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Strengthening European research cooperation on plant genetic resources conservation and use

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Abstract: Plant genetic resources (PGR) are a vital research infrastructure and an important asset to increase the resiliency of agri-food systems, conserve agrobiodiversity and mitigate the effects of climate change. In the current scenarios of climate change and biodiversity loss, it becomes increasingly urgent to ensure the conservation of existing crop diversity and assure its availability for research and breeding to enable the development of new, adapted crops. Throughout Europe, more than 400 collections conserve PGR of over 6,500 genera, with more than 2 million accessions documented in the European Search Catalogue for Plant Genetic Resources (EURISCO). To make these resources available to breeders, more research investment in these collections is needed. Here, we analyze the participation of European genebanks in collaborative projects within the EU Horizon scheme as an indicator for the use of PGR collections in research. We highlight two Horizon projects, AGENT and G2P-SOL as well as the ECPGR initiative European Evaluation Network (EVA), which have brought together genebanks and other stakeholders to create tools and knowledge on PGR. Their experience could be translated into a dedicated, large European research infrastructure for PGR (GRACE-RI), suggested in the *Plant Genetic Resources Strategy for Europe* and currently in the concept phase by the Horizon Europe project PRO-GRACE. GRACE-RI will connect European research institutes involved in PGR conservation and research and will be key to ensuring access to well-documented and maintained PGR and methods for their characterization and utilization, preventing further loss of plant biodiversity which is increasingly threatening European agriculture and natural landscapes.

Keywords: plant genetic resources, genebank, research, breeding, documentation, infrastructure, biodiversity, conservation, sustainable use

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Introduction

Plant genetic resources (PGR) are important assets to address the challenges associated with climate change, sustainability in agriculture and food and nutrition security, as they provide the genetic diversity necessary to develop adapted crop cultivars for agriculture in

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diverse and rapidly changing ecosystems (Haussmann *et al*, 2004; McCouch *et al*, 2013; Swarup *et al*, 2021). They are also an invaluable reservoir of genetic information that scientists can decipher thanks to modern technologies and the increasing understanding of the relationship between genomes and the metabolic functions of living organisms (Bilbrey *et al*, 2021; Derbyshire *et al*, 2022)

An important prerequisite to ensure PGR availability is their active conservation and documentation (Weise *et al*, 2020) with the involvement of all relevant stakeholders, including genebanks, *in situ* conservation sites, farmers, researchers and breeders (Engels and Ebert, 2024). PGR conservation falls under the responsibility of national programmes in each country, with international agreements such as the Convention on Biological Diversity (CBD) and its Nagoya Protocol (CBD, 2011), as well as the International Treaty for Plant Genetic Resources for Food and Agriculture (ITPGRFA, FAO (2009)) providing the legal frameworks for conservation and facilitated access to germplasm and its associated information and the shared benefits deriving from their use. Since the establishment of the first genebank collections in the 1950s, now more than 4.4 million accessions are documented in the worldwide data platform Genesys (https://www.genesys-pgr.org/).

These diverse national PGR collections are becoming more and more relevant for research and breeding programmes as they provide the wild relatives and locally adapted landraces necessary for breeding improved varieties. Therefore, ensuring the availability of these plant materials is of crucial importance (Gullotta *et al*, 2023). Adding genotypic and phenotypic information on accessions in the collections greatly facilitates their management and use, helping with identifying duplicates and selecting appropriate material for further studies and breeding activities (McCouch *et al*, 2013; Mascher *et al*, 2019). Accessing international funding through participation in collaborative projects and networks has been a way to improve knowledge about institutes' PGR collections and their management, build capacity and strengthen connections among stakeholders. At the European level, since 1980 the European Cooperative Programme for Plant Genetic Resources (ECPGR) has built a network for national PGR conservation programmes currently encompassing 36 countries, and has been instrumental in building capacity and developing tools for the use of the PGR community, including the European Search Catalogue for Plant Genetic Resources (EURISCO) (Kotni *et al*, 2023) and the European Genebank Integrated System (AEGIS). The latter aims at standardizing quality management across participating genebanks and establishing a European collection of unique PGR accessions, promptly available under the same terms and conditions. Still, overall funding is inadequate to effectively conserve, document and exploit the available PGR diversity, as outlined in the *Plant Genetic Resources Strategy for Europe* (ECPGR, 2021).

A worldwide survey conducted among stakeholders within ITPGRFA contracting parties identified a number of bottlenecks in the PGR use system, including insufficient support and implementation of national policy systems, lacking personal and institutional capacities, insufficient involvement of important stakeholders such as farmers and breeders as well as lack of awareness of the importance of PGR conservation in the general public (Kell *et al*, 2017). They also identified several important constraints for access to PGR and connected data, including insufficient characterization and evaluation across diverse gene pools, the fragmentation and inaccessibility of generated data and the difficulty to access material with specific traits. The survey further highlighted the value of collaboration, between public sector administrations and researchers as well as between the public and private sectors, in programmes towards sustainable use of PGR in research and breeding (Kell *et al*, 2017). Improving our knowledge of crop genetic diversity conserved across the world, in particular to promote coverage of genetic and phenotypic data on PGR as suggested by McCouch *et al* (2013) will enable focused research and breeding of well-adapted, nutritious and resilient crops.

With the world's biodiversity in decline (IPBES, 2019) and the loss of genetic diversity in our crops threatening food security (Pilling *et al*, 2020), more decisive actions and policies are thus needed to ensure the conservation of PGR for their use in research and breeding. In the recently published *Plant Genetic Resources Strategy for Europe* (ECPGR, 2021), issues and relevant gaps in conserving and facilitating PGR use across Europe were highlighted, and the authors called for a transformative change whereby Europe should reinforce its leading role in their conservation and sustainable use. The strategy's objectives by 2030 include the expansion, improvement and consolidation of *ex situ*, *in situ* and on-farm conservation activities, strengthened data management and germplasm information systems, increased access and sustainable use of PGR and monitoring of progress in PGR conservation and use (ECPGR, 2021). In order to ensure the availability of well-documented PGR for use by future generations, the strategy proposed a number of actions to strengthen national programmes, build capacity of conservation actors and promote international collaborations, involving all relevant stakeholders including the general public. This requires an appropriate policy and legal framework, combined with secure and appropriate financing to strengthen national and regional programmes as well as institutional and human capacity. A recommended key step to enable the transition to a fully functional European system effectively supporting high-quality research is the establishment of an efficient research infrastructure dedicated to PGR conservation, documentation, research and sustainable use.

