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REVIEW ARTICLE

Ex situ Conservation Efforts for Plant Diversity Protection with A Focus on Seeds

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Abstract:

Plant diversity underpins ecological systems and provides materials that sustain humanity. Yet, plant diversity is being lost at a rate unparalleled in recent history, and the threat largely comes from anthropogenic pressures. As an effort to halt the continuing loss of global plant diversity, *ex situ* conservation has been gaining momentum. This article reviews the current *ex situ* conservation approaches with particular attention to botanic gardens, seed banks, cryopreservation, and seed vaults. Botanic gardens and conventional seed banks present their advantages and issues for effective plant conservation with cryopreservation complementing them in useful ways. Seed vaults that store seeds permanently occupy a unique place in plant conservation efforts. Of the two existing vaults, the Svalbard vault appears to have established itself as a global institution for the public good by safeguarding food and agriculture seed. The Korean vault, a relatively newer institution, may need further strategic efforts to build its clear identity and comparative niche, and distinguish itself as a global facility. While sustainably conserving plant diversity is an uphill challenge, increasing participation in *ex situ* conservation will certainly facilitate coping with the challenge.

Keywords: Agriculture, Botanic garden, *Ex situ*, Plant diversity, Seed bank, Seed vault.

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1. INTRODUCTION

The World Economic Forum of 2022 identified climate action failure, extreme weather, and biodiversity loss as the top three global risks [1]. While the three risks are tightly interwoven, the gravity of biodiversity loss demands serious attention. Biodiversity has shaped human society and culture for millennia, with plant diversity being essential for life [2]. Plant diversity provides materials that sustain human life and underpins ecological processes such as climate regulation, carbon dioxide absorption, and protection of soil, water and air among others [3]. Yet plant diversity is currently being lost at a rate unparalleled in recent geological history [4]. Studies estimate that globally 20 to 39% of all plant species are at risk of extinction, and the threat comes largely from anthropogenic pressures including land use change, direct exploitation, pollution, introduction of invasive alien species, and excessive resource use [5]. Importantly, the threatened plant diversity may possess untapped potential to confront major challenges to humanity in food security, energy availability, habitat restoration and climate change [3].

In a bid to halt the continuing loss of global plant diversity, the Convention on Biological Diversity adopted the Global Strategy for Plant Conservation in 2002 [4]. The strategy outlines 16 targets set to be achieved by 2020 [3]; the Post-2020 Global Biodiversity Framework has yet to be published as of this writing. Especially relevant to plant conservation are targets 8 and 9 of the strategy. Target 8 requires that at least 75% of threatened plant species be conserved *ex situ* with the aim of at least 20% available to be used for recovery and restoration programs. Target 9 calls for the conservation of 70% of the genetic diversity of crops, their wild relatives, and other socio-economically valuable plant species [6]. Adopting and implementing sustainable conservation strategies thus is critical if the decline of global plant diversity is to be slowed down [7].

Biodiversity conservation in its natural habitat or *in situ* conservation is the most appropriate conservation approach for preserving plant species because *in situ* conservation preserves the original genetic and geographic centers of biodiversity. However, when *in situ* conservation is not feasible or when *in situ* conservation needs to be complemented in order for more effective conservation efforts, different strategies should be implemented to support *in situ* protection of plant species [8]. *Ex situ* conservation, or conservation of biodiversity outside its natural habitats, can support *in situ* conservation [9].

Ex situ conservation involves human intervention, and the conservation takes the forms of living plants in botanic gardens

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and arboreta, and forms of seeds, tissues, or any part of plants in seed or germplasm banks [9,10]. The main roles of *ex situ* conservation include preserving a significant portion of the genetic diversity of the species, creating a backup of genetic materials if *in situ* conservation actions fail, and propagating species for restoration and further uses [11]. In some cases, *ex situ* conservation is the only option to preserve certain plant species [8]. In recent years, botanic gardens and seed banks have made significant progresses towards conserving plant species [11]. Additionally, both living plants in botanic gardens and plant parts in seed banks offer invaluable sources for agricultural research and food security since crop breeding depends largely on the availability of and accessibility to plant genetic materials [10].

Conventional seed banks with seeds dried and stored at low temperatures may be the most practical method for conserving a wide range of plant diversity. Banking seeds is relatively cost and space efficient, and methodologies for storing seeds are comparatively well established [8,12]. However, not all plant species can be preserved as seeds in seed banks. Recalcitrant or desiccation-sensitive seeds cannot stand a drying and low-temperature treatment without losing their viability. Only orthodox or desiccation-tolerant seeds can generally be stored in the long term. Besides, there are plant species that do not produce seeds, instead propagate vegetatively. For those plant species, botanic gardens and field collections provide an alternative option [8].

Botanic gardens have long conserved plant diversity through their living collections, often collected in the wild including threatened species. Yet not all their collections are maintained for conservation purposes only. Other important functions of botanic gardens involve research, display, education, and public outreach. Accordingly, botanic gardens offer an essential means to inform the public of conservation issues and the significance of the issues [10]. Conserving plants as living collections in botanic gardens, however, has its limitations; it usually requires large land areas and is labor intensive; collections in botanic gardens are mostly unprotected from plagues and natural disasters [8].

