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RESEARCH ARTICLE

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The role of Alpine botanical gardens in integrating germplasm bank collections and mission

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Societal Impact Statement

This study underscores the vital role of Alpine botanical gardens (ABGs) in safeguarding Europe's alpine biodiversity amid climate change and habitat loss. By acting as living laboratories and reservoirs of plant genetic resources, ABGs bridge ex situ and in situ conservation, supporting ecosystem resilience and informing restoration strategies. Our findings reveal significant opportunities for ABGs to collaborate with germplasm banks, enhance genetic diversity in collections, and refine propagation protocols. Strengthening these integrative networks not only preserves unique alpine flora but also provides adaptive tools for conservation policies and sustainable land management in mountain regions facing rapid environmental change.

Summary

- The Alps are one of Europe's most diverse ecosystems, but their biodiversity is threatened by climate change, habitat loss, and land-use changes. Alpine botanical gardens (ABGs) play a crucial role in preserving plant diversity in this region. This study evaluates 14 ABGs across the Alps to assess their effectiveness in preserving the region's flora, with a particular aim to investigate how ABGs can integrate with and strengthen the conservation mission of germplasm banks.
- We assess representation of alpine flora in the living collections of these 14 ABGs relative to the 5797 taxa of the flora of the Alps, noting cases cultivated at the infraspecific level and examining the overlap of these collections with global germplasm banks.
- Our findings show that 32% of the 5797 taxa of the flora of the Alps are represented in ABGs, with some species cultivated at the infraspecific level, reflecting

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both ecological specializations and the expertise of ABG curators. Notably, ABGs contribute significantly to ex situ conservation, although gaps exist in certain taxonomic families and species, especially endemic and policy taxa. Many species in the living collections of ABGs are still missing from global germplasm banks.

- These findings highlight an opportunity for these gardens to strengthen conservation by contributing seeds and helping to grow species that are difficult to propagate, including narrow endemics. Collaboration with germplasm banks could address existing gaps in genetic diversity, with ABGs acting as field-based experimental stations to refine propagation techniques. Overall, the importance of ABGs in both ex situ and in situ conservation strategies is underscored, urging stronger collaborations with research facilities and improved propagation protocols to optimize the conservation of alpine plants.

KEYWORDS
Alps, ex situ, gap analysis, Genesys, living collections

1 | INTRODUCTION

The Alps are home to one of Europe's most diverse floras, encompassing approximately 4450 vascular plant taxa (Aeschimann et al., 2004). Despite this extraordinary richness, the biodiversity of this unique ecosystem is under severe threat because of a suite of escalating environmental pressures. Climate warming is inducing shifts in species' elevational ranges, altering phenological timings, and impacting plant reproductive success (Erschbamer et al., 2011; Lodetti et al., 2024; Pauli et al., 2012; Porro et al., 2019). Concurrently, changes in land use (e.g., agricultural abandonment, and urbanization) and management practices intensify these threats, promoting invasive species incursions and creating mismatches between plants and their pollinators, soil biota, and nutrient cycles (Chemini & Rizzoli, 2003; Tasser & Tappeiner, 2010). Such pressures not only shift plant distributions and cover but also reduce reproductive success, ultimately leading to biodiversity loss. Collectively, these factors are driving declines in species abundance and diversity and eroding genetic variability and ecological integrity (Becker et al., 2005; Fabbro & Körner, 2004).

In response to such challenges, conservation efforts commonly rely on two complementary strategies: in situ and ex situ conservation. In situ measures safeguard species within their native habitats, encompassing single-taxon recovery plans, community-level management, and broad-scale habitat protection (Körner, 2022). In contrast, ex situ conservation secures Plant Genetic Resources (PGR) outside their natural habitats, for example, by maintaining living specimens in botanical gardens or storing seeds and propagules in germplasm banks. These collections serve as critical reservoirs of propagation material, facilitating reintroductions, translocations, and population reinforcements (sensu IUCN 2013) and have been increasingly used in conservation efforts targeting the flora of the Alps (Bonomi et al., 2005; Müller et al., 2017; Shaw, 2015).

While ex situ conservation has improved the protection of many plant taxa of the Alps, significant knowledge gaps remain—particularly when it comes to extending these practices to critical species that are difficult to propagate using conventional methods. Moreover, flowering and seed-set may be sporadic or depend on precise climatic cues, seed viability can be low, and appropriate dormancy-breaking treatments often remain elusive (Chambers, 1989; Fernández-Pascual et al., 2021; ENSCONET, 2009a, 2009b). Also, seeds of high-elevation plants frequently exhibit shorter lifespans compared to their lowland counterparts, complicating long-term storage and demanding repeated, logistically challenging field collections (ENSCONET, 2009a, 2009b; Mondoni et al., 2011). Unlike domesticated crops easily propagated in field trials, wild species demand extensive effort, and even more in the vast geographic scenario of the Alps and the inherent variability in their life-history traits. This makes ensuring adequate genetic representation in germplasm banks and living collections highly resource-intensive and demanding.

One emerging approach to overcome these hurdles is *quasi* in situ conservation, as suggested by Volis and Blecher (2010). This method merges the strengths of in situ and ex situ approaches by maintaining PGR in natural or semi-natural conditions that approximate a species' ecological niche (Maxted et al., 1997). By doing so, plant material can be harvested periodically without eroding local adaptations, reducing the pressure of repeated and potentially disruptive seed collections from wild populations. The success of such an approach, however, depends on effective horticultural techniques, the adoption of harmonized good practices, and the development of robust collaborative networks across botanical gardens.

Alpine botanical gardens (ABGs) have a key role in this context, because they hold living collections serving as experimental grounds for developing best practices in horticulture, seed handling, and plant care. By maintaining species under conditions closely mirroring their ecological requirements, ABGs offer opportunities to test germination protocols, refine propagation methods, and implement small-scale ecological manipulations. Such endeavors enhance our understanding of species-specific needs, directly informing seed banking procedures and field-based conservation measures, thereby strengthening the synergy between ex situ and in situ strategies.

This study examines the role of ABGs to determine how well they support *quasi* in situ approaches to plant conservation. Specifically, it explores key research questions across three thematic areas: (i) Do the living collections of ABGs preserve valuable species for conservation, including protected, threatened, or endemic taxa? (ii) To what extent are these species represented in the collections of germplasm banks? Are the germination requirements of such species known? (iii) Can ABGs serve as integrated, *quasi* in situ conservation facilities for the collection and preservation of alpine germplasm?