In this paper, we provide an overview of European genebank collections documented in EURISCO and analyze the current engagement status of European

genebanks and other PGR-holding institutes in international projects funded by the EU as an indicator for the use of PGR collections in research. We provide examples of successful cooperation between research institutes, genebanks and other stakeholders in three European projects that highlight the usefulness of international collaboration in advancing research on PGR. Finally, we propose a coordinated European approach to PGR research involving a dedicated Research Infrastructure (GRACE-RI) that will enable effective conservation and sustainable use of PGR through the provision of a suite of relevant technical services to facilitate adaptation of European agriculture to the climate emergency and food security issues.

Materials and methods

To conduct a summary analysis of the information stored in EURISCO to describe the current situation in terms of genebank documentation, data were extracted from EURISCO on 27/01/2025 and filtered for size of collections with regard to level of safety duplication, biological status and genera represented.

To map the involvement of European genebanks in such projects, we conducted a keyword search with relevant terms against the EU Horizon project databases (FP7, https://data.europa.eu/data/datasets/cordisfp7projects?locale=en; H2020, https://data.europa.eu/data/datasets/cordish2020projects?locale=en; Horizon Europe, https://data.europa.eu/data/datasets/cordis-eu-research-projects-under-horizon-europe-2021-2027?locale=en; accessed on 10/09/2024). Out of 35,386 projects granted within the Horizon2020 framework, 424 projects contain the keywords 'biodiversity', 'agriculture', 'breeding', 'crop wild relative', 'genetic resource' or 'plant' in varying combinations in their titles and objective descriptions. This list was manually curated to eliminate projects that were not directly working on PGR or were involving only one institute, yielding 40 projects with multi-actor consortia working on PGR in the years 2014–2022 (Supplemental Table 1). A similar filtering approach for Horizon Europe projects yielded 40 PGR-related projects out of 13,215 total, which started in the years 2022–2024 and are ongoing (Supplemental Table 2). Within the Framework Programme FP7 funding scheme, which was active between 2008 and 2018, we identified 33 multi-actor projects related to the above keywords (Supplemental Table 3).

Projects were analyzed and grouped according to the crops and PGR studied and the overarching topics of their research questions. We then compared the involved project partners against the EURISCO institutes list (downloaded from EURISCO: http://eurisco.ecpgr.org, accessed on 23/04/2024) since these officially conserve germplasm that is part of the European countries' national inventories. Some project partners could represent multiple holding institutes (e.g. INRAE,[1] CSIC[2] or CREA[3]); in these cases, the projects were analyzed to match the correct institute. In this way, we identified 76 institutions from 25 countries listed in EURISCO that have participated in projects financed by the European Commission since 2008 (Supplemental Tables 1–4).

We contacted genebank curators and managers of the identified institutes with a short survey to collect additional information on their involvement in the listed projects, including whether or not they contributed PGR and how research materials produced in the projects were conserved and received responses from 35 institutes.

The qualitative analysis of Horizon2020 projects AGENT and G2PSol as well as the ECPGR European Evaluation Network (EVA) is based on data available to project partners among the authors.

Results

Overview of European genebank collections

Across Europe, more than 400 institutes in 43 countries conserve PGR in *ex situ* and field collections, with at present more than 2 million accessions recorded in EURISCO (Kotni *et al*, 2023). These holding institutes vary greatly in size, capacity and mandate within national conservation programmes, with documented collections of between one (recorded by 22 holding institutes) and more than 680,000 accessions (by the Nottingham Arabidopsis Stock Centre NASC, Figure 1A). Figure 1B shows the number of genebanks conserving the most represented genera (excepting *Arabidopsis*), with collections of more than 100 and 1,000 accessions emphasized, further highlighting the diversity in size of European genebanks. Thirty-four countries have safety-duplicated parts of their collections in genebanks located in other countries or in the Svalbard Global Seed Vault, although overall, only 5.4% of European *ex situ* accessions have been added to the Svalbard Seed Vault so far (Figure 1C, Asdal (2025)). The collections cover more than 6,500 different genera of crop species and their wild relatives (CWR) stored as seeds, in vitro, in cryo or field collections and provide long-term storage of the plant reproductive material. Reviewing the biological status of material in the collections (Alercia *et al*, 2015), wild or natural materials (code 1xx) represent around 13% of collections but have the greatest diversity with 6,185 genera (Figure 1D). Around 15% of the collections are traditional cultivars and landraces (code 300), with 599 genera represented. The largest part of the documented collections are

[1] INRAE, *Institut national de recherche pour l'agriculture, l'alimentation et l'environnement* (France's National Research Institute for Agriculture, Food and Environment)
[2] CSIC, *Consejo Superior de Investigaciones Científicas* (Spanish National Research Council)
[3] CREA, *Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria* (Council for Agricultural Research and Economics, Italy)

breeding materials (code 4xx) and advanced/improved cultivars (code 500) with together ~44% of the documented accessions, covering 473 and 549 genera, respectively. Material of unknown status (999 or NA) makes up ~27% of accessions, representing more than 1,600 different genera, highlighting the need to improve knowledge of the European genebank collections and their documentation. A coordinated system for *in situ* conservation of PGRs and its documentation is still in its infancy, with a recent extension of EURISCO facilitating the documentation of *in situ* populations of CWR. Information on *in situ* conserved PGR is more difficult to review as data are slowly being inserted into the public domain.

Survey of EU-funded research on plant genetic resources

In the European research strategy, funding has been made available through the 7^{th} Framework Programme and Horizon schemes to support research on genetic resources and breeding, providing crucial innovation towards developing more sustainable agrosystems in the face of changing environments. Research and innovation actions create platforms for collaborative research consortia that connect institutions from diverse countries and with complementary expertise to produce valuable outputs for the European research agenda. Using a keyword search of all projects recorded in the EU Cordis database we identified 33, 40 and 40 multi-actor projects funded through the FP7, Horizon2020 and Horizon Europe frameworks, respectively (Supplemental Tables 1–3). We focused our survey on these funding mechanisms because they offer frameworks for international cooperation, cover all EU and associated countries and provide the backbone of European research funding. Additional analyses exploring other funding sources (national, bilateral, philanthropic, etc.) would complement our analysis. As per the project descriptions, these addressed various aspects of biodiversity research, agronomy, policy actions and development of research infrastructures. Many of these projects are transdisciplinary, working on the development of methods and practices on a variety of crops and agricultural systems, rather than focusing on specific PGR genera.

