -term storage. As a result, the majority of live clonal material collections are frequently used to maintain woody perennial crops (Khadivi *et al.*, 2018; Migicovsky *et al.*, 2019). New genetic information from diverse plant populations contributes to the development of more hardy and productive crops (Cruz-cruz *et al.*, 2013; Engelmann, 2006). Through in-situ and ex-situ conservation, landscapes, wildlife ecosystems, and the restoration of a sustainable species diversity are all preserved (Engelmann, 2006). Keeping our local breeds alive is important for farm animals because 36% of livestock lines lack documentation and 20% of livestock lines are in danger. Cryopreservation can be a successful tactic for conserving these genetic varieties rather than maintaining a healthy population of every type of livestock species (Morrell and Mayer, 2017). By implying High Throughput (HT) phenotyping of traits over a few years, germplasm collections aberration in identifying accessions and wild relatives possessing traits that are advantageous to new altering regimes and our knowledge of fundamental plant biology (Khadivi *et al.*, 2018). Somatic nuclear transfer has made it possible to clone farm animals, a very costly and wildly popular technique (Zhou and Gomez-sanchez, 2000). In order to activate and cultivate the byproduct after cloning, a donor cell is fused with an enucleated, mature oocyte (Engelmann, 2006). Since a small number of reproduced individuals are unsure about preserving the genetic variety, a sizable biobank of the genetic material from prior parents must be managed to ensure a healthy genetic pool (Engelmann, 2006; Harris, 2004). Genetic variability research using germplasm collections has improved our understanding of basic plant biology. These collections may be crucial for determining the phenotypic plasticity that perennial woody plants will use to adapt to changing climatic conditions (Khadivi *et al.*, 2018). The goal of the pedigree study

Table 5. Important institutes and their mandate crops for conserving and collection.

S. No.	Name	Institute	Mandate crops	References
1	LCRI	Lake Chad Research Institute	Sorghum, Wheat, millet, barley	Borokini, 2013; Ishaq and Falusi, 2008
2	CIAT	Center International de-agricultural Tropical Palmira, Columbia	Cassava and beans, (also maize and rice) in collaboration with CIMMYT and IRRI	Priyanka *et al.*, 2021; Ramya *et al.*, 2014
3	CRIN	Cocoa Research Institute of Nigeria	Cocoa, Kola, Cashew, Tea, coffee	Borokini, 2013
4	ISAT	Sorghum Investigators of Tropical America	Sorghum	Ishaq & Falusi, 2008
5	IPGRI	International Plant Genetic Research Institute, Rome Italy	Plants	Brown & Hodgkin, 2015; Jaradat, 2016; Priyanka *et al.*, 2021
6	NCRI	National Cereals Research Institute	Sesame, Sugarcane, Rice, Soyabean, beniseed, acha, castor	Borokini, 2013; Ishaq and Falusi, 2008
7	SHRS	Subtropical Horticulture Research Station	Avocado	Kuhn *et al.*, 2019
8	NIOPR	Nigerian Institute for Oil Palm Research	Oil palm, coconut, date palm, shea butter, raphia palm, and other palms	Borokini, 2013
9	RRIN	Rubber Research Institute of Nigeria	Para rubber, gum Arabic, and other latex producing plants	Borokini, 2013
10	IRRI	International Rice Research Institute, Los Banos, Philippines	Rice	Bisne and Sarawgi, 2008; Ghimiray and Vernooy, 2017; Kandel and Shrestha, 2018; Kumar *et al.*, 2016; Smith *et al.*, 2021
11	JITA	International Institute of Tropical Agriculture	Cowpea	Ishaq and Falusi, 2008
12	IAR	Institute of Agricultural Research	Cowpea, sorghum, maize, groundnut, cotton, sunflower	Borokini, 2013; Ishaq and Falusi, 2008
13	CASS	Institute of Crop Germplasm Resources	Amaranth	Joshi *et al.*, 2018
14	ICRISAT	International Crops Research Institute, for Semi-Arid Tropics, Hyderabad, India	Bengal gram, Sorghum, Groundnut, Redgram, Pearl millet	Priyanka *et al.*, 2021; Ramya *et al.*, 2014
15	IAR&T	Institute of Agricultural Research and Training	Cowpea, Maize, Soybean, Kenaf, jute	Borokini, 2013; Ishaq and Falusi, 2008
16	IITA	International Institute of Tropical Agriculture, Ibadan, Nigeria.	African yam, Soybean, Cassava, Rice, cowpea, Maize, Bambara groundnut	Ishaq and Falusi, 2008; Ramya *et al.*, 2014
17	NACGRAB	National Centre for Genetic Resources and Biotechnology	All recalcitrant plants	Borokini, 2013
18	CIP	Centre International de-papa-Lima. Peru	Potato	Maquia *et al.*, 2013; Priyanka *et al.*, 2021
19	NHRI	National Horticultural Research Institute	Banana, pineapple, Giant star apple, walnut, African bush pear, avocado pear, bush mango, locust tree, hog plum, Tropical fruits (citrus), vegetables (grain amaranth, tomato, leaf amaranth, okra, Egusi Melon, pepper) mango, Telfaria occidentalis, spices and ornamental plants.	Borokini, 2013
20	AVRDC	The Asian Vegetable Research and Development Centre, Taiwan	Tomato, Onion, Peppers Chinese cabbage	Ramya *et al.*, 2014
21	CIMMYT	Centre International de-Mejoramients de maize Trigo, El Baton, Mexico	Maize, barley, sorghum, triticale	Ghimiray and Vernooy, 2017; Hammer and Teklu, 2008; Priyanka *et al.*, 2021; Wen *et al.*, 2012
22	FRIN	Forestry Research Institute of Nigeria	All forest tree crops	Borokini, 2013
23	WARDA	West African Rice Development Association, Monrovia, Liberia	Rice	Ishaq and Falusi, 2008; Ramya *et al.*, 2014
24	NRCRI	National Root Crop Research Institute	Cassava, yam, potato, sweet potato, cocoyam, ginger	Borokini, 2013

