Importance of Access to Genetic Diversity for Breeding

Subjects: Biodiversity Conservation

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Plant breeders develop competitive, high-yielding, resistant crop varieties that can cope with the challenges of biotic stresses and tolerate abiotic stresses, resulting in nutritious food for consumers worldwide. To achieve this, plant breeders need continuous and easy access to plant genetic resources (PGR) for trait screening, to generate new diversity that can be built into newly improved varieties. International agreements such as the Convention on Biological Diversity (CBD), the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) and the Nagoya Protocol recognized the sovereign rights of countries over their genetic resources. However, some of the rules and conditions that regulate access and benefit-sharing arrangements have been established under these framework agreements hamper or limit access of public and private plant breeders as well as other users of these increasingly threatened plant genetic resources. Thus, these restrictive conditions cause a potential threat to the continued improvement and adaptation of crops and varieties to the ever-changing growing conditions.

Keywords: vegetable genetic resources ; global germplasm conservation and use systems ; plant breeding ; access and benefit-sharing

1. Introduction

Free access to and exchange of germplasm have been the foundation for all plant domestication and improvement efforts since the start of sedentary farming. Through most of human history, access has been constrained by physical distance and limited knowledge, not by an unwillingness to share or legal instruments. Until the signing of the Convention on Biological Diversity (CBD) in 1992–1993 (**Table 1**), germplasm was considered a common heritage of humankind to be preserved and to be freely available for use, for the benefit of present and future generations as per the International Undertaking (IU) established by the FAO Commission on PGR in 1983 [1][2][3]. Plant breeders obtained the required germplasm for their crop-improvement efforts from a wide variety of existing commercial varieties, public and private genebanks, public and private collecting missions, working collections maintained at research institutions and private companies, and from farmers' fields and commercial stores.

Table 1. Main (legal) instruments regarding access and benefit-sharing of PGRFA and some of their main features.

Legal Instrument	Year of Entering into Force	Hosting Organisation and Location of Secretariat	Year of Termination	Main Legal Principles/Aspects	PGRFA Coverage	Number of Parties
International Undertaking (IU) *	**1983**	**FAO, Rome, Italy**	**2004?**	**Voluntary agreement; common heritage principle**	**All plant species for food and agriculture**	**n.a.**
CBD	**1993**	**UNEP, Montreal, Canada**	**ongoing**	**National sovereignty; PIC; agreed terms for use and benefit-sharing; Cartagena Protocol (biosafety)**	**All plant species (focus on wild); information**	**196 contracting parties (31 July 2023)**
ITPGRFA	**2004**	**FAO, Rome, Italy**	**ongoing**	**MLS, SMTA**	**All PGRFA and information; Materials in MLS: Annex I plus Art. 15 collections (i.e., CGIAR), plus voluntarily added materials**	**150 contracting parties (1 January 2023)**

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Nagoya Protocol	**2014**	**UNEP, Nagoya, Japan**	**ongoing**	**ABS; Clearing House Mechanism**	**All crops and species that do not fall under ITPGRFA**	**140 contracting parties (31 July 2023)**

* The IU was a voluntary agreement, not a body of international law.

Plant breeding is a long and tedious process and requires a lot of investment and ample genetic diversity. Vegetable seed companies use up to 30% of their turnover for research and development. With the aim of encouraging continuous development of new plant varieties for the benefit of society at large, plant breeders' rights (PBR) were introduced through the creation of plant variety protection and internationally harmonised through the International Union for the Protection of New Varieties of Plants (UPOV) Convention, adopted in Paris in 1961 and revised in 1972, 1978 and 1991 [4]. Article 15 of the UPOV Convention provides a compulsory breeders' exemption to the exclusive right [5], allowing everyone to freely use any protected variety for further breeding and commercialising the newly created ones without any obligation to the original PBR holder as long as the newly developed product is sufficiently different from the protected variety used in the breeding process. This provision constitutes an essential and principal element towards ensuring continued access of plant breeders worldwide to elite privately owned germplasm as parental material [6].

With the advent of biotechnological innovations during the 1980s, some countries allowed certain inventions to be protected through patents. The patenting of biotechnological inventions can be traced back to 1980 when the Supreme Court of the United States decided that a genetically modified organism, in that specific case a bacterium, is patentable [7]. Thereafter, several proprietary products were released in plant sciences, such as traits/genes and genetically engineered varieties.