Overall, the number of projects on biodiversity, agriculture and PGR funded through EU research actions have increased over time reflecting the increasing importance of related topics in the European research agenda in Horizon Europe (Figure 2A), with an investment of more than 625 million euros. Considering the main topics and crops covered by these projects, there is a clear tendency towards cross-cutting projects covering multiple crops or agrobiodiversity in general, with a focus on breeding (Figure 2B). The main crops studied by these projects were cereals, legumes and Solanaceae, while other vegetables, perennials and non-food crops were represented in fewer projects (Figure 2C).

Survey of research involvement of European genebanks

Within the above-mentioned projects we analyzed the involved project partners to identify those who are holding institutes of PGR included in EURISCO and thus potentially contributing to the projects by providing genebank materials. We identified 40, 28 and 25 projects in H2020, Horizon Europe and FP7, respectively, involving 76 organizations from 25 countries listed in EURISCO (Supplemental Tables 1–4). Some genebanks are embedded in larger organizations and universities (e.g. INRAE, WUR[4], IPK[5]) and therefore their parent institutions may participate in projects in other capacities. Table 1 shows the participation of institutes listed in EURISCO in projects under the different funding schemes disaggregated by countries, highlighting that some countries and organizations are well represented in project consortia, as also reflected in the number of projects per institute (Supplemental Table 4). However, many countries and EURISCO institutes take part in only one project at a time, suggesting limitations exist in organizations to fully participate in and benefit from international research opportunities.

To better understand the role of EURISCO-listed institutes in European research, we contacted genebank managers of the identified organizations to confirm whether they provided PGR accessions to the Horizon or other European projects they participated in and received feedback from 35 institutes (Table 2). Of these, three did not contribute PGR to the projects they participated in, indicating that they played a different role in these projects. In total, respondents listed 29 projects funded by different mechanisms (e.g. Horizon, PRIMA or ERANET as well as the ECPGR EVA project) for which they had provided PGR accessions from their collections. Nineteen genebanks indicated that they had incorporated material developed in 15 Horizon projects back into their collections to make them available for further exploitation, mainly covering different cereals, legumes, Solanaceae and *Brassica* species. Based on the identified involvement of their institutes in European projects (Supplemental Table 4), these responses suggest that while some organizations are very active in Horizon projects, European genebanks and their collections are not systematically involved or effectively utilized in European PGR-related projects. In addition, European projects working on PGR appear to utilize plant germplasm that may not be documented within EURISCO and included in European national collections, showing an obvious gap in PGR documentation. Lastly, promising plant materials generated by European projects are not systematically introduced in genebank collections for further conservation and exploitation. It would be especially interesting to further research

[4] WUR, Wageningen University & Research, The Netherlands
[5] IPK, *Leibniz-Institut für Pflanzengenetik und Kulturpflanzenforschung* (Leibniz Institute of Plant Genetics and Crop Plant Research, Germany)