By exploring these questions, this study offers new insights into the potential of ABGs as essential hubs within integrated conservation frameworks. It situates ABGs at the interface of ex situ and in situ approaches, evaluating their capacity to bridge existing gaps in germplasm resources, improve propagation outcomes, and ultimately reinforce the long-term resilience and adaptability of the flora of the Alps amid rapid environmental change.

2 | MATERIALS AND METHODS

2.1 | The study area and its flora

The Alps are a major mountainous arc in Europe, forming the continent's largest natural space and serving as an ecological, geographical, and socio-economic unit. According to the International Standardized Mountain Subdivision of the Alps (ISMSA), the boundary of the Alps corresponds to the perimeter adopted by the Alpine Convention (Permanent Secretariat of the Alpine Convention, 2010). This area extends from east to west for approximately 1200 km and encompasses a total surface area of 170,000 km^2. It comprises 1599 peaks, with the highest point reaching 4809 m (Monte Bianco–Mont Blanc, situated on the Italian–French border). To determine the representation of the ABGs living collections in relation to the overall plant biodiversity of the Alps, we took as taxonomic reference the flora of the Alps by Aeschimann et al. (2004). Plant names have been updated through rWCVP (Brown et al., 2023), an R package based on the "The World Checklist of Vascular Plants" (Govaerts et al., 2021) dataset. Among the available open access datasets, WCVP provides the most reliable results in terms of taxonomic information, ensuring the highest level of accuracy and precision (Schellenberger et al., 2023). All synonyms were thus replaced by the current species names being either accepted or—in rare cases—unplaced.

2.2 | ABGs checklist: data collection and validation

Curators of ABGs were contacted between 2023 and 2024 to provide a full list of taxa grown in their garden. We employed a snowball sampling approach (Vogl & Vogl-Lukasser, 2004), asking informants to suggest other alpine gardens that could join the study. Additionally, data for two ABGs ("Valcava" and "San Marco") have been obtained from bibliographic sources (Ardenghi et al., 2019; Casarotto, 2005).

The taxonomic and nomenclatural consistency of the ABGs living collections was validated using the rWCVP R package as explained before. While many ABGs also include alpine plant species from other mountain regions (e.g., the Himalayas, Rocky Mountains, Caucasus, Pyrenees, etc.), this study focuses exclusively on species naturally occurring in the Alps. Therefore, the rWCVP package was also used to filter the ABG dataset by removing all taxa that are not part of the study area. This process resulted in a taxonomically harmonized checklist of taxa from the flora of the Alps represented within the ABGs living collections.

We then added information on the distribution status of each taxon to the checklist, indicating whether it is native, endemic, introduced, or locally extinct (extinct in the Alpine perimeter). The endemic factor is defined as a binary category—either "endemic to the Alps" or "not endemic to the Alps"—based on whether a taxon occurs exclusively within the perimeter of the Alpine Convention or also beyond it. The other factors are categorical numeric variables ranging from zero to six. A value of zero indicates that the species is not native, has not been introduced, or is extinct in any of the countries considered. Conversely, a value greater than zero reflects the number of countries in which the species is native, introduced, or extinct. The species list was then cross-referenced with the GBIF database (GBIF, 2024) to determine, for each taxon, its ranks in the taxonomy hierarchy: kingdom, phylum, order, family, and genus.

Additionally, we added information about conservation and protection status using two online open repositories: (1) the IUCN Red List of threatened species (IUCN, 2022) and (2) the Directive on the Conservation of Natural Habitats and of Wild Flora and Fauna (ECC, European Economic Community, 1992 Directive 92/43/EEC). The IUCN Red List provides a straightforward and widely adopted system for classifying species based on their risk of global extinction, with the following categories: globally extinct, critically endangered, endangered, vulnerable, near threatened, least concern, data deficient, and not evaluated. However, the "Habitats" Directive represents a fundamental element of European environmental legislation, devised with the objective of guaranteeing a favorable conservation status of the species and their habitats within the European Union. Together, these two repositories allow for an assessment of the completeness of ABGs' living collections in terms of their representation of threatened and protected species from the flora of the Alps. The same operation regarding taxonomic hierarchy, distribution and conservation status has been repeated for the whole flora of the Alps.

2.3 | Data analysis

After data collection and validation, we visualized the taxonomic diversity of the checklist of ABGs living collections and of the whole flora of the Alps using the "metacoder" (Foster et al., 2017) and "ggplot2" (Wickham, 2016) R packages. This allowed us to understand which plant families of the flora of the Alps are underrepresented in the ABGs living collections.

To assess the taxonomic similarity among ABGs living collections, we examined how widely each species is represented across institutions. This allows us to understand whether collections are largely overlapping or exhibit significant diversity. We therefore calculated the prevalence index of each species using the "mia" R package (Ernst et al., 2023). High prevalence values indicate that the taxon is commonly found across many institutions.

To evaluate the ex situ conservation status of the taxa represented in the ABGs living collections, we conducted a gap analysis focusing on their presence in germplasm banks. A gap analysis is a strategic assessment used to identify which taxa are underrepresented in existing collections. Specifically, we queried the Genesys PGR database (Alercia and Mackay, 2013; Obreza, 2024) to retrieve the number of germplasm accessions available worldwide for each taxon that is part of the ABG living collections and of the whole flora of the Alps. Genesys PGR is an online platform that provides access to information about Plant Genetic Resources conserved worldwide in germplasm banks; even if Genesys PGR was originally developed for PGR connected to food and agriculture, it currently aggregates databases of germplasm banks working on the conservation of wild plants. This allowed us to identify which species are already conserved in germplasm banks and which remain underrepresented or absent, thereby highlighting the potential immediate contribution that ABGs could give to germplasm banks in terms of new seed accessions. The data gathered from the aforementioned repositories were visualized using the "webr" (Moon, 2020) and "ggplot2" (Wickham, 2016) R packages.

Additionally, given the crucial role of seed collections in conservation actions and biodiversity restoration initiatives, the germination requirements and the storage behavior of each species included in the living collection were verified via the Seed Information Database (https://ser-sid.org/; Liu et al., 2019), currently hosted by the Society for Ecological Restoration. For each species cultivated in at least one botanical garden, we verified (i) if any germination requirements have already been tested, and (ii) if the species are suitable for cryo-preservation in germplasm banks (orthodox seeds), or not (recalcitrant), or if the proper storage behavior is still unknown (not tested) or uncertain (requiring additional data for confirmation). If no available information was present in the Seed Information Database, we performed an additional literature review, mainly through Baskin and Baskin (2014) and ENSCOBASE (ENSCONET, 2009a, 2009b).