Irregular access and use of genetic resources and related traditional knowledge of countries, indigenous peoples and local communities without their consent and the patenting of derived or associated information for further commodification is understood as biopiracy [8]. Cases of biopiracy and the perception in the Global South that the breeding industry in the Global North was earning money based on the genetic resources collected in the Global South without sharing due benefits were major reasons why the continuous free availability and accessibility of genetic resources as foreseen under the IU was no longer considered an acceptable paradigm [9]. This led to the development of new global legal frameworks.

2. The Importance of Genetic Diversity and Plant Breeding for Agricultural Production and Food and Nutrition Security

Since the transition from hunting–gathering to sedentary farming, producing enough food for a growing population has always been a significant challenge. The origins of agriculture can be traced back to about 12,000 years ago, when wheat and barley domestication and cultivation started in the Fertile Crescent in the Near East [10], and a 'crop package' spread from there into Europe, Asia and Africa several thousand years later. Climate change and population growth are considered to have major impacts on sedentary farming. Today, population growth and greater per capita purchasing power, coupled with higher meat, dairy and egg consumption, and the use of agricultural crops for biofuel production are considered to be major driving forces for the continuously growing global demand for food, fibre and fuel crops until 2050 and beyond [11][12]. However, the increasing human population, scarcity of fertile land for the expansion of cropping areas, the negative impact of agriculture on the environment and the increasing threats from climate change mean that further increases in food production must primarily be based on yield enhancement and productivity growth. This can be achieved through continuous plant breeding efforts and sustainable intensification of crop production practises on existing croplands, on which current crop yields are well below the yield potential [13].

In many parts of the world, plant breeding has contributed considerably to increased productivity, apart from increased use of agricultural inputs such as irrigation water, chemical fertilisers and pesticides. This led to stable markets, lower food prices and reduced price volatility [14][15], among others, evidenced by the 'Green Revolution' [16]. Studies conducted by Noleppa and Cartsburg [15] indicated that plant breeding has contributed, on average for all major arable crops grown in the European Union (EU), a yield increase of about 67% since the turn of the millennium. This translates into an average yield enhancement of 1.16% per annum for the major crops. These values are higher than the individual crop yield gains reported by Evenson and Gollin [17] from 1960 to 2000. The development of high-yielding varieties with multiple disease resistances and enhanced water- and nutrient-use efficiency also has considerable societal and environmental benefits, reducing pesticide- and fertiliser-induced hazards and greenhouse gas emissions, apart from avoiding the further expansion of agricultural land [15]. In terms of production volume, similar observations have also been made for tomatoes, the globally dominant vegetable crop, and alfalfa, a globally important forage crop [18].

Breeding and agricultural intensification efforts led to a significant availability of food, which, in turn, contributed to a notable decline in the number of people suffering from chronic hunger. However, after years of steady decline, the trend in world hunger reverted in 2015 and remained relatively constant until 2019 (618.4 million undernourished; 8%). From 2019 to 2020, the prevalence of undernourished people rose sharply, from 8.0 to 9.3%, and to 9.8% in 2021, meaning that approximately 767.9 million people were affected by hunger in 2021 [19]. The Covid-19 pandemic is likely to have contributed to this sharp rise in the number of undernourished people. Current projections indicate that close to 670 million people, or about 8% of the global population, will still face chronic hunger in 2030, approximately the same proportion of the population as in 2015 when the Zero Hunger target of the 2030 Agenda for Sustainable Development was launched by the United Nations [20]. In 2021, 425 million people in Asia, 278 in Africa and 56.5 in Latin America and the Caribbean were suffering from hunger. All in all, around 2.3 billion people (nearly one-third of the world population) were moderately or severely food insecure in 2021 and suffered from chronic micronutrient deficiencies [19][21].

Crop domestication and improvement were based on intentional, ongoing selection for traits that improved the quality and palatability of plant organs for human consumption, facilitated crop cultivation and harvesting (e.g., suitable for mechanical harvesting and non-shattering seeds), enhanced yield and productivity, resistance against pests and diseases and tolerance to a variety of environmental stresses [22][23]. Professional plant breeding basically started with the re-discovery of the laws of inheritance by Gregor Mendel, first published in 1866 in the Proceedings of the Natural History Society of Brno, 157 years ago [24]. Many scientists consider Mendel the father of modern genetics. Various methods are used in plant breeding [25][26]. They can be based on the visual selection of plants with desired variants occurring in nature or within traditional varieties. Often, new genetic diversity is introduced into breeding populations by intercrossing selected elite plants with desired traits that complement each other or by introgression of desired traits/genes from CWR into an advanced breeding line. Modern marker-assisted precision breeding is based on monitored recombination of specific genes with the help of molecular tools that systematically track within-genome variation.