is to evaluate the international reach of recently introduced varieties and the country's reliance on exotic cultivars. Genetic diversity is easily maintained because pathogens and their biotypes are less likely to develop in newly introduced crops (Ghimiray and Vernooy, 2017). Germplasm repositories are an invaluable resource for studying somatic variation among replicas (Khadivi *et al.*, 2018). Germplasm collections aim to conduct systematic evaluation to learn more about their various physical, biological, and evolutionary characteristics, including some distinctive traits like disease resistance, stress adaptability, and pest resilience (Maji *et al.*, 2012). Despite the fact that somatic mutation creates new strains in perennial crops, bud sports with unique phenotypes are frequently preserved as new prospective races or material. This method is effective for cultivars with desirable traits that have been economically viable for decades or even centuries (Khadivi *et al.*, 2018). Sperm cryopreservation is most frequently used in germplasm banking; it has been used in animal breeding for more than 50 years and is widely regarded as the cornerstone of contemporary dairy animal production. The preservation of patrilineal and matrilineal data is advantageous for conservative projects (Morrell and Mayer, 2017). To confirm inheritance patterns in germplasm collections, which serve as a general description of the lineage of accessions and are essential for tracking the evolution of an interesting characteristic, genotyping accessions is used. The ability to access genetic information from different germplasm collections has proven to be a useful tool for verifying and reconstructing plant lineages (Khadivi *et al.*, 2018).

Germplasm conservation involves preserving the genetic diversity of plant species, including those that may have natural resistance to pests. By conserving diverse germplasm, researchers can identify and utilize genes for pest resistance in crop breeding programs, ultimately leading to the development of pest-resistant crop varieties (Sharma *et al.*, 2022; Yadav *et al.*, 2023a). This integrated pest management approach reduces reliance on chemical pesticides and promotes sustainable agricultural practices (Yadav *et al.*, 2022a; Yadav *et al.*, 2022b). Additionally, botanical and sterile insect techniques offer environmentally friendly pest management options that can be integrated into germplasm conservation strategies (Yadav *et al.*, 2022c; Yadav *et al.*, 2022d). Also, understanding how different crops respond to pest pressure and insecticide applications can inform breeding programs aimed at developing resilient crops with enhanced pest resistance (Karki *et al.*, 2023; Katel *et al.*, 2023; Yadav *et al.*, 2024a). Further, the competition between native plants and few invasive species can lead to the displacement or extinction of native plant species, resulting in the loss of genetic diversity within native plant populations (Yadav *et al.*, 2024b). Germplasm conservation efforts aim to preserve genetic diversity within native plant species, making it important to address the threats posed by invasive alien species. Likewise, proper fertilizer management ensures that essential nutrients are available to plants, promoting their growth and reproduction (Adhikari *et al.*, 2023; Yadav *et al.*, 2022e). This is particularly important for maintaining the vigor and viability of germplasm collections, as nutrient deficiencies can lead to reduced seed production and genetic degradation over time. Fertilizer management practices influence soil health by affecting factors such as soil structure, nutrient cycling, and microbial communities (Yadav *et al.*, 2023b). Healthy soils support diverse plant populations, including wild relatives and landraces, which are important components of germplasm collections. Sustainable fertilizer management practices reduce environmental impacts such as nutrient runoff and soil erosion, which can threaten natural habitats and wild plant populations. By minimizing these impacts, fertilizer management supports the conservation of native plant species and their genetic diversity.