3 | RESULTS

3.1 | ABGs living collections

A total of 14 ABGs located within the Alpine Convention perimeter provided up-to-date information on their living collections (Figure 1 and Table S1). The participating ABGs are distributed across five countries within the Alpine Convention area: France, Germany, Italy, Slovenia, and Switzerland. The number of taxa from the Alps cultivated at each garden varies, ranging from 140 to 865 species (Figure 1 and Table S1).

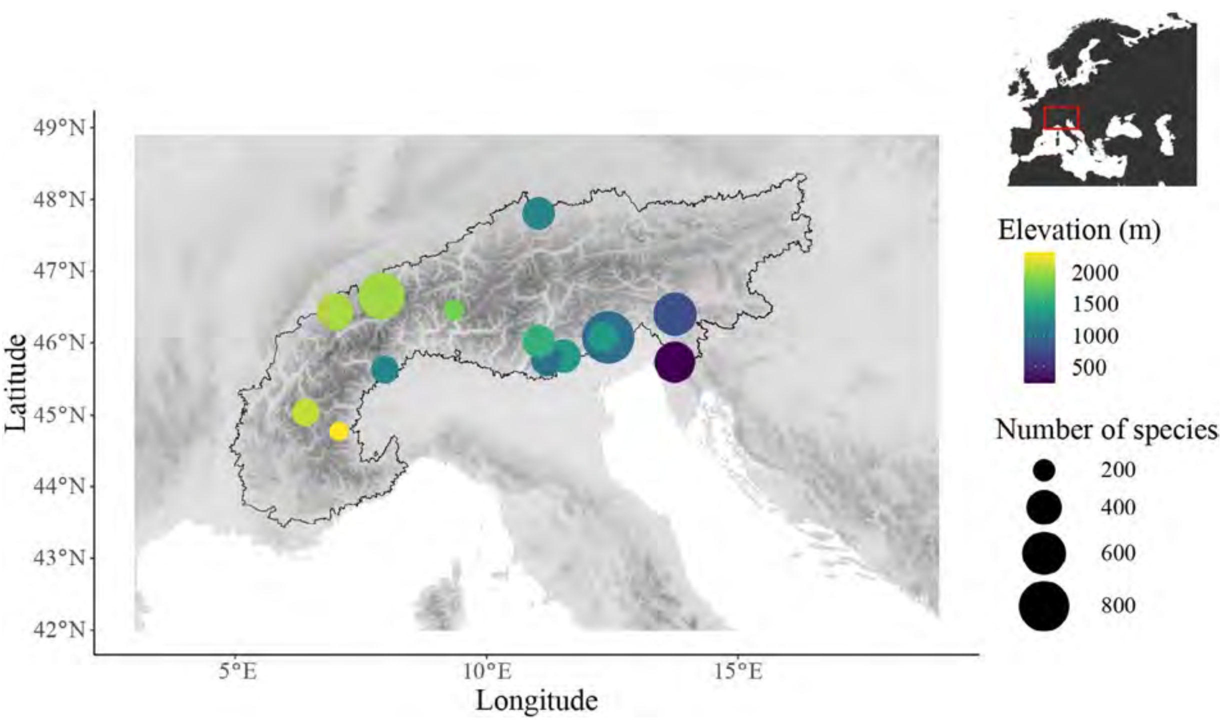

FIGURE 1 The locations of the 14 Alpine botanical gardens are represented by dots of varying sizes and colors. Larger dots correspond to a higher number of cultivated species at each garden, while the dot color reflects the respective altitude (meters). The perimeter Alps according to the Alpine convention is delineated by a black line. The grid highlights altitude variations, with high-altitude areas shown in dark gray and low-altitude areas in light gray. The map was created using the "raster" (Hijmans, 2023) and "sf" (Pebesma & Bivand, 2023) R packages.