The choice of the breeding method being applied is often crop-specific, determined by the mode of reproduction and the breeding objectives [26]. In the commercial breeding of vegetable crops, the production of hybrids is steadily increasing, as it allows the exploitation of heterosis and facilitates the multiple stacking of desired traits. Careful pollination control is required to ensure efficient hybrid production. Depending on the crop, technologies that inhibit pollen production in mother plants may include manual or mechanical emasculation and genetically controlled systems, such as male sterility [27]. Once desired traits have been fixed in a new variety, and genetic uniformity, yield stability and local adaptation have been verified, seed production and commercialisation of the new variety commence.

3. Current and Evolving Policies and Procedures for Germplasm Collecting, Conservation, Exchange, Use and Related Benefit-Sharing—CBD, International Treaty, Nagoya Protocol, DSI Debate

The intergovernmental negotiations that led to the signing of the CBD in 1992–1993 made member states agree to conserve the biological resources existing in their respective territories, make them available and share benefits deriving from their use on agreed terms. These terms were further specified and formalised in the Nagoya Protocol, which entered into force in October 2014 [28]. With the objective of harmonising the existing access and benefit-sharing (ABS) regulations for plant genetic resources for food and agriculture (PGRFA), as established by the FAO Commission for Genetic Resources for Food and Agriculture (known as International Undertaking), with those established under the CBD, the International Treaty for PGRFA (ITPGRFA) was negotiated by the member states of FAO, adopted in 2001 and came into force in 2004. As part of the ITPGRFA, the Multilateral System (MLS) addresses facilitated access to PGRFA for specific uses, such as conservation, research, breeding and training for food and agriculture. The MLS provides a transparent, multilateral access and benefit-sharing mechanism for both providers and users of PGRFA through the signing of a Standard Material Transfer Agreement (SMTA), thus reducing transaction costs. However, it only covers a limited number of so-called Annex I crops [29] but includes the collections maintained by the CGIAR and other international agricultural research centres that fall under Art. 15 (see below). For access to germplasm of other crops and plant species not covered by the MLS and Art. 15 of the ITPGRFA, the ABS regulations of the CBD, as specified under the Nagoya Protocol, are applicable.

Navigating and complying with these international treaties and their specific ABS regulations, especially the Nagoya Protocol, is complex. There is apparent ambiguity about the scope and application of many provisions of the international agreements regulating access to PGRFA and related benefit-sharing schedules. Access to vegetable genetic resources is severely restricted, especially since most vegetable crops are not included in the list of Annex I crops of the ITPGRFA. Access to genetic sequence information is still being debated and is subject to change.

3.1. The Convention on Biological Diversity (CBD)

The CBD entered into force in December 1993 and had as its main objectives the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising from the utilisation of genetic resources [30]. Under the CBD, states can use their national sovereignty to exercise control over the genetic resources within their national territories.

Access to genetic resources is granted under prior informed consent (PIC) and mutually agreed terms (MAT) by the party owning and providing those resources (Article 15 of the CBD) [31]. The CBD does not define or describe terms of ABS of genetic resources but expects the contracting parties to develop and implement national laws to that effect (Articles 6 and 15), based on guidelines provided in the Nagoya Protocol.

3.2. The Nagoya Protocol

The Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilisation is a supplementary agreement to the CBD [28]. It was adopted in October 2010 in Nagoya, Japan, and entered into force in October 2014. Contracting parties of the Nagoya Protocol are required to implement and adhere to measures regarding access to genetic resources, benefit-sharing and compliance. Provider countries must set out clear conditions for granting PIC and establishing MAT, including access to traditional knowledge associated with genetic resources that are held by indigenous communities, while user countries are required to monitor use and compliance with the MAT.