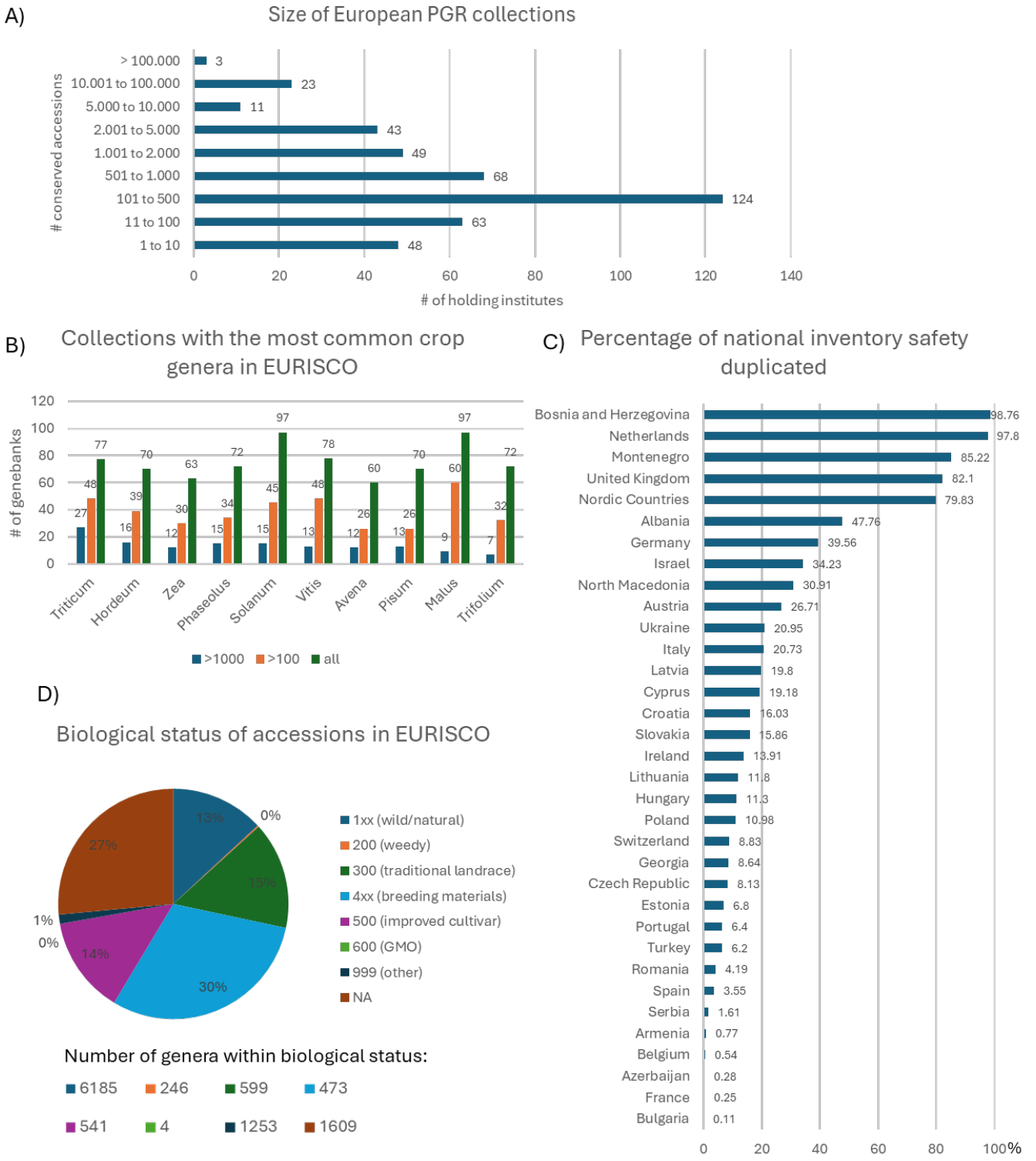

Figure 1. European plant genetic resources (PGR) collections documented in EURISCO (data from 27/01/2025). A) European holding institutes grouped by size of their collections documented in the EURISCO catalogue. In total, 432 institutes have deposited passport data for a total of 2,101,833 PGR conserved accessions in EURISCO as of that date. B) Distribution of main crop genera holdings among European holding institutes, with collections with more than 100 (>100) and 1,000 (>1,000) accessions indicated. The most represented genus *Arabidopsis* is mainly conserved at the Nottingham Stock Centre and not included in this analysis. C) Percentage of safety duplication of *ex situ* national inventories. D) Distribution of documented accessions according to biological status, with associated number of represented genera. Numbers for biological status 1xx and 4xx include several subclasses, which were combined for ease of viewing (Alercia *et al*, 2015).

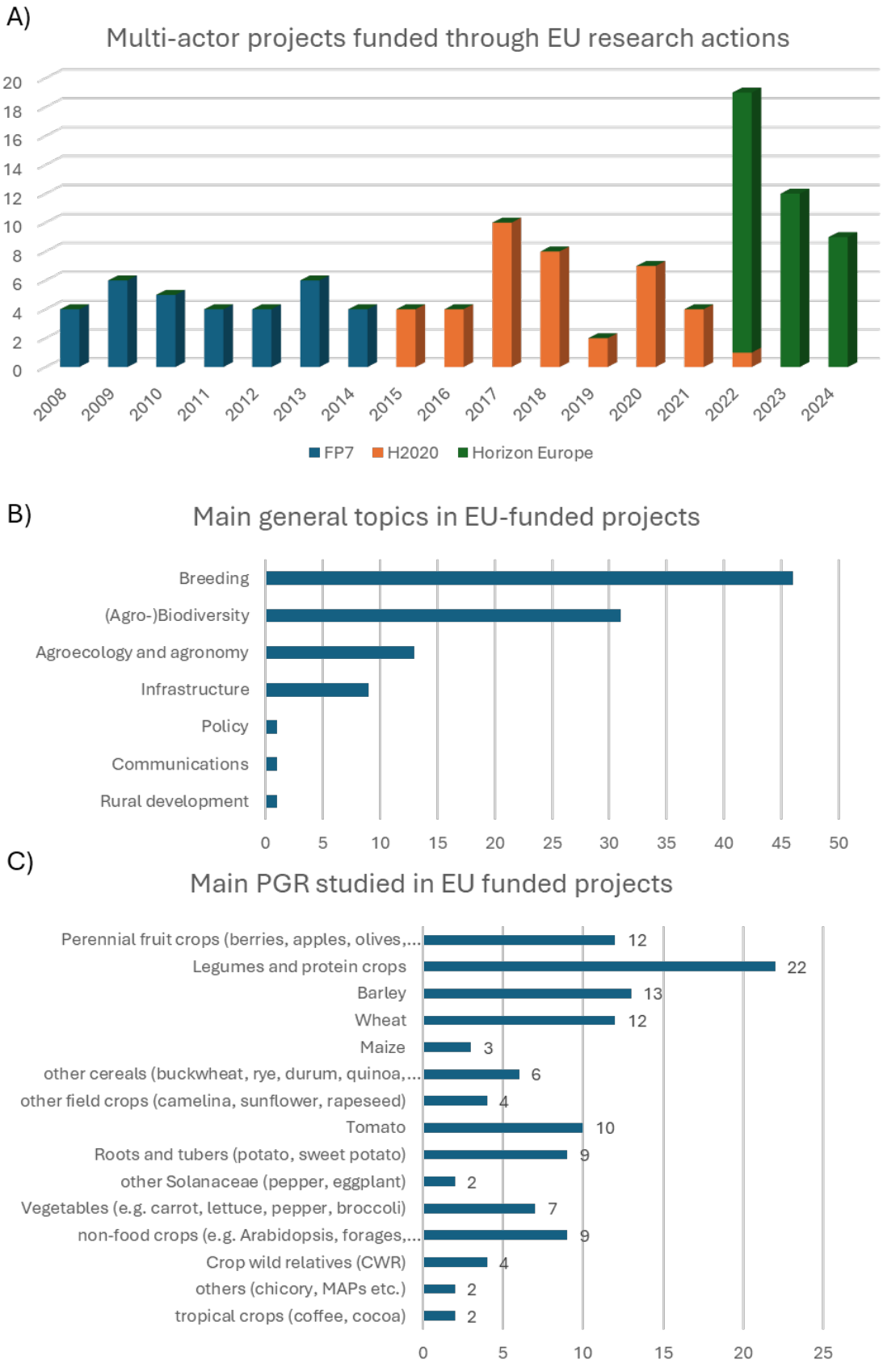

Figure 2. EU-funded multi-actor projects on plant genetic resources since 2008. A) Number of projects on biodiversity and plant genetic resources funded through European funding schemes 7^{th} Framework Programme (FP7), Horizon 2020 (H2020) and Horizon Europe since 2008, listed by starting date. Data extracted on 09/10/2024, hence additional projects may still start in 2024. B) Main general topics and C) major crops studied in these projects.

Table 1. Participation of 76 EURISCO institutes from different countries in multi-actor projects on biodiversity and plant genetic resources funded by the European funding schemes 7^{th} Framework Programme (FP7), Horizon 2020 (H2020) and Horizon Europe between 2008 and 2024. Details are included in Supplemental Table 4.

Country	# Institutes	Participation in EU projects			
		FP7	H2020	Horizon Europe	Total
Austria	2	1	5	0	6
Belgium	4	5	7	11	23
Bosnia and Herzegovina	2	0	1	1	2
Bulgaria	1	0	1	1	2
Croatia	1	0	0	1	1
Czechia	2	0	3	2	5
France	9	15	25	15	55
Germany	4	7	10	7	24
Hungary	1	0	0	1	1
Israel	3	1	7	1	9
Italy	11	6	22	14	42
Latvia	1	1	1	0	2
Lithuania	1	0	1	1	2
Netherlands	1	10	16	8	34
Poland	4	2	6	0	8
Portugal	2	3	1	3	7
Romania	2	0	3	0	3
Russia	1	0	2	0	2
Serbia	2	1	4	5	10
Slovakia	1	0	2	0	2
Slovenia	2	0	3	4	7
Spain	9	5	22	12	39
Sweden	1	0	2	1	3
Switzerland	2	5	10	10	25
United Kingdom	7	14	12	12	38

the contributions of genebank collections in terms of the numbers of accessions provided and conserved for projects.