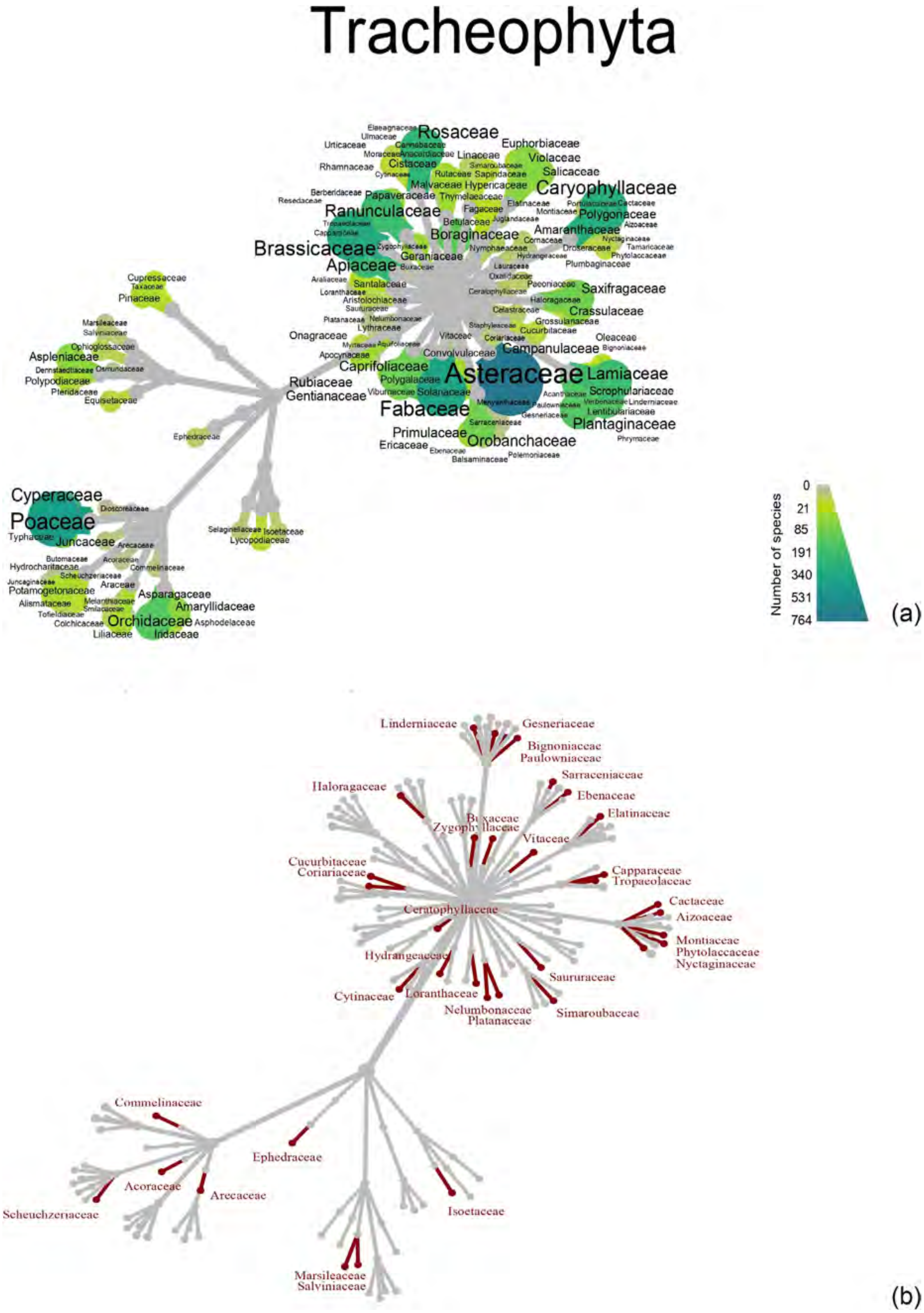

FIGURE 2 A heat tree visualizing the overall tracheophyta biodiversity of the flora of the Alps, from phylum to family level. (a) The size of the labels and the colors of the branches indicate the total amount of species per each family and whether a (b) taxonomic rank is absent (dark red) or present (gray) in the Alpine botanical gardens living collections.

3.2 | Taxonomical diversity of collections in ABGs

After WCVP curation, the flora of the Alps comprises 5814 taxa, belonging to 147 plant families and including the following infraspecific ranks: 1206 subspecies, 90 varieties, and 87 hybrids. All the botanical names are accepted, except eight taxa that are in an "unplaced" taxonomic status.

Overall, the ABGs living collections (Table S2) represent 32% of the taxa belonging to the flora of the Alps (Table S3). The living collections in ABGs encompass a taxonomic diversity of 1869 species, spread across five classes, 41 orders, 111 families, and 583 genera (Table S2 and Figure 2). The class Magnoliopsida accounts for the majority of records, representing 80% of the total, followed by Liliopsida with 17% (Table S4 and Figure 2). At the order level, the most represented orders are Asterales (16%), Poales (10%), Lamiales (10%), and Caryophyllales (6%) (Figure 2 and Table S5). At the family rank, Asteraceae is the most abundant, comprising 13% of the total records and hosting the highest number of genera (Figure 2 and Table S6), followed by Rosaceae, Poaceae, and Caryophyllaceae. Regarding the taxa ranked at the infraspecific level, the living collections include 72 subspecies, two varieties, and nine hybrids for a total of 4.4% ABGs taxa.

Of all species represented in the living collections, only five—belonging to the classes Magnoliopsida and Liliopsida—are shared across all institutions (Table 1). In contrast, 742 species (41% of the total) are cultivated in only a single institution (Table 2 and Table S2).

3.3 | Evaluation of ABGs living collections

Ninety-eight percent of the taxa in the living collections are native (Figure S1A) to the Alps. Furthermore, 3% of these native species are endemic (Figure S1A). Six taxa are locally extinct in the Alps, including *Betula nana* L. (extinct in Italy), *Carex curvula* All. (extinct in Germany), *Clematis integrifolia* L. (extinct in Italy), *Isopyrum thalictroides* L. (extinct in Switzerland), *Salix myrsinifolia* Salisb. (extinct in Italy), and *Saxifraga hirculus* L. (extinct in Austria and Germany).

Twenty-three species are listed under the "Habitats Directive," with 18 included in Annex II and five in Annex IV (Table S3). According to the IUCN Global assessment, one species in the living collections is classified as "Critically Endangered" (*Callianthemum kernerianum* Freyn ex Kern.), four are "Endangered" (*Aster pyrenaeus* DC., *Picea omorika* [Pančić] Purk., *Platanthera bifolia* (L.) Rich., and

TABLE 1 Summary of taxa identified at the infraspecific level in the Alpine living collections.

Class	Infraspecific rank	Counts	Orders
Liliopsida	subsp.	7	Asparagales, Liliales, Poales
Liliopsida	var.	1	Liliales
Pinopsida	var.	1	Pinales
Magnoliopsida	subsp.	72	Apiales, Asterales, Boraginales, Brassicales, Caryophyllales, Dipsacales, Ericales, Fabales, Gentianales, Lamiales, Malvales, Ranunculales, Saxifragales

TABLE 2 Summary of taxa cultivated in most of the Alpine botanical gardens ("common" taxa) and taxa cultivated in just one ABG among the ones part of this study ("rare" taxa).

COMMON SPECIES AMONG INSTITUTIONS			
Class	**Order**	**Species**	**Prevalence**
Liliopsida	Liliales	*Lilium bulbiferum* L.	0.86
Magnoliopsida	Malvales	*Daphne mezereum* L.	0.86
Magnoliopsida	Lamiales	*Globularia cordifolia* L.	0.86
Magnoliopsida	Fabales	*Hippocrepis comosa* L.	0.86
Magnoliopsida	Saxifragales	*Saxifraga paniculata* Mill.	0.86

RARE SPECIES CULTIVATED IN ONLY ONE INSTITUTION			
Class	**Order**	**Number of species**	**Prevalence**
Liliopsida	Alismatales, Asparagales, Dioscoreales, Liliales, Poales	136	0.07
Lycopodiopsida	Lycopodiales	2	0.07
Magnoliopsida	Apiales, Asterales, Boraginales, Brassicales, Caryophyllales, Celastrales, Cornales, Crossosomatales, Dipsacales, Ericales, Fabales, Fagales, Gentianales, Geraniales, Lamiales, Laurales, Malpighiales, Malvales, Myrtales, Piperales, Ranunculales, Rosales, Santalales, Sapindales, Saxifragales, Solanales	594	0.07
Pinopsida	Pinales	1	0.07
Polypodiopsida	Equisetales, Ophioglossales, Polypodiales	9	0.07

Note: Most of the taxa that are part of the living collections are 'rare', and they are here shown clustered by orders.