3.3. The International Treaty for Plant Genetic Resources for Food and Agriculture (ITPGRFA)

The ITPGRFA was adopted in November 2001 by FAO member states and came into force in June 2004 [32]. The ITPGRFA is in full compliance with the CBD. In contrast to the bilateral negotiations required under the CBD/Nagoya Protocol, the ITPGRFA establishes, through its multilateral system (MLS), a globally harmonised system to provide farmers, plant breeders and the scientific community with transparent and facilitated access to plant genetic resources. The International Treaty also ensures recipients share the benefits of using these genetic resources. The MLS currently only covers crops specified on a defined list, known as Annex I, consisting of 35 food and 29 forage crops. MLS crops should be made freely available (or at minimal transaction cost) for the purposes of conservation, research, breeding and training under a Standard Material Transfer Agreement (SMTA). The germplasm recipients shall not claim any intellectual property or other rights that limit access to these resources or their genetic parts or components in the form received from the MLS [32].

The European Cooperative Programme for Plant Genetic Resources (ECPGR) recommended in 2016 under Article 32–ECPGR and the Treaty/Nagoya Protocol: “It is recommended that all ECPGR member countries (36 as of June 2023) as appropriate and in line with national legislation, use the SMTA for distribution of both Annex I and non-Annex I PGRFA accessions, independently of whether material is conserved in ex situ collections or held in situ” [33]. A few countries, such as Germany and the Netherlands as well as NordGen, acting for the Nordic countries (Denmark, Finland, Iceland, Norway, Sweden and the autonomous territories of the Faroe Islands and Greenland) [34], have already adopted this recommendation.

4. Implications of the Complexity of ABS Regulations for Germplasm and Related Information for Genebank Curators and Public and Private Sector Breeders

4.1. Uncertainties Regarding the Current ABS Regulations

Germplasm users and conservationists are ready to share benefits, especially through capacity development in the countries where germplasm collecting is taking place. However, many germplasm collectors struggle with the complexity and lack of clarity of how this sovereignty is exercised and interpreted by individual countries [35][36][37]. The same is true for many plant breeders [38]. Uncertainties regarding ABS regulations and procedures to secure ABS compliance include the questions on how and with whom ABS can be negotiated bilaterally, who is subject to those conditions, how compliance is monitored and how regulations apply to plant biodiversity beyond the time frame of the current instruments [37][38].

4.2. The Issue of Stacking Obligations, Retroactive Effect, Tracking and Tracing and Related Costs

The complex, and often unclear ABS regulations, implemented with a high degree of variation among countries, sometimes with retroactive effect, and the use of different germplasm sources in the long process of developing new varieties require extensive tracking and tracing and raise associated costs and administrative burdens for genebanks, botanic gardens and public and private breeders alike [35][38]. Moreover, the development of improved, resilient varieties may stack obligations and costs as it involves the incorporation of PGRFA, traditional knowledge (TK) and/or DSI from several countries. Every cross made by plant breeders stacks the contractual ABS requirements of its parental lines.

The legal uncertainty ensuing from the complex and unclear national ABS regulations and the length of time needed and the costs involved in navigating the ABS regulations and negotiating PIC and MAT will often obstruct rather than facilitate ex situ conservation and associated research by genebanks and research institutions [35] as well as R&D investments by the public and private sector into horticultural innovations [38][39]. The efforts in terms of time and human resources that seed companies need to spend on ABS tracking and compliance issues are often considered disproportionate to the benefits that are generated and shared through bilateral ABS agreements [38].

The mentioned uncertainties also adversely affect collaboration among genebanks as well as the collaboration between genebanks and breeding companies. Genebank curators will be more hesitant to rationalise their own collections by reducing duplication with other genebanks since they cannot be sure of access to other collections in the future [36]. Such uncertainties are forcing countries to stockpile plant genetic resources to ensure future access to genetic diversity for their own research organisations and plant breeders, resulting in redundancies and further stress on the already limited capacity of the PGRFA community. Similarly, private-sector breeding companies feel compelled to stockpile and conserve for the long term the currently available PGRFA in working collections and breeding lines in already existing or yet-to-be-established private genebanks.

4.3. The Added Complexity Due to Inclusion of Digital Sequence Information (DSI)

The current stalemate regarding the inclusion of DSI into existing ABS mechanisms or the creation of separate ones for DSI only is of major concern. Genebank curators, conservationists and plant breeders agree that access to and use of DSI is essential for adequate conservation, sustainable use of plant genetic resources [36] and the development of elite crop varieties. A major headache for genebank curators is the unresolved definition of DSI, as genebanks share germplasm with associated accession-level information [40]. Should countries pre-emptively include DSI in their national ABS legislation before standard access mechanisms have been agreed upon in international fora, genebanks may no longer wish to conserve and exchange material from those countries due to the increased complexity of germplasm handling and distribution and consequent compliance issues. Similarly, the botanical gardens community also fears that individual countries may implement disparate regulations regarding access to DSI as has been the case for physical access to genetic resources [41].