Examples of successful cooperations of genebanks in international projects

AGENT

In the H2020 project Activated Genebank Network (AGENT, https://agent-project.eu/) running from 2020–2025, partners created a network of genebanks and bioinformatics institutes with the aim to improve genebank operations and data management through the development of standardized approaches to data curation and management, data integration and analysis pipelines. The goal was to apply the concept of 'genebank genomics' (Mascher *et al*, 2019) to accession management, whereby genomics data would facilitate the identification of potential duplicate accessions and enable tracking the identity of accessions through regeneration cycles for quality management. In combination with relevant phenotypic data, genomics data would also allow prediction and association analyses to identify useful germplasm for further research and breeding.

During the project, 12 genebank partners (11 of which are in EURISCO) created precision collections (with an emphasis on unique material from the individual genebanks) and bridging collections (potential duplicates between different European genebanks) of the target crops wheat and barley. In total, 6,956 wheat and 5,315 barley accessions were genotyped and phenotyped for agronomic traits by the holding institutes. Additional trials for biotic and abiotic stress traits on subsets of the collections complemented the phenotyping and provided data for association analyses.

Furthermore, genebanks digitized historical data collected during regenerations of their collections, in some cases going back almost 80 years. These historical datasets have proven useful for predicting performance in view of various stresses (Gonzalez *et al*, 2021).

Table 2. EURISCO institute involvement and plant genetic resource (PGR) provision to European projects. Information represents survey responses received from Genebank managers. #N/A, not applicable.

WIEWS code	Institute, location	Involved in European projects	Provided PGR to projects	Conserved PGR derived from projects
BGR001	Institute for Plant Genetic Resources 'K.Malkov', Sadovo, Plovdiv district, Bulgaria	PRO-GRACE, AGENT, EVA	AGENT, EVA	AGENT
CHE001	Agroscope Changins, Nyon, Switzerland	AGENT, EVA	AGENT, EVA	#N/A
CHE063	ProSpecieRara, Basel, Switzerland	GenResBridge, BRESOV, Farmers Pride, Diversifood, PRO-GRACE	BRESOV	BRESOV
CZE122	Gene bank, Prague 6 - Ruzyne, Czech Republic	AGENT, ECOBREED, BRESOV, PRO-GRACE, EVA	AGENT, ECOBREED, BRESOV, EVA	AGENT, ECOBREED
DEU146, DEU159, DEU271	Genebank, Leibniz Institute of Plant Genetics and Crop Plant Research, Germany	EUCLEG, Farmer's Pride, GenRes Bridge, G2P-SOL, AGENT, INCREASE, PRO-GRACE, COUSIN, EVA, Legume Generation	EUCLEG, AGENT, INCREASE, EVA, Legume Generation	#N/A
ESP004	Centro Nacional de Recursos Fitogenéticos, Alcalá de Henares. Madrid, Spain	INCREASE, AGENT PRO GRACE, EVA	INCREASE, AGENT, EVA	AGENT
ESP009	Consejo Superior de Investigaciones Científicas. Misión Biológica de Galicia, Pontevedra, Spain	PRO-GRACE, EVA	EVA, MineLandDiv (SUSCROP-ERAnet 2022), Dromamed (PRIMA)	#N/A
ESP026	Generalidad Valenciana. Universidad Politécnica de Valencia. Escuela Técnica Superior de Ingenieros Agrónomos. Banco de Germoplasma, Valencia, Spain	TRADITOM, BRESOV, Farmers' Pride, G2P-SOL, HARNESSTOM, PRO-GRACE	TRADITOM, BRESOV, G2P-SOL, HARNESSTOM	#N/A
ESP032	Principado de Asturias. Servicio Regional de Investigación y Desarrollo Agroalimentario, Villaviciosa, Spain	BRESOV, INCREASE, LegumeGeneration	BRESOV, INCREASE, LegumeGeneration	BRESOV, INCREASE, LegumeGeneration
FRA010	Institut de Génétique Environnement et Protection des Plantes, Plant Biology and Breeding, INRAE Ploudaniel, France	G2P-SOL, BrasExplor, Nem-Emerge, Pro-Wild	G2P-SOL; Nem-Emerge; Pro-Wild	BrasExplor

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Table 2 continued

WIEWS code	Institute, location	Involved in European projects	Provided PGR to projects	Conserved PGR derived from projects
FRA065	Plant Biology and Breeding, INRAE Versailles, France	G2P-SOL, TRADITOM, GenRes Bridge, HARNESSTOM, AGENT, INVITE, GenBeCon, PROWILD, NEM-EMERGE, InnOBreed, PJI-FACCE GrassLandscape, PRIMA BrasExplor, PRIMA FREECLIMB, PRIMA DROMAMED, SusCrop ERANET MineLandDiv	All projects except GenRes Bridge, AGENT, INVITE	BrasExplor, InnOBreed; Harnesstom
FRA250	Institut Agro Rennes-Angers IRHS, Angers, France	OPTIMA, EVA	OPTIMA, EVA	#N/A
GBR004	Millennium Seed Bank - Royal Botanic Gardens Kew	PRO-GRACE, AGENT	#N/A	#N/A
GBR016	Genetic Resources Unit, Institute of Biological, Environmental & Rural Sciences, Aberystwyth University, United Kingdom	EUCLEG, CropDiva, Legume Generation, Legendary, EVA	EUCLEG, Legume Generation	#N/A
GBR140	Nottingham Arabidopsis Stock Centre, Loughborough Nottingham, United Kingdom	PRO-GRACE, PGR Secure	Any project that has requested them	*Arabidopsis* lines from various projects
GBR247	Germplasm Resources Unit, John Innes Centre, Norwich, United Kingdom	LegumeGeneration, ProWild, EVA	Legato, LegumeGeneration, ProWild, EVA	Gediflux, LEGATO
GBR251	The James Hutton Institute, Dundee, Scotland, United Kingdom	G2P-SOL, PRO-GRACE, EVA	G2P-SOL	G2P-SOL
HRV041	Faculty of Agriculture, University of Zagreb, Croatia	BELIS, GEroNIMO, GRASS Ceiling, PASTINNOVA, RESBIOS, TODO, PRO-GRACE, Strenght2Food, Farmers Pride, TREASURE, MendTheGap, EVA	EVA	#N/A
HUN003	Centre for Plant Diversity, Tápiószele, Hungary	PRO GRACE	#N/A	#N/A
ISR001	Department of Field and Vegetable Crops, Hebrew University of Jerusalem, Rehovot, Israel	G2P-SOL, EVA	G2P-SOL	G2P-SOL
ISR002	Israel Gene Bank for Agricultural Crops, Agricultural Research Organisation, Volcani Center, Bet Dagan, Israel	G2P-SOL	G2P-SOL	G2P-SOL