Across the world, the Royal Botanic Gardens Kew with its Millennium Seed Bank and the Svalbard Global Seed Vault (thereafter the Svalbard vault) are probably the most prominent institutions for *ex situ* conservation to protect plant diversity. Both the garden and the vault are exceptional in the extent of their international nature and scale, albeit with different focuses [10]. The former is the world's largest repository of wild plant genetic diversity as both a botanic garden and a seed bank; it is known to store approximately 997,000 accessions (a distinct, uniquely identified sample of seeds or plants [13]) with 2.4 billion seeds representing over 40,000 species. On the other hand, the Svalbard vault holds the world's most diverse collection of food and agriculture seeds. It is estimated that the vault stores over 1.1 million seed accessions of around 6,000 species. Technically, the vault preserves seeds permanently, a distinct feature of the vault whereas seed banks propagate and distribute seeds to users, thus their seeds are flowing in and out of the banks [10]. Recently, a uniquely positioned seed vault was established in the Republic of Korea; the Baekdudaegan National Arboretum Seed Vault (thereafter the Korean vault). The Korean vault focuses on endemic wild plants including tree species as the Millennium Seed Bank does while the Korean vault preserves the deposited plant materials permanently as the Svalbard vault does.

Against this backdrop, the main objective of the article is to examine the current *ex situ* conservation efforts for plant diversity protection, review the two existing seed vaults in detail, and draw useful policy implications for more effective functions of the Korean vault. The article is organized as follows; it reviews botanic gardens, seed banks, and cryopreservation in general, followed by examination of the Svalbard vault; then it discusses the Korean vault with conclusions.

2. BOTANIC GARDENS

Currently, around 3,269 botanic gardens are distributed across 180 countries, and various definitions of a botanic garden exist [3]. A generally recognized definition of it is an institution holding documented collections of living plants for the purposes of scientific research, conservation, display, and education [14]. As the definition indicates, botanic gardens serve multiple functions and adopt different methods to fulfill their purposes. Those methods include cultivating and displaying living plant collections, banking seeds, and maintaining other plant materials *via* tissue culture or cryopreservation [14]. However, the range of methods adopted would depend on the focus and capacity of individual gardens.

Recognizing the unique role of botanic gardens for plant conservation, the International Union for Conservation of Nature and the World Wide Fund for Nature published the first Botanic Gardens Conservation Strategy in 1989. Throughout the 1990s, the roles of botanic gardens in conservation were gradually developed. Then in 1998, the Botanic Gardens Conservation International, a consortium of 800 botanic gardens in over 100 countries, launched an international consultation process to update the 1989 strategy, taking into account the Convention on Biological Diversity [3].

Botanic gardens historically focused on taxonomy and plant discovery although common ornamental plants may consist of a considerable proportion of their plants [11,15]. Yet, many botanic gardens have shifted their focus to conservation science and research due in part to the development of conservation biology and the rising threats to global plant biodiversity [15]. In 2017, the Botanic Gardens Conservation International updated and published a list of criteria, which defines a botanic garden, in order to emphasize stronger conservation aspects and scientific research. Among the updated defining criteria, the two most relevant to the shift are; conserving rare and threatened plants in *ex situ* collections and, wherever possible, in their natural habitats; undertaking scientific or technical research on plants in the collections while integrating a wide range of relevant disciplines. In the previous version of the criteria, those two were less explicit [16].

To date, over 105,600 plant species are known to be conserved in different forms in botanic gardens [10]. This number equates to about 30% of plant species diversity, 59%

of plant genera, 75% of land plant families, and 93% of all vascular plant families. These numbers are highly conservative as the analysis is based on data derived from just a third of botanic gardens worldwide. Furthermore, botanic gardens appear to be effectively responding to the threat of species extinction by housing at least 13,218 species at risk of extinction. This is equivalent to over 41% of the world's known threatened flora [3]. These plant species maintained in botanic institutions may likely be important in helping to ensure the wellbeing of the ecosystem as well as that of humanity.

Despite the growing role of botanic gardens in conserving plant diversity, the use of living collections presents constraints. First, genetic variation of *ex situ* populations could decline after several generations of cultivation due to high inbreeding rates, genetic drift, or a small number of founders originally collected in the wild, especially for very rare species [3]. Specimen collections in botanic gardens are frequently limited in the number of individuals, and therefore often represent a poor genetic variation and genetic bottleneck [4]. To address genetic degradation issues, botanic gardens purposefully add specimens to existing living collections to maintain or increase genetic diversity. Strategic material exchanges among botanic gardens can help maintain genetic diversity for cross-fertilization plants, unlike exchanges with clones or inbred individuals that would result in genetically identical stocks. However, there is a tradeoff. Improved genetic diversity entails increased maintenance costs for additional plants, and swapping living plants or their parts may invite undesired hybridization or inadvertent pathogen-disease transfers [3,17].

The second constraint in botanic gardens is the potential effects on the evolution of *ex situ* plant populations and plants' ability to tolerate stress. Cultivation environment under control may work as a selective force on specific genotypes and traits in the garden populations [3]. Those effects are likely larger on annual and short-lived plants than long-lived perennials such as trees. Although the exact effects from selective forces cannot be predicted, they may turn negative; the plants could fail to tolerate biotic and abiotic stresses because of their weakened ability to do so when released to their natural habitats [3,17].