Germplasm conservation aims to maintain the genetic diversity of plant species, including those used in agriculture. Sustainable agriculture practices, such as agroecology and organic farming, prioritize diverse crop varieties and landraces adapted to local conditions. Sustainable agriculture promotes practices that enhance the resilience and adaptation of agricultural systems to changing environmental conditions (Yadav *et al.*, 2023c). Germplasm conservation provides a repository of genetic resources that can be used to breed crop varieties with traits such as drought tolerance, pest resistance, and nutrient efficiency. Sustainable agriculture emphasizes practices that promote soil health, biodiversity, and ecosystem services (Yadav *et al.*, 2023d). Germplasm conservation efforts focus on collecting, preserving, and characterizing diverse varieties of these crops to ensure that valuable genetic traits are not lost over time. Researchers and breeders can access preserved germplasm collections to identify genes associated with desirable traits and incorporate them into breeding programs to develop new varieties or genotypes that meet the evolving needs of farmers and consumers (Yadav *et al.*, 2023e). There are several researches that aid in understanding of genetic diversity of several crops, which is important for germplasm conservation efforts (Mehata *et al.*, 2023; Yadav *et al.*, 2023f). Conservation initiatives for germplasm frequently involve safeguarding heirloom or landrace cultivars with cultural and historical importance. Conserving these varieties not only maintains genetic diversity but also preserves cultural heritage and traditional knowledge associated with their cultivation and use. Rice, okra, and other cereals or vegetables are staple food crops for millions of people worldwide. Researches such as Ghimire *et al.* (2023) and Yadav *et al.* (2023g) contributes to the preservation of genetic diversity within rice and wheat germplasm collections, which are valuable genetic resources for future breeding programs and research. Preserving their genetic diversity through germplasm conservation ensures that diverse genetic resources are available to support food security and nutrition.

Future thrusts and prospects

Due to climatic change and the evolution of pests and pathogens, crop production is becoming more challenging. As a result, untapped genetic resources must be used to improve the situation and meet future population demand (Kofsky *et al.*, 2018; Ramya *et al.*, 2014). The most effective method for genetically

enhancing agricultural plants by changing a variety of complex yield-contributing and stress-responsive traits may involve combining genomics-assisted breeding and transgenics (Marfil *et al.*, 2015; Merritt *et al.*, 2014; Singh, 2019). To efficiently analyze complex quantitative aspects of crops, various features related to genomics, epigenomics, proteomics, metabolomics, and genomics-assisted breeding can be applied at different times (Imarhiagbe *et al.*, 2016; Ramadas, 2019; Singh, 2019). These inputs can then be used in various of marker-assisted breeding techniques to create highly improved crop varieties (Singh, 2019). Certain crop species should receive extra attention during identification. The development of desirable genotypes for food and ornamental value requires the augmentation of germplasm from various regions (Borokini, 2013; Pandey and Rita, 2014). The collection, screening, and selection of genotypes of significant species at the regional level; the use of genetic markers in the screening of species resistant to drought; the use of biotechnological methods for controlled breeding to produce hybrids; the study of genetic variability for quality and quantity of products of various crops; and the preservation of genetic diversity of various plant species through in-situ, ex-situ, and on-farm approaches are some of the future thrusts (Selvan, 2018). Due to the lack of nutritional profile data from germplasm collections and the lack of tools for analyzing traits inherited in breeding populations, the application of germplasm for improving crop nutritive value is relatively low (Singh, 2019). Thus, increased use of germplasm is possible in the near future to improve the nutritional value of various crops (Ferguson *et al.*, 2012; Singh, 2019). For plants to develop sustainably, plant genetic resources must be used and evaluated (Bradshaw, 2017). Numerous landraces and wild relatives hold the genetic building blocks for future plant breeding (Bradshaw, 2017; Ramadas, 2019). Soil salinity is one of the major obstacles to crop improvement and productivity, so it has become essential to use resistance varieties. This is made possible by gathering the germplasm of various crops, preserving it for the future, and using it for better outcomes (Ferguson *et al.*, 2012; Imarhiagbe *et al.*, 2016; Kofsky *et al.*, 2018). The name of institutes and their mandate crops to be conserved and collected is given in Table 5.