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Table 2 continued

WIEWS code	Institute, location	Involved in European projects	Provided PGR to projects	Conserved PGR derived from projects
ITA331	Facolta di Agraria, Università degli Studi di Catania, Italy	BRESOV, COUSIN	BRESOV, COUSIN	BRESOV
ITA363	Dipartimento di Chimica, Biologia e Biotecnologie, Universitá degli Studi Perugia, Italy	Farmers Pride, PRO-WILD	#N/A	#N/A
ITA382	CREA-Centro di Ricerca Genomica e Bioinformatica - Sede di Fiorenzuola d'Arda, Italy	NEURICE, BEST-CROP, GP2-SOL, PRO-WILD, PRO-GRACE, EVA	GP2-SOL, PRO-WILD, EVA	NEURICE, BEST-CROP, GP2-SOL, PRO-WILD
ITA383	CREA-Centro di Ricerca Cerealicoltura e Colture Industriali - Sede di Vercelli, Italy	AGENT, PRO-GRACE, EVA	AGENT, EVA	AGENT
ITA391	CREA-Centro di Ricerca Orticoltura e Florovivaismo - Sede di Pontecagnano, Italy	G2P-SOL, PRO-GRACE, EVA	G2P-SOL, EVA	G2P-SOL
ITA394	CREA-Centro di Ricerca Zootecnia e Acquacoltura - Sede di Lodi, Italy	BELIS, DIVINFOOD, INTERCROPVALUES, LIVESEEDING, INVITE, LIVESEED, REMIX, EVA	EVA	#N/A
ITA436	Istituto di Bioscienze e Biorisorse, Consiglio Nazionale delle Ricerche, Bari, Italy	PRO-GRACE, EVA	EVA	#N/A
LVA024	Institute of Agricultural Resources and Economics, Riga, Latvia	LIVESEED, EVA	EVA	#N/A
NLD037	Centre for Genetic Resources, the Netherlands, Wageningen, Netherlands	PRO-GRACE, G2P-SOL, AGENT, PrepActGR, Framers Pride, GenRes Bridge, EVA	AGENT, G2P-SOL, EVA	#N/A
POL003	Plant Breeding and Acclimatization Institute, Blonie, Poland	AGENT, INCREASE, RustWatch, G2P-SOL, ECOBREED, DETECTIV	INCREASE, AGENT, G2P-SOL	AGENT, INCREASE, G2P-SOL
PRT001	Banco Português de Germoplasma Vegetal, Braga, Portugal	Farmer´s Pride; LIVESEED, PRO-GRACE, EVA	LIVESEED, EVA	LIVESEED
SRB062	Institut for forage crops Krusevac, Krusevac, Serbia	EUCLEG, BELIS, EVA	EUCLEG, BELIS	#N/A
SVK001	National Agricultural and Food Centre (NPPC), Research Institute of Plant Production (RIPP), Piestany, Slovakia	RustWatch, Ecobreed, AGENT, EVA	Ecobreed, AGENT, EVA	Ecobreed
SVN019	Crops and Seed Production Department, Agricultural Institute of Slovenia, Ljubljana, Slovenia	Ecobreed, MedVitis, BrasExplor, Diversilience, INCREASE, Liveseeding, Root2Res, EVA	Ecobreed, MedVitis, BrasExplor, Diversilience	#N/A

To manage the data, the bioinformatics partners involved in the project (IPK, INRAE, WUR, RBGK[6]) created a range of tools, starting with standard data collection templates, an online data curation tool, a web application, REST interfaces using the Breeding API specification (Selby *et al*, 2019) and various data analysis pipelines, which allow the users (primarily genebank data managers) to effectively manage and exploit the data on their collections (Beier *et al*, 2022; Berkner *et al*, 2022, 2024; El-Hanafi *et al*, 2023). Several in-project training events and datathons were an opportunity for capacity building and four rounds of genebank peer reviews following the ECPGR AQUAS protocol have provided useful feedback on genebank operations and identified gaps and areas for improvements (https://www.ecpgr.org/aegis/aquas/peer-visits).

European Evaluation Network (EVA)

Some of the tools developed by AGENT build on project outputs of the ECPGR initiative European Evaluation Network for PGR (EVA, https://www.ecpgr.org/eva). This network brings together genebanks, public research institutes, private sector breeders and farmers' organizations in public–private partnerships to jointly evaluate genebank accessions for relevant traits in multilocation trials across Europe. Activities are typically provided in-kind and are distributed among partners according to their expertise and capacity. These activities include provision of accessions, regeneration of material (where necessary as single-seed descent lines or crosses), evaluation in the field, lab or greenhouse, genotyping, data curation and data analysis. ECPGR funds, so far provided by the German Ministry for Food and Agriculture, have been essential to kick-start activities that would be difficult to carry out as in-kind inputs, especially seed multiplication or genotyping. Participation of breeding companies was incentivized by the agreement to enforce a 3-year embargo on the publication of evaluation data outside the consortium. The crop-specific networks have been operating since 2019 and currently have more than 120 partners including around 50 private breeding companies working on 15 crops. So far, the networks have generated phenotypic data on more than 5,000 accessions in almost 400 trials, where they have so far collected more than half a million datapoints on more than 200 different traits (Table 3).

The use of standard phenotyping protocols, along with standardized metadata and phenotypic data collection templates, was imperative for the integration of data collected by different partners in more than 100 locations. The EURISCO-EVA Information System, a project-internal platform, developed using the same framework as the public EURISCO catalogue, enabled effective data management and analysis (Kumar *et al*, 2024) and provided the template for the AGENT database structure. Within their collaborative networks, EVA partners have developed a new tool for the genotyping of lettuce (Tripodi *et al*, 2023) and have investigated the genetic diversity of European carrot and maize accessions (Goritschnig *et al*, 2023; Balconi *et al*, 2024), generating valuable knowledge for the genebanks and research and breeding communities. The plant material exchange within the networks is governed by the rules of the ITPGRFA Multilateral System (FAO, 2009), using their Standard Material Transfer Agreement (SMTA) also for crops not included in Annex 1, thus facilitating access to PGRFA for further research and development activities by all partners.