The third issue on conserving plants in botanic institutions is a substantial biogeographic gap in the representation of their plant collections. In other words, 93% of the plant collections occur in the northern hemisphere [3]. This positive latitudinal gradient, where plant species diversity in botanic gardens increases in temperate latitudes, runs counter to natural latitudinal gradients, where tropical ecosystems contain the majority of plant species diversity. It is shown that 76% of species absent from the botanic garden network are tropical species, and a tropical species stands only a 25% probability in *ex situ* cultivation across the botanic garden network. This is comparable to the 60% probability for a temperate species [3]. Relatedly, one study notes that only a third of the worldwide plant conservation collections occur across the 36 global biodiversity hotspots [10].

The disparity between the location of conservation sites and the location of biodiverse habitats can be partly attributable to the economic disparity; two-thirds of the 551 gardens that provide records for plant conservation programs are based in the high-income countries defined by the World Bank [10]. While it is hard to contradict the existence of a biogeographic gap in plant conservation in botanic gardens, it can be argued that the gap may not be as severe considering the shortage of relevant data from tropical regions. From technical perspectives, it may be difficult to conserve tropical taxa on a meaningful scale in temperate climates due to high costs and limited space [3]. The findings, nonetheless, highlight the need to continue incorporating and supporting botanical institutions in tropical regions to address their under-representation [10].

Overall, botanic gardens have massive potential to contribute to the global outcome of plant diversity, conservation, and restoration since they are well-equipped with geographic networks, necessary infrastructure, and technical knowledge [18]. At the same time, gardens are increasingly fostering seed banks as part of their tool to conserve plant species; in the last two decades, the number of seed banks affiliated with botanic institutions has doubled [14]. As botanic gardens are disproportionately located in the global north, their seed banks are also located in the global north, particularly in Europe and North America [10]. Seed banks, whether affiliated with specific botanic institutions or run independently, vary in size and capacity for seed storage. Yet their purpose remains the same, *i.e.*, preserving high-quality, viable plant germplasm until requested for use [10]. It should be mentioned that the following section mostly covers the conventional seed banks with plant seeds among different kinds of plant germplasm. In literature, the terms 'seed banks', 'plant germplasm banks', 'biobanks' or 'plant gene banks' may be used interchangeably or distinctively, but a discussion on those terms is beyond the scope of this article.

3. SEED BANKS

Seeds are part of the plant germplasm, that is, any part of the plant which can be used to regenerate a new individual and maintained for breeding, research, and conservation efforts [10,13]. Seeds tend to be highly adaptive to harsh conditions for survival and are able to establish when conditions improve [9]. As such, banking seeds is the most widely employed among the *ex situ* methods. Depending on the scope and function of seed banks, they may be referred to as differently, but the general concept of seed banks stays unchanged; they use controlled drying-cooling environments to preserve plant diversity. Seed banks also hold well-documented information on their seed collections to ensure the effective use of their collections [10].

Over 1,750 seed banks are estimated to exist across the world. The majority of them concentrate on crop species and, to some extent, their close wild relatives. A study indicates that such seed banks maintain up to 7.4 million accessions of plant genetic resources for food and agriculture [10]. The dominance of food and agriculture plants may not be surprising, given that traditionally agricultural institutions have utilized seed banks to prioritize conserving crops with global and national importance [14].

Seed banks have several advantages over other conservation methods. The first advantage is their ability to store many plant species in a limited space at a high density [3]. The high density storage of seeds can help reduce maintenance costs and accommodate seeds in quantity [3]. This attribute thus can facilitate a wider genetic representation of plant species in a given storage area [17]. Secondly, seed banks can take advantage of long survival periods of seeds [9]. Survival periods of seeds tend to be much longer than the lifespan of individual living plants under general seed storage conditions, for example, drying seeds at 15% relative humidity at 15 °C and storing them at -20 °C [17]. Under such conditions, seed germinability might take many years to decline considerably [3]. Yet, even under optimal storage conditions, gradual loss of seed viability is likely to occur as a result of seed aging over time. This in turn affects seedling emergence and survival. Seed longevity is known to vary depending on multiple factors. For instance, seeds from plants living in hot, dry areas tend to last longer than those from cool, wet climates. Other correlates with seed longevity include an embryo size and maturity, and a seed dispersal pattern [3]. The third advantage of seed banks can be their ability to store plant species that are extremely difficult to keep in cultivation, such as parasitic species that must be grown together with host species [17].

Despite such advantages, it has long been recognized that conventional seed banking is not suitable for all seeds. Conventional seed banks can store only orthodox seeds that are tolerant to the drying and freezing process for longer survival, and about 75-80% of seed-bearing plant species are known to produce orthodox seeds [3]. Some plants produce orthodox seeds that can be dried frozen, but are too short-lived for conservation purposes [4]. Other plants produce recalcitrant seeds that are unable to survive the drying process, therefore, cannot be frozen. Research indicates that up to 10% of all angiosperms produce recalcitrant seeds, and approximately 36% of critically endangered plant species do so [3]. Morever, a study notes a positive relationship between the likelihood to produce recalcitrant seeds and the proportion of tropical tree species [4].