Saxifraga tombeanensis Boiss. ex Engl.), three are "Vulnerable" (*Cardamine pratensis* L., *C. pratensis* subsp. *rivularis* [Schur] O. Bolòs & Vigo, and *Potentilla delphinensis* Gren. & Godr.), nine are "Near Threatened" (*Asplenium fissum* Kit.; Willd., *Eryngium alpinum* L., *Fraxinus excelsior* L., *Galanthus nivalis* L., *Gentiana pannonica* Scop., *Medicago pironae* Vis., *Sanguisorba dodecandra* Moretti, *Saxifraga valdensis* DC., and *Trifolium saxatile* All.), 284 are "Least Concern," 13 are "Data Deficient," and the rest of them have not been evaluated (Figure S2A).

The cross-check with the Genesys PGR database revealed that 75% of the taxa in the living collections are also preserved ex situ in seed banks. The average number of seed accessions per taxon (excluding taxa with no accessions) is 93 ± 838, with a median of five accessions (Figure 3 and Table S3). Eighty-one Alpine endemic taxa are cultivated in the ABGs considered in this study, but 30 of them are not preserved in any germplasm bank worldwide (Figure 4a). Additionally, 67 other Alpine endemics are not cultivated in any ABG living collection, and 31 of these are also absent from all known germplasm collections (Figure 4b).

Only 56% of the seed-reproducing taxa in the living collections have documented germination requirements that have been tested and made available through public databases or the scientific literature (Table S7). The remaining taxa either lack germination protocols or have uncertain procedures. As for seed storage behavior, 44.98% of these taxa produce orthodox seeds, which can be preserved—albeit with variable longevity—through cryopreservation in germplasm banks. The rest are composed of 53.77% with uncertain or intermediate storage behavior and 1.25% with recalcitrant seeds.

4 | DISCUSSION

This study presents the first comprehensive, region-wide assessment of the role ABGs play in conserving the flora of the Alps. Rather than serving solely as static repositories of biodiversity, ABGs emerge as dynamic, integrative hubs where horticultural innovation, ex situ and *quasi* in situ strategies, ecological experimentation, and germplasm

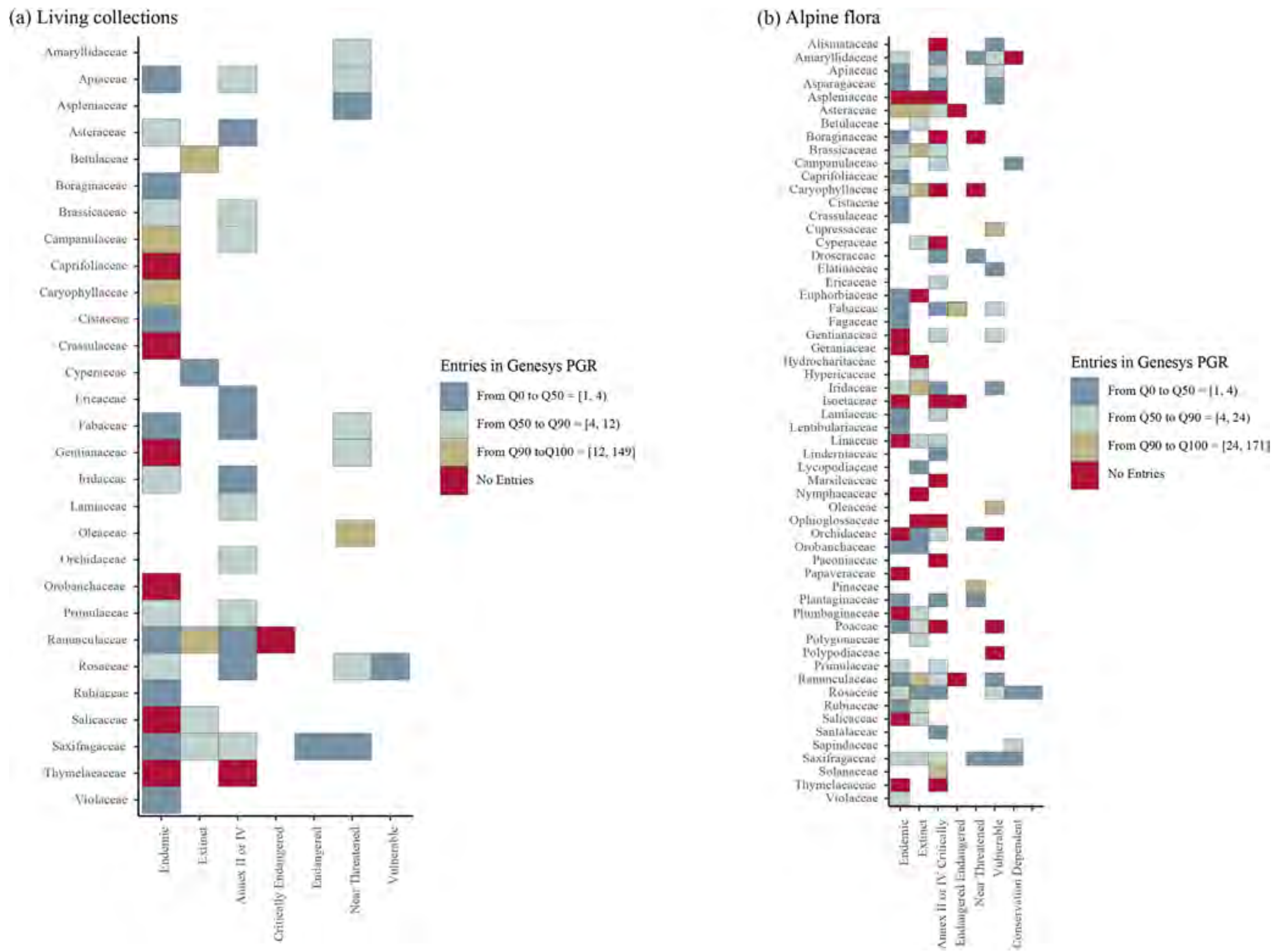

FIGURE 3 The number of entries in the Genesys Plant Genetic Resources database for species with special categorization status (endemic, extinct, habitat directives, critically endangered, endangered, near threatened, and vulnerable) is presented for both (a) the living collections in Alpine botanical gardens and (b) the total biodiversity of flora of the Alps. The color reflects the number of accessions found in Genesys PGR, corresponding to the 0–50 quantile, 50–90 quantile, and 90–100 quantile. Red squares represent the entities with no accessions found in Genesys PGR. PGR, Plant Genetic Resources.