G2P-SOL

The Horizon 2020 project G2P-SOL (www.g2p-sol.eu) was active from 2016 to 2021 and involved 19 partners (including 13 genebanks of which nine are listed in EURISCO) as well as 12 external collaborating institutions from three continents. G2P-SOL focused on four major Solanaceae crops (tomato, potato, eggplant, pepper), for which the partner genebanks held around 65,000 accessions, of which around 14,000 CWR (Table 4).

The project consisted in five phases: 1) inventory of the partner genebanks, in which the images and passport data from the different genebank information systems were collected, manually curated and published, 2) genotyping of a subset of approx. 40,000 accessions with 2,000–10,000 high-quality SNPs and analyses of population structure, duplicates and taxonomic classification (Toppino *et al*, 2021), 3) establishment of core collections of around 350–400 accessions (both cultivated and wild) for each crop, representing the worldwide genetic and phenotypic diversity of each genepool (e.g. Nankar *et al* (2020)), 4) phenotyping of the core collections in multiple locations for resistance to biotic and abiotic stresses, agronomic, and (limited to the three fruit crops) metabolic traits (Gramazio *et al*, 2020), and 5) pre-breeding, in which markers for described and novel traits from CWRs were established and the traits pre-bred into the genetic background of each cultivated species (Stefa´ *et al*, 2020). G2P-SOL has been classified as a success story by the European Commission, and its core collections are available under SMTA and with phytosanitary certificates from partner genebanks acting as distribution points.

Discussion

Benefits of international cooperation in PGR research

In the three projects highlighted above, partners described the possibility of engaging in active networks and exchanging pre-competitive ideas and knowledge as primary benefits of participation. Novel traits for a more sustainable agriculture have been identified and some partners have already applied approaches and

[6] RBGK, Royal Botanic Gardens, Kew, United Kingdom

Table 3. Summary of partnership and outputs of five crop-specific ECPGR European Evaluation Network EVA (data as of 30 June 2024).

	All Networks	EVA Wheat Barley	EVA Carrot	EVA Lettuce	EVA Pepper	EVA Maize
Crops	8	3	1	2	1	1
Accessions	5,092	3,608	67	367	183	867
Partner institutes	89	47	14	12	15	18
Countries of operation	33	25	8	8	13	9
Experiment locations	119	58	14	6	11	30
Traits	285	46	138	24	26	51
Trials with available data (2020–2024)	384	265	27	14	15	63
Phenotypic datapoints available	539,678	318,891	95,695	10,717	24,016	90,359

Table 4. Summary of Solanaceae accessions included in the G2P-SOL collection by participating genebanks. AVRDC, the World Vegetable Center, Taiwan (TWN); IPK, Leibniz Institute of Plant Genetics and Crop Plant Research, Germany (DEU); HUJI, The Hebrew University of Jerusalem, Israel (ISR); INRAE, Institut national de recherche pour l'agriculture, l'alimentation et l'environment, France (FRA); CIP, International Potato Center, Peru (PER); WUR, Wageningen University & Research, the Netherlands (NLD); UPV, Universitat politecnica de Valencia, Spain (ESP); JHI, James Hutton Institute, United Kingdom (GBR).

Partner Country	AVRDC TWN	IPK DEU	HUJI ISR	INRAE FRA	CIP PER	WUR NLD	UPV ESP	JHI GBR	All others	Total
Tomato	8,260	3,840	8,100	1,600	0	1,332	2,220	0	390	**25,352**
Of which wild	812	26	100	200	0	108	220	0	50	**1,466**
Potato	0	6,020	0	1,500	6,000	1,446	0	2,300	390	**17,266**
Of which wild	0	2,845	0	500	1,800	1,243	0	1,400	300	**7,788**
Pepper	8,235	1,530	0	1,460	0	1,010	1,400	0	850	**13,635**
Of which wild	464	63	0	46	0	783	80	0	56	**1,436**
Eggplant	3,713	110	0	2,015	0	510	260	0	280	**6,608**
Of which wild	1,499	0	0	1,120	0	373	70	0	40	**3,062**
All four crops	20,208	11,500	8,100	6,575	6,000	4,298	3,880	2,300	1,910	**62,861**
Of which wild	2,775	2,934	100	1,866	1,800	2,507	370	1,400	446	**13,752**

tools developed by these projects to other species and in other projects. Early career researchers in the AGENT and G2P-SOL projects highlighted the opportunity to learn diverse aspects ranging from fieldwork to data curation and analysis, which was facilitated by mentors from different project partners. In general, the standardization approaches followed by both AGENT and EVA are prime examples of how access to data can be facilitated according to FAIR (Findable, Accessible, Interoperable, Reusable) principles (Wilkinson *et al*, 2016), providing pipelines for data curation and management that will allow their reuse in future investigations. However, while these projects have shown a possible new way of working for genebank data management and collaboration, its long-term adoption and implementation involving the majority of European genebanks and covering more crops would require significant investment and political commitment to provide the necessary framework. At present, the ECPGR Secretariat is best positioned to disseminate standards and methodologies for genebank operations and crop evaluations throughout their European networks.

An assessment of the long-term impact of EU-funded research projects overall is difficult to produce but should consider the availability of generated materials, tools and project data for further research and the level at which project outputs have been exploited after the end of the projects. A well-known issue with project data is that they are often stored in fragmented form, and websites or databases are only maintained for a limited period after projects end. All these considerations call for the need to operate within a more coherent framework that facilitates and promotes genetic resources conservation, documentation and sustainable use, as the *Plant Genetic Resources Strategy for Europe* (ECPGR, 2021) is advocating and a suitable EU Research Infrastructure might implement.