Many crop species are identified to produce orthodox seeds, and their seed storage behaviors are relatively well studied. As such, the seed storage behaviors of crop wild relatives can be better predicted than those of wild plant species since the seed desiccation response is largely conserved at a species or genera level [4]. To date, there has been little research on methods to predict seed storage behaviors of many untested wild species. Most of the theories for processing and conserving wild plants' seeds are derived from studies on crops [19]. Thus, a knowledge gap exists in which wild plants would be suitable for conventional seed banking [4]. In some cases, however, *ex situ* conservation of recalcitrant seeds is possible with cryogenic technologies; seeds are rapidly cooled in liquid nitrogen at -196 °C [3]. In the later section, this method will be further discussed.

Besides the recalcitrant seeds, an additional issue with seed banks is the limited genetic diversity of the plant population, which reflects the genetic diversity only at the time of collection [3]. This might not be a concern for plant resurrection. But the material in seed banks is no longer evolving, unlike the plant population in natural environment. As previously discussed, living plant collections *ex situ* have a similar issue; their plants may adapt and evolve to the given controlled conditions [10]. For this reason, seeds from old *ex situ* collections may be unable to adapt to abiotic and biotic conditions when grown *in situ*. This is particularly relevant for species long missing from their natural habitats; after rearrangement of the ecosystem following the species' extinction in nature, their seeds may no longer find a suitable niche to thrive [3].

Compared to crop plants, interest in utilizing seed banks to conserve wild plants is relatively more recent with increasing attention to plant diversity [14]. In habitat restoration and reintroduction of wild plant species, seed banks' collections of wild plants can play a key role. However, there are usually fewer accessions per wild plant species in conservation collections to work with, and accessions from wild populations are highly likely heterogeneous with unknown growth requirements [9]. Crop species have been bred for shattering resistance and uniformity in flowering and seed maturation. But wild species tend to disperse their seeds readily and have indeterminate flowering, and their populations may not be found growing in isolation. These all pose difficulties with collecting a large number of homogenous seeds from wild species, and what is collected may show various maturity and viability. Therefore, those attributes of wild plants' seeds limit the number of seeds available for storage, testing, and distribution [19]. It is acknowledged that seed banking is not a solution to conserve all wild plants, but the advantages of banking seeds demand that seed banks should be considered a viable option in wild plant conservation.

Regarding seed conservation, a recent study raises a more fundamental question on the standing of seeds from wild threatened plants and stresses the need for a critical review of the current status of their seeds. The study argues that the International Union for Conservation of Nature (IUCN) Red List is inconsistent in its treatment of seeds [17]. *In situ*, seeds are recognized as immature individuals capable of maintaining a species in the habitat and of avoiding extinction even when all plants have died. But in *ex situ* facilities, seeds are not afforded the same status as *in situ*. Instead, plant taxa extirpated from the wild are classified as extinct, even when collections of good quality seeds exist for *in situ* restoration in the future. The study further points to a discrepancy arising within *ex situ* conservation when plant taxa are formally recognized as absent from *in situ* habitats; if the taxa are only represented by plant collections in botanic gardens, the Red List assessment classifies the taxa as extinct in the wild; yet if the taxa are reduced to seeds in *ex situ* seed banks, they will be categorized as extinct. This situation is attributable to the category development that preceded recent advances in *ex situ* seed banking [17]. Another complicated view on the Red List assessment on seeds is raised in the context of de-extinction of plant species. A study notes that if a seed of an extinct species is alive, the species is technically not extinct, which makes the use of the term de-extinction questionable [5]. However, the study further discusses complications that involve seeds being alive or dead; when it is impossible to know a priori whether a seed is able to germinate, plants preserved only as seeds should still be considered extinct [5].

Seed banks can be the last resort for many plant species, thus the classification without updates presents inflexible barriers to meaningful attempts at species restoration and conservation. In this respect, it is recommended that the Red List guidelines reexamine and reflect the recent advances in seed banking and treat seeds consistently, regardless of their *in situ* or *ex situ* status for effective plant conservation [17].

4. CRYOPRESERVED PLANT COLLECTIONS

As noted earlier, seed banking requires drying and low-temperature storage, and the method can only be applied to plant species that produce orthodox seeds. Plant species with recalcitrant seeds or seeds falling in the intermediate category may show a range of tolerance and sensitivity to the drying and freezing process. The seed banking approach is hardly applicable to species that produce few viable seeds, and to taxa such as ferns, mosses, and algae [7]. Those that cannot be conserved *ex situ* using the conventional seed banking method are collectively referred to as exceptional plant species. And, those exceptional species entail alternative *ex situ* conservation methods [15].

Cryopreservation involves storing seeds and plant tissues in liquid nitrogen. It maintains -196 °C and can increase the longevity of seeds and plant tissues that age quickly at -20 °C. The usefulness of cryopreservation is further enhanced by its being relatively inexpensive, chemically inert, and readily accessible [7]. Based on the type of plant exceptionality, cryopreservable parts include embryos, dormant buds, and *in vitro* tissue cultures of shoot tips or somatic embryos as well as seeds [15]. Those plant tissues with a liquid nitrogen treatment are shown to revive after two to three decades [7].