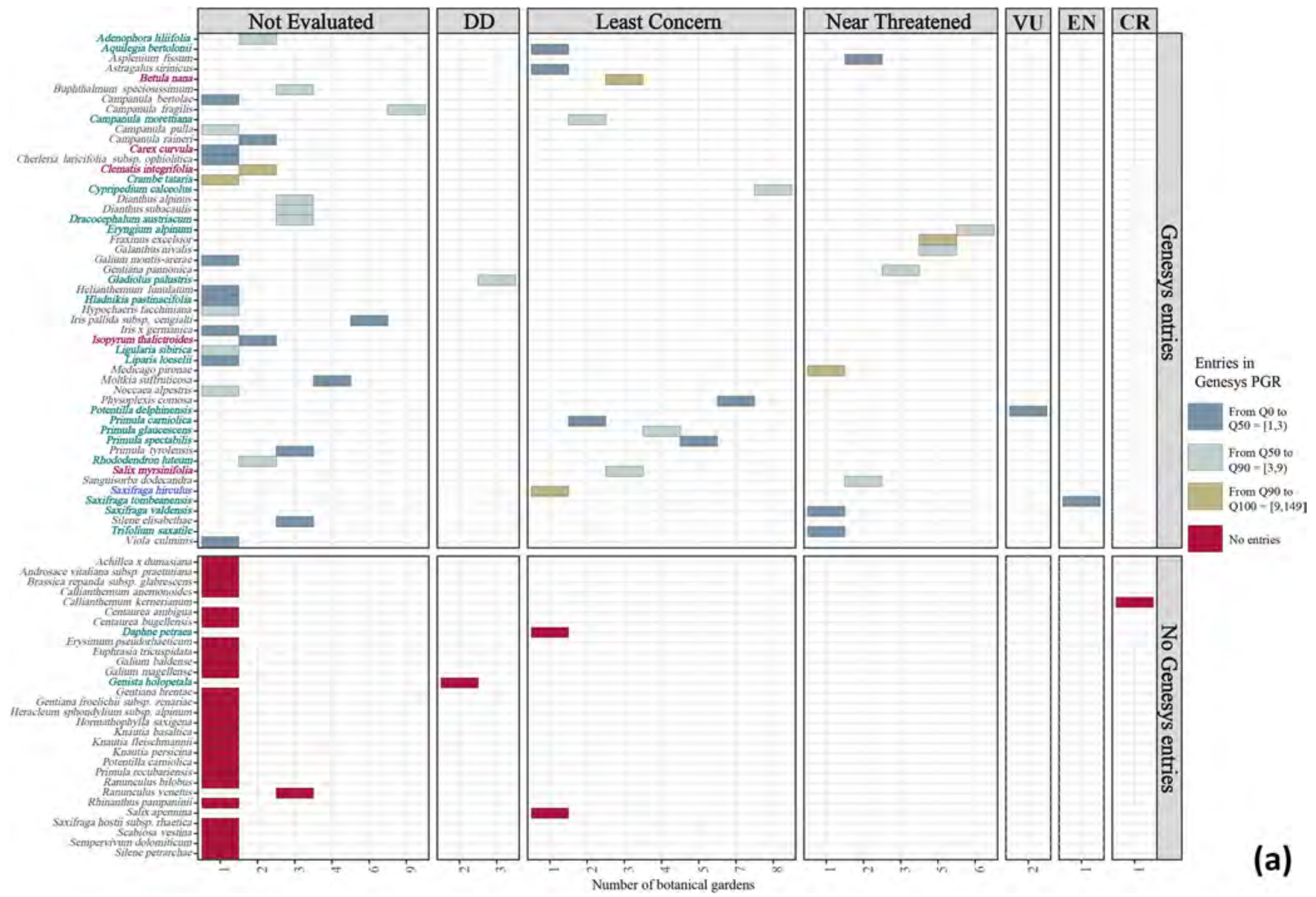

FIGURE 4 (a) Summary of the taxa from Alpine botanical gardens living collections that are either endemic or categorized by the IUCN: critically endangered (CR), endangered (EN), vulnerable (VU), near threatened (NT), least concern (LC), data deficient (DD), and not evaluated (NE) is provided. Species names are highlighted in green if listed under the "habitat" directive, in red if extinct within the Alpine convention perimeter, and in blue if they meet both criteria. The color reflects the number of accessions found in Genesys Plant Genetic Resources, corresponding to the 0–50 quantile, 50–90 quantile, and 90–100 quantile. Red squares represent the entities with no accessions found in Genesys PGR. (b) Summary of the taxa part of the Alpine Flora that are either endemic or categorized by the IUCN but not cultivated in the living collections. Color palettes follow Figure 4a. PGR, Plant Genetic Resources.

management converge. Additionally, this study provides a taxonomically harmonized checklist of the living collections from 14 ABGs across the Alps, paired with an updated reference flora of the Alps derived from the World Checklist of Vascular Plants.

4.1 | Do the living collections of ABGs preserve valuable species for conservation, including protected, threatened, or endemic taxa?

ABGs excel at cultivating a broad range of taxa belonging to the flora of the Alps, including many threatened or endemic taxa. For example, critically endangered endemics such as *Isoëtes malinverniana* Ces. & De Not. (Italian endemic, CR according to IUCN), which require in vitro propagation and highly specific freshwater conditions in terms of water electroconductivity and pH (Abeli et al., 2012), exemplify the technical expertise and conservation capacities of ABGs. Similarly, *Campanula morettiana* Rchb., a species with demanding ecological requirements, benefits from the ability of ABGs to replicate fine-scale environmental conditions and maintain genetic diversity over time.

However, not all alpine specialists can be effectively maintained in ABGs. Species adapted to ephemeral snow beds, wind-swept substrates, or karstic dolines—such as *Ranunculus glacialis* L.—pose major challenges, as they depend on subtle ecological interactions that gardens cannot fully reproduce. For these taxa, in situ conservation remains irreplaceable, and ABGs should be viewed as complementary components within a broader conservation network. While they offer refuges, research platforms, and avenues for public engagement, they cannot replace habitat-based efforts. This integrated approach is consistent with global conservation frameworks that advocate for multifaceted strategies to safeguard biodiversity.

ABGs surveyed in this study represent a substantial share of the region's plant diversity, with individual collections ranging from a few hundred to several thousand taxa. Located at varying altitudes and leveraging local microclimatic conditions, ABGs often recreate a mosaic of alpine habitats within small areas, effectively serving as condensed representations of the flora of the Alps. Curators carefully identify taxa to the species or infraspecific rank, enhancing both taxonomic precision and scientific value. Such accuracy is crucial, as misidentification can distort diversity assessments and compromise conservation prioritization (Guzzon & Ardenghi, 2018). By maintaining well-documented and correctly identified taxa, ABGs reinforce the integrity of their own collections and contribute meaningfully to the broader conservation network.