Limitation of germplasm conservations

The short lifespan of recalcitrant seeds does not favor the long-term preservation of diverse seed germplasm (Imarhiagbe *et al.*, 2016). Soma clonal variations in plant tissue culture are a major barrier to germplasm conservation. Changes in ploidy, chromosome structural alterations, and aberrations during mitosis are examples of variations. Field testing and other techniques selected based on the crop life cycle cannot avoid morphological traits (Rajasekharan and Sahijram, 2015). Bulky, heavy seeds that are recalcitrant in growth. Its bulkiness makes handling difficult, which results in an additional cost. When gathering germplasm seeds, breeders encounter a number of challenges (Engelmann, 2006). There is a good chance that genetic changes and chromosome damage will take place during seed storage. Because the gene pool is reduced when seeds die, the genetic makeup of mixed seed stocks changes (Bonner, 1990). Many tree and shrub species' seeds also have difficulty being preserved at low temperatures because they are still immature when they are shed, have higher moisture contents, and are more susceptible to chilling (Imarhiagbe *et al.*, 2016). Loss of genotypes, subspecies, or varieties (Jaradat, 2016) or the extinction of a portion of a species' gene pool in a particular location. The spread of modern varieties in improvement programs is the main cause of genetic depletion (Hammer and Teklu, 2008). Global equality and wealth are reduced as a result of the decrease in geological diversity because the global gene pool is also diminished (Priyanka *et al.*, 2021). Crop seeds that have been clonally propagated are difficult to store because they require specific conservation techniques for stakes, pieces of budwood, tubers, corms, or suckers (Imarhiagbe *et al.*, 2016; Rajasekharan and Sahijram, 2015). Contamination during germplasm collection: It is important to take into account that different species and tissues have different sensitivities to surface sterilants. Since the procedure is done in an open space, in-vitro collection presents more contamination challenges than traditional tissue culture (Imarhiagbe *et al.*, 2016).

Conclusion

This study emphasizes the crucial significance of conserving plant genetic resources for global biodiversity and food security. Various conservation methods, such as cryopreservation, DNA banks, farmer's fields, botanic gardens, and genetic reserves, are crucial in maintaining genetic diversity and preventing the loss of valuable plant resources. The preservation and use of germplasm are also essential for future agricultural innovation to effectively address global food security challenges by characterizing and studying genotypic and phenotypic diversity. Our study revealed the following key findings:

- Urgent action is required to conserve the most important crops immediately, as an estimated 22% of all plant species are at risk of extinction.
- Genetic erosion caused by the loss of variation is a significant threat to plant genetic resources, which has a direct impact on future food security.
- Collaboration between scientists and conservationists is crucial in developing better plans for preserving plant species' genetics that are in danger of extinction.
- The preservation and availability of germplasm are critical to ensuring the success of conservation efforts and agricultural innovation.
- Prioritizing germplasm conservation efforts and investing in the preservation of plant genetic resources are necessary to benefit future generations.

In conclusion, our study highlights the urgent need to preserve plant genetic resources and maintain genetic diversity for ensuring future food security. By investing in better conserva-

tion methods and collaborating across disciplines, we can effectively preserve plant species' genetics and address global food security challenges sustainably.

Authors contribution

Conceptualization, BY; Methodology, SB; Software, DLP, DB, DKM; Validation, DLP, DB, DKM; Formal analysis, DLP, DB, DKM; Investigation, DLP, DKM, SB; Resources, SB; Data curation, SB, DKM; Writing—original draft preparation, SB, NPG, PP, DLP, DB, DKM; Writing—review and editing, PP, NPG, DLP; Visualization, NPG; Supervision, PY; Project administration, PY; Funding acquisition, PP. All authors have read and agreed to the published version of the manuscript.

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