Seeds short-lived at -20 °C under conventional seed storage conditions may require cryopreservation for longer-term storage. Studies indicate that the reduced longevity at -20 °C and coldness-sensitivity appeared to be associated with lipids that crystallize just below 0 °C. A high chlorophyll content and instability of aqueous glasses formed during freezing are also related to reduced longevity. Several crops with freeze-sensitive seeds, including coffee and citrus, have been subjects of such research [7]. Yet, few studies are available for wild or endemic plant species [8].

An essential question on cryopreservation is the degree of maintenance of genetic integrity in the long run. The vast majority of cryopreserved tissues that have been analyzed show little to no change immediately following a short-term cryostorage. Some genetic changes observed are from longer-stored samples, and many changes are found epigenetic and confounded by long-term *in vitro* cultures. On the whole, a review article suggests that genetic changes from cryopreservation itself appear relatively small and concludes the value of cryopreservation could outweigh the risk of small genetic changes to prevent plant extinction [7].

Another question with cryopreservation is the cost. The cost of cryopreservation with *in vitro* culture is expected to be higher per sample than that of conventional seed banking. Yet, it is unlikely to predict the exact cost for developing an *in vitro* and cryopreservation protocol for a new plant species. Understanding the cost structure, nevertheless, is critical to devise workable strategies to preserve plant species, particularly with recalcitrant seeds [15]. Studies show that the overall long-term costs of cryopreservation are less than maintaining living collections in botanic gardens or field gene banks [7]. Relatedly, a recent study evaluates the cost and resource need for the *ex situ* conservation of exceptional plants [15]. The study examines an exercise process from identifying seed behaviors, initiating *in vitro* cultures to cryopreserving seeds or tissues. The study demonstrates that a nominal financial investment helps facilitate primary research and method development for the effective conservation of exceptional plants even if full protocols are not immediately developed. From technical and financial perspectives, this finding implies that a relatively small investment can make a significant progress on cryopreservation in preserving exceptional plants [15].

5. SVALBARD SEED VAULT

Both seed banks and seed vaults serve to conserve plant diversity with seeds. One characteristic difference between the two institutions is that seed banks distribute seeds to users on request while seed vaults do not, except under extraordinary circumstances. Seed vaults instead keep safety duplicates of seeds from other seed banks [20]. Therefore, the vaults provide seed banks with an insurance policy against their loss of seed collection caused by, for example, natural disasters or man-made crisis [21]. Currently, there exist two seed vaults in the world: the Svalbard vault opened in 2008 in Norway centering food and agriculture plants, and the Korean vault opened in 2015 focusing on wild plants including tree species.

The Svalbard vault is the global figurehead of *ex situ* conservation of plant genetic resources for food and agriculture [20]. The vault offers free-of-charge long-term storage for duplicates from seed banks around the world. The idea of establishing an international seed collection, in fact, dates to the early 1980s. It took about two decades before technical, legal, and political contexts allowed the idea to be realized [21]. In the 1980s, the Nordic Gene Bank for Agricultural and Horticultural Plants established a seed storage facility in a coal mine on the Arctic island, Svalbard by exploiting permafrost cooling. The island was conceived as a safe place where a duplicate copy of the Nordic Gene Bank's base collection could be housed for long-term conservation [22]. This served as an early model for the vault [20]. Soon after, a proposal was followed to create an Arctic seed storage facility for international use, and throughout the 1990s, the Svalbard vault took shape as an additional security measure for the conservation of diverse crop varieties in seed banks worldwide [22]. In 2006, five Nordic prime ministers participated in the cornerstone-laying ceremony at Svalbard, and the vault officially opened in 2008 [21].

The global nature of the vault necessitated involving several international agreements relevant to plant conservation. The International Treaty on Plant Genetic Resources for Food and Agriculture was a keystone legal agreement enabling the vault to receive international support [20]; the Treaty created a legal framework for having one international security facility [23]. Other crucial international agreements include; the 1994 agreement to place the gene bank collections of the Consultative Group on International Agricultural Research (CGIAR) under the auspices of the Food and Agriculture Organisation (FAO); the agreement on international standards for gene banks, originally published in 1994 and subsequently revised in 2014; and the development of a standard material transfer agreement with rules for the exchange of genetic resources among parties to the International Treaty on Plant Genetic Resources [20].

While the Norwegian government covered the costs associated with the vault construction, it is operated through a tripartite agreement among the Government of Norway, the Nordic Genetic Resource Center, and the Global Crop Diversity Trust [20,21]. In general terms, the Norwegian Ministry of Agriculture and Food carries overarching responsibility for the vault, whereas the Nordic Genetic Resource Center provides practical management and coordinates activities with international seed depositors. The Crop Trust is central in raising and dispersing funds for the vault's operation [20]. Additionally, the International Advisory Council oversees the vault's operation, which includes national gene banks, FAO, CGIAR, and the governing body of the International Treaty on Plant Genetic Resources [21].

As briefly mentioned, seed banks normally perform multiple activities that include distributing seeds to users, conducting analysis on seeds, monitoring seed viability, and regenerating seeds regularly to retain high-quality seed collections. But the vault does none of them [20]. If the vault opens seed storage boxes to conduct such activities, it may undermine seed depositors' confidence that their seeds are not legally violated. Accordingly, there is no ownership transfer of the safety duplicates and only the depositing institution can obtain access to the seeds it deposited in the vault [2, 24]. The seed depositors are not limited to international, regional, and national seed banks. Indigenous communities have deposited seeds; for instance, the Cherokee Nation entrusted the vault with samples of heirloom food crops [25].