Some taxonomic groups pose particular challenges. The Lindernaceae family, represented in the Alps solely by *Lindernia procumbens* (Krock.) Philcox, is difficult to maintain in ABGs because of its short annual life cycle, extremely small seeds, preference for intermittently flooded habitats, and vulnerability to competition from the non-native *Lindernia dubia* (L.) Pennell (Corli et al., 2024). Conversely, certain families present in the Alps include only non-native taxa, which ABG curators generally exclude as they fall outside conservation priorities. Examples include Nelumbonaceae, Elatinaceae, and Paulowniaceae, whose casual non-natives are not considered relevant to the conservation missions of ABGs.

4.2 | To what extent are these species represented in the collections of germplasm banks? Are the germination requirements of such species known?

Beyond their on-site living collections, ABGs can play a critical role in global germplasm banking by supplying seeds, spores, and vegetative propagules, especially for taxa with complex dormancy or storage requirements. However, integration with broader ex situ conservation efforts remains limited, hindered by insufficient standardization and minimal data sharing. Accurate taxonomic identification is essential, as misidentifications can skew diversity estimates, complicate gap analyses, and misdirect conservation priorities.

The importance of improving germplasm representation is emphasized by established guidelines. For example, ENSCONET (2009a, 2009b) recommends collecting at least five accessions per species to ensure sufficient genetic variability. Our gap analysis revealed that many taxa are either absent from germplasm banks or represented by fewer than five accessions, highlighting the potential of ABGs to enhance genetic breadth in ex situ conservation. Systematically documenting germination cues, storage conditions, and propagation techniques will support ABGs in meeting these standards and enable more effective species reintroductions, population reinforcements, and long-term resilience. Advanced techniques such as cryopreservation, tissue culture, and in vitro propagation further expand the conservation toolkit, especially for orchids, aquatic ferns, and clonal species that are poorly suited to conventional seed banking.

A significant challenge to maintaining genetic integrity in ABGs is the risk of hybridization in ABGs, particularly between species that are geographically isolated in the wild. To mitigate this, curators must prioritize controlled pollination for threatened species, and technical staff must be adequately trained to prevent unintentional hybrid formation.

At the family rank, the gap analysis identified six endemic-rich families represented in ABGs but entirely absent from global germplasm banks, making botanical gardens critical sources of unbanked genetic material. Numerous taxa currently underrepresented in seed banks (i.e., fewer than five accessions) are well maintained in ABGs and could significantly enhance the genetic diversity and resilience of ex situ collections. Endemic taxa are especially vital in this context, with eight families and several species listed under the EU Habitat Directive lacking adequate representation in germplasm repositories.

At the species and infraspecific levels, several endemic taxa absent from long-term germplasm storage were identified. Notably, most of these taxa have never been evaluated by the IUCN, revealing gaps in both ex situ and in situ conservation planning. Among them, only *Callianthemum kernerianum* Freyn ex A. Kern. is listed as CR, while others remain data deficient. Some, such as *Saxifraga valdensis* DC. (NT), *Potentilla delphinensis* Gren. and Godr. (VU), and *Liparis loeselii* (L.) Rich. (NE), are well represented in ABGs. In addition, ABGs maintain some locally extinct taxa, offering valuable opportunities for genetic research and potential future restoration.

Repeating the gap analysis for the entire flora of the Alps and for endemic taxa not yet cultivated in ABGs reveals further needs. These comparisons uncovered both taxonomic and conservation gaps, including missing endemic Orchidaceae and endangered Ranunculaceae and Caryophyllaceae species listed under the Habitat Directive. Several high-priority "policy species," such as the critically endangered *Isoëtes malinverniana*, as well as non-policy but threatened *Artemisia inspida* Boiss. and *Gymnadenia* R.Br. species, remain uncultivated. Targeted acquisition and propagation of these species would expand ABG collections and reinforce their complementarity with germplasm banks. The SID served as a screening tool to verify whether baseline information on germination conditions and storage behavior is available for taxa of the Alpine flora. While not comprehensive, it enabled us to distinguish species for which at least one tested condition exists from those for which no available data. In this framework, the presence of a record does not imply that a protocol is optimal, but only that a trial has been conducted; storage behavior is assigned to orthodox, intermediate, or recalcitrant categories only when tests have been performed. Many Alpine species remain unstudied in this respect, including representatives of *Primula*, *Saxifraga*, and *Androsace*. Additionally, alpine seeds often show short longevity under -20°C storage (Mondoni et al., 2011), and several groups are likely to include species with complex dormancy (Baskin & Baskin, 2014). The lack of baseline information for these taxa highlights clear priorities for future research on germination ecology and seed persistence, and underscores the role of ABGs in generating and sharing such knowledge.

4.3 | Can ABGs serve as integrated, *quasi* in situ conservation facilities for the collection and preservation of alpine germplasm?

While germplasm banks focus on long-term storage, ABGs adopt a hybrid approach that integrates on-site propagation, field collection, and collaboration with specialized nurseries and research centers. Their routine publication of *index seminum* reflects a longstanding commitment to germplasm exchange and networking, both within and beyond the Alpine Convention.

Maintaining the genetic integrity of ABG accessions is essential. To mitigate hybridization risks, fruits resulting from open pollination are regularly removed, and only seeds derived from controlled pollination are included in *index seminum*. Regular staff training in pollination techniques across plant families is crucial to uphold these standards.