4.4. The Consequence of Overly Complex ABS Regulations

The abundance of diverse ABS regulations established by individual countries, based on the Nagoya Protocol, combined with legal uncertainties regarding their interpretation and implementation may hamper conservation and the exchange of biodiversity. Consequently, food and nutrition security, which are within the scope of international agreements such as the CBD, the ITPGRFA and the Sustainable Development Goals of the United Nations, may also be negatively impacted. Reduced international collaboration as a consequence of overly complex regulations for access to PGRFA and associated information will likely slow down capacity building and technology transfer to less advanced countries, thus deepening global inequalities.

5. Options for Addressing Current Constraints on Access and Benefit-Sharing of Genetic Resources and Related Information at the Policy Level

5.1. Expanding the MLS of the ITPGRFA to Cover All PGRFA, Combined with a Subscription System

Most plant breeders would prefer the open-source option of the heritage of humankind principle as established under the IU. However, this is no longer a viable option. The MLS of the ITPGRFA significantly reduces the burden of tracking and tracing and associated costs, avoids bilateral contracts and is, therefore, an option widely supported by public and private-sector breeders. In the current situation, the most straightforward ABS option for PGRFA would be an expansion of the MLS of the ITPGRFA to cover all genetic resources for food and agriculture, amongst others including all vegetable crops and species. This proposal is in line with the current efforts of the Open-ended Working Group to Enhance the Functioning of the MLS (see Section 3; [42]). If an expanded MLS covering all PGRFA is then based on a subscription system linking payment obligations to access rather than use or commercialisation, there would be no need to track single germplasm samples obtained under the MLS down to the final commercialisation of a new variety, plus its use by further breeding with this new variety, over and over again. Alternatively, if users do not want to adopt the subscription system, commercial utilisation of germplasm obtained under the MLS could be determined with the help of intellectual property tools, aided by using digital object identifiers (DOIs) [43]. Confirmed commercial utilisation of genetic resources would then trigger monetary benefit-sharing payments [44].

5.2. MLS of the ITPGRFA Covering all PGRFA, Combined with a Seed Sale Tax or Levy Option at the National Level

A seed sales tax or levy paid by contracting parties of the ITPGRFA would allow easy access to PGRFA under an expanded MLS covering all PGRFA, without the need for tracking and tracing measures to follow the movement of PGRFA up to the final product: a newly released variety. For 12 consecutive years, Norway has paid annual contributions to the benefit-sharing fund of the International Treaty, equivalent to 0.1% of the value of annual seed and plant material sales in the agricultural sector in Norway [45]. The CGIAR is recommending that contracting parties make annual payments to the Plant Treaty's benefit-sharing fund based on seed sales within their jurisdictions (similar to the Norway levy), using a fixed royalty rate that corresponds to the value of access to, and use of, both PGRFA and DSI. Contracting parties would then have the option to recoup a portion of that levy payment from commercial users in their jurisdictions [46]. Other countries could also follow the example of Germany, the Netherlands and the Nordic countries and share all PGRFA, whether they are within or outside of the MLS of the ITPGRFA, under the SMTA.

5.3. Harmonised, Multilateral ABS Regulations under the CBD/Nagoya Protocol

Harmonisation of ABS regulations under the CBD/Nagoya Protocol at the global level, in a similar manner as under the MLS of the ITPGRFA, would genuinely facilitate the work of all curators of collections at genebanks and botanic gardens and users in the public and private sectors alike [38]. The European Union's ABS Regulation No. 511/2014 (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R0511; accessed on 31 July 2023) is a first step in that direction. However, this directive defines only the compliance measures that must be followed by all 27 member states of the EU to secure ABS compliance under the Nagoya Protocol, while ABS regulations still follow the principle of national sovereignty and can vary significantly from country to country.