The vault does not take all seeds from its potential depositors. The terms and conditions for the use of the vault are laid out in the standard deposit agreement, and criteria exist for determining which accessions can be safety duplicated. First, the accessions should be plant genetic resources for food and agriculture in order to restrict its mandate to food and forage crops and their gene pools. Second, the accessions should not be already deposited by another gene bank in order to avoid identical seed accessions being duplicated more than once in the vault. Third, the depositing institutes facilitate access to accessions to users in compliance with national laws and applicable international treaties [2].

With seeds already deposited in the vault, a recent study imposes an interesting question, which is whether genetically modified (GM) crops are stored in the vault [20]. Currently, the vault does not store seeds of such crops for several reasons; first, the vault does not meet the European law's requirements for GM crops; second, the vault lacks the political will to obtain a necessary legal certificate for GM crops partly to avoid any controversy surrounding GM crops; third, GM crops do not meet the requirements for mutual access and benefit sharing in principle. However, the study mentions that unintentional deposits of GM seeds in the vault may not be excluded. The vault, in fact, does not require seed depositors to test for GM mixes and submit the results to the vault. In this regard, the study speculates that some samples might possibly be mixed with GM seeds *via* seed mixtures or gene flows [20].

To date, about two-thirds of the seeds in the vault have been deposited by international agricultural research centers with four centers entrusting over 100,000 samples each. The four include the International Maize and Wheat Improvement Center in Mexico, the International Rice Research Institute in the Philippines, the International Crop Research Institute for the Semi-Arid Tropics in India, and the International Institute for Agricultural Research in Dry Areas (ICARDA) [26]. Until recently, the ICARDA gene bank was stationed in Syria, and as of 2023 ICARDA does offer the only exceptional case where deposited seed samples were retrieved from the vault under extraordinary circumstances.

By the time the war broke out in Syria in 2011, ICARDA had already safety duplicated more than 100,000 accessions in the vault. The ICARDA gene bank further managed to prepare and ship an additional 14,363 accessions *via* three shipments in 2012, 2013, and 2014, according to the security situation in Aleppo, Syria. When the last staff was forced to leave Syria later in 2014, the total number of safety duplicates at the vault was 116,476 samples, or 83% of all accessions stored in the gene bank at the time of the outbreak of the war. In addition, 13,939 accessions that were not safety duplicated in Svalbard or any other gene bank were sent to Türkiye. Those safety duplicates in the vault then enabled ICARDA to rebuild its collections in Morocco and Lebanon, and resume its seed distribution to users internationally. ICARDA's Syrian case, therefore, reveals the vulnerability of seed banks, and their resilience largely relies on multilateral collaborations [2].

All in all, Svalbard is considered a uniquely appropriate location to nest the vault. Literature summarizes its uniqueness with four factors: coldness, accessible remoteness, political stability, and trust. These four factors collectively offer the salient feature through which secured plant conservation is understood [22]. First, permafrost offers natural freezing and unparalleled insulation properties for the seeds [21]. It is reckoned that the vault may take two centuries to warm to the freezing point if the unlikely case of cooling equipment breakdown occurs [27]. Second, Svalbard offers an exclusive combination of remoteness and accessibility [21]; it is situated on an island close to the North Pole where an airport and a village are accessible [20]. This feature provides security against human-related dangers while allowing seed transportation to and from the vault [21]. Third, Norway is a politically stable country with a history of political non-alignment, and Svalbard remains demilitarized under the terms of the Svalbard Treaty [21,22]. The Svalbard Treaty from 1920 recognizes Norway's sovereignty, whereas the treaty ensures the right of other treaty nations to enter and use natural resources. Fourth, Norway carries a significant level of trust from the global community for its commitment to the conservation of food and agriculture plants [20,21]. These four features help the vault function effectively and strengthen the concept of secured conservation of plant species.

6. KOREAN SEED VAULT

The Korean vault is a part of the Korea Arboreta and Gardens Institute under the Korea Forest Service, for which the Ministry of Agriculture, Food and Rural Affairs is responsible. The Korean vault was established in 2015 with a similar purpose to Svalbard, *i.e.*, preserving safety duplicates of seeds permanently or until a doomsday scenario comes true, except in some extraordinary cases. Yet, different from the Svalbard, the Korean vault concentrates on and collects seeds of endemic and wild plants including tree species, a similar focus to the Millennium Seed Bank of the Kew. The purpose and the focus of the Korean vault position it uniquely among the *ex situ* conservation facilities. Simultaneously, they may make the Korean vault's position somewhat ambiguous with overlapping areas with the Svalbard and the Kew, although its scope and scale are not yet comparable to that of the two.

Since its opening, the Korean vault has accumulated a total 137,880 accessions from 4,892 plant species while the vault has the capacity to conserve up to two million accessions. Of the total accessions, 19.5% came from the vault's own collecting and the rest 80.5% originated from various depositors. Its depositors are mostly public organizations followed by private entities and individuals, all retaining their ownership and control over the samples [28]. Conserving wild plants' seeds by storing them permanently is an uphill challenge; the plants may present low reproduction capacity with few seeds available for effective conservation; the seeds from wild plants may be heterogeneous in genetic composition, seed shattering, flowering and maturity; the collected seeds may have unknown seed storage behaviors with their physiology little studied; the target plants may be legally protected, which restricts their collection; the seeds may lose viability considerably during the storage; the plants grown from the seeds may fail to adapt and thrive in a new environment [8]. The ideal situation would be that the seeds to be deposited have their storage behaviors and relevant information known, and the vault is able to check all deposited seed samples regularly and frequently for their viability. However, it may not be the case with many seed samples.