Improving coordination with germplasm banks could include expanding seed handling and curation capabilities within ABGs. Tools such as sieves, column blowers, or laminar flow hoods are relatively low-cost investments that, when paired with basic training, can substantially improve germplasm quality. Orthodox seeds could be partially stored in ABGs as short- to medium-term deposits (e.g., using silica gel dehydration), with duplicate batches sent to germplasm banks for long-term preservation (e.g., cryopreservation or in vitro storage). Greater integration of ABGs into international networks would ensure that both accessions and associated data are accessible to global conservation stakeholders. Among the taxa missing from germplasm bank collections, several fall into the category of "exceptional species" sensu Pence et al. (2022). This framework recognizes species that cannot be efficiently conserved through conventional seed banking because of specific biological constraints. These include (i) species with limited or unpredictable seed availability, or for which seed collection is impractical; (ii) taxa producing desiccation-sensitive seeds that do not tolerate drying; (iii) species with seeds or spores that are short-lived under standard -20°C storage; and (iv) taxa whose recovery after storage is hindered by deep or complex dormancy or the requirement of symbiotic partners. Within the Alpine flora, such cases are found across multiple groups. Orchidaceae such as *L. loeselii* (L.) Rich., *Platanthera bifolia* (L.) Rich., and *Gymnadenia* R.Br. species are difficult to conserve by seed banking because of their obligate mycorrhizal associations and poor longevity in conventional storage. Members of Salicaceae, including several *Salix* L. species, produce seeds that are inherently short-lived even under controlled conditions. Ranunculaceae such as *R. glacialis* L. and the endemic *Callianthemum kernerianum* Freyn ex A.Kern. combine limited storage longevity with complex dormancy. Ferns and lycophytes provide another example, as their spores often lose viability rapidly at -20°C, making long-term storage ineffective. Some geophytes, such as *G. nivalis* L., display intermediate storage behavior, with partial desiccation sensitivity that reduces their suitability for conventional seed banking. These examples illustrate that part of the flora of the Alps cannot benefit from standard germplasm bank techniques. For such taxa, ABGs can provide alternative conservation strategies by maintaining living collections that function as "living seed banks", while also supporting the development of cryobiotechnologies and in vitro propagation protocols to complement traditional ex situ approaches. Despite these strengths, several limitations constrain the conservation potential of ABGs. Geographic gaps, particularly in the northeastern Alps, and the lack of complete or up-to-date collection inventories impede strategic conservation planning. Cano et al. (2025) showed that historical botanical gardens reached their peak in plant diversity preservation in the early 2000s, followed by declines, underscoring the need for renewed missions and adaptive management. In this context, smaller, thematic collections like those maintained by ABGs are gaining recognition as valuable experimental platforms for exploring climate adaptation, microhabitat optimization, and assisted migration strategies.

Importantly, the number of individuals per taxon maintained in ABGs may be insufficient to safeguard genetic diversity. Curators should prioritize genetic representativeness over taxon richness, adjusting the number of cultivated individuals accordingly. While some ABGs monitor phenology in selected indicator taxa to study climate change effects, systematic data collection on functional diversity and reproductive success remains limited. Strengthening the role of ABGs in conservation will require more detailed knowledge of population structures and genetic diversity within the plant genetic resources they manage. ABGs can address the limitation of maintaining few individuals per taxon by concentrating on priority species and coupling propagation with coordinated action across conservation actors. The Giardino Botanico Alpino Viote has applied this approach within EU LIFE projects, where ex situ propagation is directly linked to reinforcement and reintroduction in protected areas (see, e.g., LIFE SEEDFORCE, 2025). The Alpengarten Schynige Platte maintains experimental plots where threatened alpine taxa are cultivated and monitored under controlled conditions, providing both plant material and tested protocols for future conservation interventions. At the Jardin du Lautaret, living collections are complemented by experimental grassland plots and nurseries that support ecological restoration and species translocation under climate change scenarios. Integrating ABGs into international networks further ensures that deposited accessions and their associated data remain accessible to stakeholders worldwide. For example, collaborations between the Jardin du Lautaret and the Millennium Seed Bank (KEW Royal Botanic Gardens) involve not only the deposition of Alpine PGR but also the joint development of germination protocols for challenging alpine endemics to propagate, such as *Saxifraga longifolia* L. and *R. glacialis* L. These initiatives exemplify how ABGs can function as propagation nodes—connected on one side with natural area managers, ensuring that cultivated material feeds into population-level actions, and on the other with germplasm banks, where seed accessions can be stored for long-term security. In this way, ABGs extend their role beyond maintaining taxonomic breadth, developing targeted programs that strengthen both ex situ and in situ conservation of Alpine flora.

5 | CONCLUSIONS

This study highlights not only the current role of ABGs but also their untapped potential as key actors in the conservation of alpine plant biodiversity. ABGs are uniquely positioned to bridge ex situ and in situ approaches, refine germination protocols, integrate horticulture with ecological restoration, and translate scientific research into applied conservation. While they are facing challenges, such as limited geographic coverage, incomplete inventories, and resource constraints, these gaps also present opportunities for strategic innovation and collaboration.

By strengthening networks, adopting advanced technologies, prioritizing taxa of high conservation value, improving data sharing, and engaging a wider range of stakeholders, ABGs can significantly amplify their impact. They are well placed to demonstrate how horticultural expertise, taxonomic precision, adaptive experimentation, and strong partnerships can drive biodiversity conservation in the face of accelerating environmental change.

To advance the ABGs' conservation mission, we propose the following priority actions and future directions: (i) Focusing on challenging taxa: targeting species that are difficult to propagate or bank is essential to prevent "silent extinctions" and improve ex situ coverage. (ii) Enhancing in situ–ex situ integration: While ABGs complement broader conservation strategies, intact habitats remain irreplaceable. Harmonizing habitat protection with ABG-based experimentation can foster more resilient and context-specific outcomes. (iii) Standardizing germination and propagation protocols and improving data sharing: Developing open, standardized databases for germination requirements, storage behavior, and propagation techniques will strengthen collaboration and improve conservation outcomes. (iv) Embracing advanced technologies: Incorporating cryopreservation, tissue culture, and other methods will expand the conservation toolkit, particularly for taxa poorly suited to conventional seed banking. (v) Leveraging international collaboration and innovative funding models: expanding transnational networks, partnering with research and conservation institutions (e.g., germplasm banks), and exploring novel financing mechanisms will help ensure that ABGs remain agile, impactful, and forward-looking. Together, these actions will position ABGs as strategic, science-based hubs in securing the future of the Alps' unique plant diversity.

AUTHORS CONTRIBUTIONS

Work idea: Marco Canella, Núria Beltran-Sanz, Nicoletta La Rocca, and Francesco Dal Grande.

Data collection: Marco Canella, Sara Natale, Andreas Gröger, Špela Pungaršek, Maxime Rome, Costantino Bonomi, Helen Catherine Wiesinger, Andrea Mainetti, Marco Valecic, Simone Sensato Monica Sommacal, Elena Piutti, Fabrizio Bottelli, Maria Teresa Pizzato, Jasmin Senn, and Anne-Catherine Monod. *Data analysis*: Núria Beltran-Sanz, Marco Canella, Sara Natale, and Andrea Scapin. *Writing*: Marco Canella, Núria Beltran-Sanz, and Francesco Dal Grande (with contribution and validation from all authors).

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CONFLICT OF INTEREST STATEMENT

The authors have no competing interests to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the Supporting Information of this article.

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