5.4. Harmonised National ABS Regulations and Compliance Measures

There is an urgent need to improve the current bilateral ABS systems. To effectively guide germplasm users trying to comply with all the different national ABS rules and regulations under the Nagoya Protocol, it would be conducive if the country profile on the ABS Clearing House website contained factual, concise information in English on how to access PGRFA in a given provider country and with whom to negotiate PIC and MAT, also including TK. All national legislation should be published on the ABS Clearing House website uniformly, including the scope and jurisdiction of the applicable ABS regulations and measures. A summary of the steps and obligations to follow should also be included.

5.5. Proposed Way Forward to Facilitate Access to Germplasm and Related Information

Curators of plant genetic resources and public and private sector breeders hope for a transparent, functional and expanded multilateral system under the International Treaty covering all PGRFA, thereby erasing all legal uncertainties and minimising transaction costs for conservers and users of genetic resources and DSI. The authors of this text strongly support a single, multilateral access mechanism for both PGRFA and DSI, if necessary combined with a subscription system as currently being negotiated under the MLS of the ITPGRFA or with a national tax or levy, similar to the Norwegian seed sales tax. If current and future international, regional, national and bilateral collaborative efforts would be guided by a focus on the promotion of inclusive innovation and enhanced equity in research, utilisation, and commercialisation of (agro)biodiversity and broader public and social benefits from the outcomes of science, instead of a predominant focus on immediate monetary benefits, greater benefits for all could be expected over time.

6. Recommendations and Concluding Remarks

Breeding improved varieties is a continuous and even cyclic effort that is essential for enhancing food and nutrition security. Crop improvement depends on access to biodiversity to source new genetic variation for breeding. Fair and non-bureaucratic rules to access and use germplasm in breeding is therefore a predisposition for food and nutrition security. Providers and users of plant genetic resources need clear information on the conditions under which the germplasm material can be accessed and used for research and breeding. It has to be clear whether the ITPGRFA, the CBD/Nagoya Protocol or any other ABS tool applies. Furthermore, adjustments to the current texts of these legal instruments are clearly needed to ensure legal certainty and strengthen access to genetic resources. Extending the list of Annex I crops of the ITPGRFA to include all PGRFA, as well as related organisms like pathogens and pests, would greatly benefit the use of new germplasm in breeding and lead to the creation of improved varieties that can cope with climate change challenges and will contribute to more sustainable forms of agriculture. Identification and documentation of the flow of benefits from the use of plant genetic resources to the different stakeholders could contribute to a better understanding of the value of plant genetic resources and related research on this material for humankind. Such a move might reduce current tension between germplasm providers and users, and eventually lead to more transparent and easy-to-follow access provisions. Crop diversity can only benefit humanity if it is not only conserved but also used.

Germplasm conserved in genebanks is most useful when it is distributed together with relevant information. Clarity on the scope of biodiversity data subject to ABS is essential for any future progress. High-throughput approaches have greatly improved genotypic and phenotypic data collection from genebank accessions. Such information can be used to strengthen germplasm management, elucidate questions regarding the taxonomy of accessions, assist in germplasm exchange through diagnostic tools for the detection of viruses and other pathogens, as well as for selecting plant genetic resources and specific traits for research and breeding. Such information can also assist in determining gaps in existing collections and help fine-tune the objectives of new collecting missions. These data could also be used to train artificial intelligence (AI) tools for a wide range of purposes, including ecophysiological crop modelling and identifying germplasm material adapted to climate change.

The outcome of the debate on the nature of DSI and the conditions for access and its use will be critical to actually using the data generated for plant genetic resources in research and breeding. Bilateral provider–user interactions for the use of DSI may be far too complex for regulating the DSI information flow. DSI policies should acknowledge the importance of using DSI across low-, middle- and high-income countries and strive to preserve open access to this crucial common good [47]. Non-monetary benefits that help bridge the scientific and technological gaps in developing countries should also be considered, as these stimulate international public–private partnerships and collaborations [48]. Such non-monetary benefits should include capacity building and technology transfer.

Curators of plant genetic resources in genebanks and botanical gardens, as well as public and private sector breeders, would benefit from a transparent, functional and efficient multilateral system under the International Treaty covering all PGRFA, thereby erasing all legal uncertainties and minimising transaction costs for conservers and users of genetic resources and DSI. Similarly, multilateral or fully open systems for exchanging biodiversity data are preferred by the wider scientific community [37]. The decision by Germany, the Netherlands and the Nordic countries to share all PGRFA under the ITPGRFA's SMTA is an encouraging example.

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