The Korean vault, similar to the Svalbard, was constructed to resist external shocks, considering the conditions of the Korean peninsula. For instance, its 46-meter deep underground tunnel is designed to withstand a 6.9-magnitude earthquake and an atomic strike. Interestingly, the vault is designated as a security facility by Korea's National Intelligence Service [28]. This feature compares it to the Svalbard which appears more guarding than guarded. Korea is also reflected differently from Norway in the global community, with the precarious geopolitical dynamics surrounding the peninsula. Putting aside the complications involving the conservation of wild plants, the Korean vault may need to make more strategic efforts for garnering international confidence when the vault intends to function as a reliable seed storage facility at a global scale.

Some questions might be asked regarding a future strategic position and role of the Korean vault. Firstly, when the functions of many wild plants in the ecosystem have yet to be known, what are the specific collection criteria for permanent storage? There seems no set of selection criteria, available or published in the literature as of this writing. Relatedly, what are its specific targets among rare, endemic, and wild plant species? Or does the vault have its target regions in the short-, mid- and long-term? Without specific criteria and targets, its collection would be largely shaped by random seed depositors since over 80% of its seed accessions came from seed depositors. More importantly, having its criteria and targets would help better develop its unique niche and identity. Secondly, does it have enough capacity with a clear vision to secure its position as a global facility? Currently, the vault appears to have limited capacity/support with a less clear vision to expand its international networking; only 43 out of its total 137,880 accessions have been deposited by other nations, including Georgia, Kazakhstan, Kirgizstan and Tajikistan. The vault has signed memorandums of understanding with various entities abroad since 2018, but there appear few active lines of international collaboration at a noticeable scale [29]. Finally, does the Korean leadership have the political will to continue prioritizing conservation efforts? Endemic and wild plants often do not offer immediate tangible benefits, which in turn may not draw sufficient political justification for public spending on conserving seeds of such plants. Therefore, safeguarding wild plant species may fall outside the list of policy priorities of the Korean decision-makers and the general public. Without a solid political driver and public pressure, the Korean leadership might be less willing to continue supporting the conservation agenda.

The Korean vault for its part should actively promote the conservation agenda *via* awareness campaigns and conduct self-promotion abroad as well as domestically. It needs to increase worldwide recognition and seek partners who are interested in contributing to the global public good through wild plant conservation. Its potential partners include national governments, public institutions, non-governmental organizations, international organizations, private entities, and individuals that share the same conservation vision. However, the partnerships should be collaborative and mutually beneficial, particularly with the global south. Due to the nature of the plant conservation efforts, simply collecting plant materials from the global south would not be welcome. Instead, the Korean vault may assist developing countries to preserve their own plant diversity and stand strong in their sovereignty over plant resources.

CONCLUSION

No one would gainsay that plants are essential for the human being and ecosystem. With the unprecedented declining rate of plant diversity, it is crucial to keep intensifying conservation efforts at a local, national, regional, and global level for plant diversity protection. And, these efforts should be made efficiently without much overlap and duplication among the same-minded entities. There is no single best way to sustainably conserve plant diversity, but collaborative and coordinated conservation efforts are certainly one of the better ways.

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CONFLICT OF INTEREST

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REFERENCES

[1] World Economic Forum. *The Global Risks Report 2022*. 2022. Available from:https://www.weforum.org/reports/global-risks-report-2022/

[2] Westengen OT, Lusty C, Yazbek M, Amri A, Asdal Å. Safeguarding a global seed heritage from Syria to Svalbard. Nat Plants 2020; 6(11): 1311-7. [http://dx.doi.org/10.1038/s41477-020-00802-z] [PMID: 33168982]

[3] Mounce R, Smith P, Brockington S. *ex situ* conservation of plant diversity in the world's botanic gardens. Nat Plants 2017; 3(10): 795-802. [http://dx.doi.org/10.1038/s41477-017-0019-3] [PMID: 28947807]

[4] Wyse SV, Dickie JB, Willis KJ. Seed banking not an option for many threatened plants. Nat Plants 2018; 4(11): 848-50. [http://dx.doi.org/10.1038/s41477-018-0298-3] [PMID: 30390079]

[5] Albani Rocchetti G, Carta A, Mondoni A, *et al.* Selecting the best candidates for resurrecting extinct-in-the-wild plants from herbaria. Nat Plants 2022; 8(12): 1385-93. [http://dx.doi.org/10.1038/s41477-022-01296-7] [PMID: 36536014]

[6] Global Strategy for Plant Conservation. 2020. Available from:https://www.plants2020.net/about-the-gspc/

[7] Pence VC, Ballesteros D, Walters C, *et al.* Cryobiotechnologies: Tools for expanding long-term *ex situ* conservation to all plant species. Biol Conserv 2020; 250: 108736. [http://dx.doi.org/10.1016/j.biocon.2020.108736]