Our preliminary survey of genebanks involved in EU-funded Horizon projects showed that some genebanks are very active in participating in European research, contributing both materials and relevant expertise in conservation, cultivation, breeding and documentation. On the other hand, a significant number of genebanks with relatively large collections do not participate in many European projects, limiting the use of these collections in international projects and the benefits to organizations from knowledge exchange. In addition, much of the funded research has been focusing on a few staple crops, e.g. cereals, legumes, Solanaceae and Brassicaceae, with minor crops only recently

receiving more attention (Figure 2, Supplemental Tables 1–3). The involvement of genebanks in crop improvement, especially in research and pre-breeding projects, should also ensure that the final products (in terms of germplasm materials) of these projects are either fully incorporated into their collections or otherwise made available for further distribution and exploitation (Hanson *et al*, 2024). It should be noted that inclusion in a genebank collection implies conservation in perpetuity. For some material, such as breeding or research material, this might not always be the proper approach and novel solutions to making project materials available for future use will be needed. Follow-up studies are also needed on the effective use of PGR in breeding and to assess the impact of publicly funded research on PGR. The survey analyzed in this paper highlights the importance of PGR use in a collaborative research framework at both the regional and international levels. This is believed to be the most promising in terms of exploitation of the immense public good that is maintained by genebanks, often with insufficient public funds but with a significant potential economic value (Gollin, 2020). Considering the growing threat of genetic erosion resulting from the changing climate and changing habitats it will also be important to mainstream *in situ* conservation activities coupled with the assurance that populations of CWR and wild food plants are made available for use in breeding and research (Khoury *et al*, 2022).

The experiences from the collaborative projects described in this paper, as well as reports from other successful projects at the European level, highlight the benefits to be gained from international cooperation of genetic resources institutes to increase our knowledge on PGR and make them accessible for further research and breeding. Collaborative activities in PGR research and breeding, through the implementation of public–private partnerships and multi-actor projects are imperative to realizing the potential of European PGR in strengthening the bioeconomy along the whole agri-food value chain (Vangheluwe *et al*, 2023). Tools and partnership models have been developed, but they may remain ineffective without a permanent coordinated approach and support for the long-term exploitation of project outputs. Similarly, a variety of technical challenges in information management as well as political and institutional considerations for access to PGR will need to be addressed in novel cooperative approaches to enhance innovation in PGR research (Halewood *et al*, 2018). The *Plant Genetic Resources Strategy for Europe* (ECPGR, 2021) identified the need for long-term European cooperation, which could be realized through the establishment of a European Research Infrastructure fully dedicated to PGR, currently in the concept development phase through the project PRO-GRACE (https://www.grace-ri.eu/pro-grace).

A European Research Infrastructure to facilitate consolidated research on PGR

The Horizon Europe project PRO-GRACE involves genebanks, research institutes, and non-governmental and stakeholder organizations in developing a framework for collaboration at the European level to assure availability and access to PGR for breeding and research. Within this project, standards have been proposed to provide guidance on PGR documentation, enabling effective linkage between conserved accessions, associated Multicrop Passport Descriptors (Alercia *et al*, 2015), and associated phenotypic and genotypic data. Surveys have established a baseline of full implementation of quality management systems (QMS) in genebanks and informed deliverables developing recommendations for implementation of QMS in genebanks and the establishment of a Genebank Certification System, ensuring reliable conservation of and access to PGR conserved in genebanks (Van Hintum and Wijker, 2024). Gap analyses and surveys have identified a clear lack of consolidated PGR research infrastructures within Europe and provided evidence for a need to establish a Europe-wide distributed research infrastructure that would effectively ensure high-quality conservation of PGR, as well as develop state-of-the-art methods, tools and services for their use in research, breeding and cultivation. This approach represents a great opportunity to further develop EURISCO into a FAIR-compliant European PGR information system that is more closely linked to regional and global platforms and integrates previously untapped data from additional sources and further data domains. The concept for a future European Research Infrastructure on PGR (GRACE-RI) covers important aspects which support the implementation of the *Plant Genetic Resources Strategy for Europe* and align with needs of stakeholders from conservation and use: 1) enhance all PGR collections across Europe to accepted standards through implementation of quality management and upgrade of genebank procedures, 2) improve and consolidate PGR documentation through advances in data integration and management, 3) develop multi-omics and phytosanitary technologies for PGR characterization, enhancing their availability for breeding, 4) assure access to all PGR across Europe through supporting genebanks in meeting legal and phytosanitary requirements, 5) mainstream *in situ* conservation of PGR, particularly of CWR, to facilitate their availability for research and breeding, and 6) develop scientific services destined to the scientific and breeding communities, as well as programmes for capacity building, training and education to achieve the abovementioned objectives. Participating countries and institutes will thus create a relevant and well-defined service for the user community, with a significant reduction of redundancies and increased efficiency through the pooling of capacities and expertise. In contrast, continued inaction in this field would mean surrendering to the loss of agricultural and general plant biodiversity which is already threatening our agriculture and ecosystems.

Conclusion and outlook

Proper management of PGR is becoming increasingly important due to the growing demand for access to PGR for breeding of new varieties and thanks to better breeding techniques using genebank accessions as raw materials. At the same time, the need to conserve is expanding due to climate change and increasing genetic erosion. Against this backdrop, international research projects have provided genetic resource centres with the possibility to participate in collaborations, improving their capacity, gaining knowledge about their collections and thus adding value to their holdings. The creation of a dedicated Research Infrastructure for PGR, as proposed by PRO-GRACE, will allow the European conservation, research and breeding communities working on PGR to better organize and monitor their activities, reduce redundancies, improve processes and conservation, develop novel methods, with the aim to ensure continued access to and utilization of high-quality PGR materials and related information. This will offer current and future researchers access to PGR and methods for their study and valorization, which are necessary for addressing the main challenges of the present time and ensuring a sustainable and biodiverse agriculture in Europe in the future. Providing a stable political and financial framework for international research collaboration on PGR will enable Europe to firmly establish a primary role in developing science-based solutions to the challenges of the twenty-first century.

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Supplemental data

Supplemental Table 1. EU-funded multi-actor projects on PGR within the H2020 funding scheme (active 2015–2027).

Supplemental Table 2: EU-funded multi-actor projects on PGR within the Horizon Europe funding scheme, which have started by mid-2024.

Supplemental Table 3: EU-funded multi-actor projects on PGR within the FP7 funding scheme (2008–2018).

Supplemental Table 4: European genebanks participating in Horizon multi-actor projects funded through the European funding schemes 7th Framework Programme (FP7), Horizon 2020 (H2020) and Horizon Europe since 2008.

Conflict of interest

The authors declare no conflict of interest.

Author contributions

SG, SW, NS, GG and LM developed the concept of the paper, SG wrote the first draft and analyzed the data. All authors commented on the paper and contributed to the writing.

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