[8] Coelho N, Gonçalves S, Romano A. Endemic plant species conservation: Biotechnological approaches. Plants 2020; 9(3): 345. [http://dx.doi.org/10.3390/plants9030345] [PMID: 32182892]

[9] Walters C, Pence VC. The unique role of seed banking and cryobiotechnologies in plant conservation. Plants People Planet 2021; 3(1): 83-91. [http://dx.doi.org/10.1002/ppp3.10121]

[10] Breman E, Ballesteros D, Castillo-Lorenzo E, *et al.* Plant diversity conservation challenges and prospects-the perspective of botanic gardens and the Millennium Seed Bank. Plants 2021; 10(11): 2371. [http://dx.doi.org/10.3390/plants10112371] [PMID: 34834734]

[11] Abeli T, Dalrymple S, Godefroid S, *et al. ex situ* collections and their potential for the restoration of extinct plants. Conserv Biol 2020; 34(2): 303-13. [http://dx.doi.org/10.1111/cobi.13391] [PMID: 31329316]

[12] Chapman T, Miles S, Trivedi C. Capturing, protecting and restoring plant diversity in the UK: RBG Kew and the Millennium Seed Bank. Plant Divers 2018; 41(2): 124-31. [http://dx.doi.org/10.1016/j.pld.2018.06.001] [PMID: 31193132]

[13] National Academies of Sciences, Engineering, and Medicine. An Assessment of Native Seed Needs and the Capacity for Their Supply: Final Report. Washington, DC: The National Academies Press. 2023.

[14] O'Donnell K, Sharrock S. Botanic gardens complement agricultural gene bank in collecting and conserving plant genetic diversity. Biopreserv Biobank 2018; 16(5): 384-90. [http://dx.doi.org/10.1089/bio.2018.0028] [PMID: 30325672]

[15] Philpott M, Pence VC, Bassüner B, *et al.* Harnessing the power of botanical gardens: Evaluating the costs and resources needed for exceptional plant conservation. Appl Plant Sci 2022; 10(5): e11495. [http://dx.doi.org/10.1002/aps3.11495] [PMID: 36258792]

[16] Paul S, Yvette H-B. BGCI Technical Reviews: Defining the botanic garden, and how to measure performance and success. Richmond,U.K: Botanic Gardens Conservation International. 2017.

[17] Dalrymple SE, Abeli T. *ex situ* seed banks and the IUCN Red List. Nat Plants 2019; 5(2): 122-3. [http://dx.doi.org/10.1038/s41477-019-0366-3] [PMID: 30737503]

[18] Merritt DJ, Dixon KW. Conservation. Restoration seed banks--a matter of scale. Science 2011; 332(6028): 424-5. [http://dx.doi.org/10.1126/science.1203083] [PMID: 21512021]

[19] Hay FR, Probert RJ. Advances in seed conservation of wild plant species: A review of recent research. Conserv Physiol 2013; 1(1): cot030. [http://dx.doi.org/10.1093/conphys/cot030] [PMID: 27293614]

[20] Wickson F. Do we care about Synbiodiversity? Questions arising from an investigation into whether there are GM crops in the Svalbard global seed vault. J Agric Environ Ethics 2016; 29(5): 787-811. [http://dx.doi.org/10.1007/s10806-016-9634-7]

[21] Westengen OT, Jeppson S, Guarino L. Global ex-situ crop diversity conservation and the Svalbard Global Seed Vault: Assessing the current status. PLoS One 2013; 8(5): e64146. [http://dx.doi.org/10.1371/journal.pone.0064146] [PMID: 23671707]

[22] Curry HA. The history of seed banking and the hazards of backup. Soc Stud Sci 2022; 52(5): 664-88. [http://dx.doi.org/10.1177/03063127221106728] [PMID: 35766360]

[23] *International Treaty on Plant Genetic Resources for Food and Agriculture*. Available from:https://www.fao.org/plant-treaty/overview/en/

[24] Fowler C. The Svalbard seed vault and crop security. Bioscience 2008; 58(3): 190-1. [http://dx.doi.org/10.1641/B580302]

[25] Cherokee Nation first tribe in US to send heirloom seeds to global vault 2020. Available from:https://www.cherokeephoenix.org/services/cherokee-nation-first-tribe-in-u-s-to-send-heirloom-seeds-to-global-vault/article_ad6c8f50-9859-5cd8-b789-d3dfce03ef52.html

[26] Asdal Å, Guarino L. The Svalbard global seed vault: 10 years—1 million samples. Biopreserv Biobank 2018; 16(5): 391-2. [http://dx.doi.org/10.1089/bio.2018.0025] [PMID: 30325665]

[27] Banking against Doomsday. 2012. Available from:https://www.economist.com/international/2012/03/10/banking-against-doomsday

[28] Hwang S. *Last resort: The seeds kept safe in a South Korean mountain*. 2021. Available from:https://phys.org/news/2021-06-resort-seeds-safe-south-korean.html#:~:text=Hidden%20in%20a%20South%20Korean,change%2C%20natural%20disaster%20and%20war.

[29] National Arboretum of Baekdudaegan of Korea. Seed Storage Status. Available from:https://www.bdna.or.kr/main/contents.do?idx=2538