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RESEARCH ARTICLE

Regulatory landscape for plant genetic resources: germplasm conservation and plant variety rights in the berry sector in Europe

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Abstract Genetic resources (GenRes), as defined by the Convention on Biological Diversity (CBD), include any genetic material with actual or potential value. The management of GenRes involves a complex international regulatory framework that governs their identification, recovery, characterization, conservation, intellectual property (IP) protection, and utilization. This intricate system, overseen by multiple international organizations, impacts the collection of new materials from the wild, the research conducted on these resources, and the manner in which research findings are shared with the countries of origin. Plant genetic resources (PGR) are critical to developing new crop cultivars by preserving traits that might have been lost during domestication. For health and nutritional security, effective conservation and judicious use of these materials are vital. Additionally, their use in breeding programs often leads to the creation of commercial cultivars, which must be registered under plant variety rights in Europe or similar protections worldwide. This review examines the regulatory landscape guiding the conservation and use of PGR, focusing on how various regulations interact to affect the conservation, exchange, protection, and commercialization of germplasm. Using the rapidly expanding berry sector as a case study, we analyse berry conservation efforts in Europe and trends in the release of commercial cultivars, covering blueberries,

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blackberries, raspberries, and strawberries, and recognizing contributions from both public and private breeding programs within and beyond the European Union (EU). This analysis seeks to promote effective conservation and sustainable use of GenRes, enhancing their contribution to agricultural innovation and biodiversity preservation.

Keywords Berries · Plant Genetic Resources · Variety Protection · Strawberry · Raspberry · Blueberry · Blackberry

Introduction

By the late 1890s, scientists and administrators realized that global access to wild and cultivated GenRes, or germplasm, was essential for accelerating advancements in agricultural systems. This realization led to efforts in germplasm recovery, the establishment of major genetic material conservation repositories, and the characterization of these resources for their potential use in breeding programs (Hummer 2003). However, the exchange and utilization of germplasm have raised concerns related to intellectual property rights, farmers' rights, and the ownership of indigenous genetic resources. These issues have driven significant changes in the approach to germplasm exchange.

The Convention on Biological Diversity (CBD), a legally binding treaty under the administration of the United Nations Environment Program, came into effect in December 1993. The CBD, along with subsequent treaties, has influenced international germplasm exchange, as well as the conservation and sustainable use of genetic resources. Plant genetic resources (PGR) are defined as the genetic material of plants that hold value for both present and future generations, contributing to food security, agricultural sustainability, and biodiversity conservation. The subset of PGR with actual or potential value for food and agriculture is known as plant genetic resources for food and agriculture (PGRFA). These resources can be found in the form of crop cultivars, landraces (LR—locally adapted, genetically diverse crop cultivars) or crop wild relatives (CWR—the ancestral species related to cultivated species). PGRFA represents the genetic diversity necessary for the controlled genetic improvement of cultivated species. They serve as a vital repository of genes that can confer desirable traits, such as adaptation to varied environments, higher productivity, improved quality, or enhanced nutritional characteristics. PGRFA can be found in situ (on farms, in gardens, or in natural habitats) or conserved ex situ in field, seed, and in vitro genebanks worldwide. However, these resources are not always adequately conserved ex situ, rarely conserved actively in situ and on-farm, and often barely accessible. Therefore, it is critical to implement practices that protect PGRFA from overexploitation and loss, and implement adequate systems for ex situ conservation and provision of access.

PGRFA are the result of millennia of interactions between the environment, agricultural systems, and human intervention, including farmer selection and formal plant breeding. As such, they occupy a conceptual space between natural and constructed cultural resources. This unique position introduces complex social dilemmas in the production, sustainable use, and sharing of PGRFA, challenges that are not typically encountered in the management of natural resources (Halewood 2013). The Food and Agriculture Organization (FAO) Global System on PGRFA is envisioned as a set of policy instruments and mechanisms to ensure the conservation, sustainable use, and fair and equitable sharing of benefits from the use of these particular genetic resources. These objectives are also central to the International Treaty on Plant Genetic Resources for Food and Agriculture, which is in harmony with the CBD.

Pre-breeding materials: a grey zone between genetic resources and cultivars

Plant breeders typically prefer to cross among elite lines due to the challenges associated with using CWR or older material, which are typically less adapted to modern agricultural environments. Pre-breeding serves as a crucial intermediary step, aiming to isolate and incorporate desirable genetic traits from non-domesticated materials into breeding lines that can be more easily crossed with elite cultivars. This process is essential not only for facilitating the use of available PGR in crop improvement but also for preserving and expanding genetic diversity.

Most horticultural crops, such as tomato (Wang et al. 2024) or strawberry (Hardigan et al. 2021; Fan and Whitaker 2024) have experienced bottlenecks during domestication, resulting in narrower genetic background relative to their wild counterparts. This makes wild germplasm, which include the progenitors of crops, as well as species more or less closely related to them, particularly valuable as they represent a vast resource of genetic diversity necessary to address emerging agricultural challenges, such as disease resistance, volatile or nutritional content, and tolerance to abiotic stresses (Khoury et al. 2022). Therefore, priority must be given to the conservation of CWR. As global concern for the loss of genetic resources has increased in recent years, much work has been carried out to conserve PGR, which is considered as a natural heritage (Rajasekharan and Ramanatha Rao 2019). However, efforts are still required as in general, and to a various degree depending on the taxa, crop wild relatives are poorly represented in germplasm collections (Castañeda-Álvarez et al. 2016).

Pre-breeding programs involve access to PGR through genebanks and the characterization of this material in order to identify the subsets of donor material that are likely to harbour novel and useful genetic variation for breeding. Once high-value traits or alleles are identified, they are incorporated into elite backgrounds through multiple rounds of backcrossing and evaluation. Additionally, smaller collections of selected lines could be phenotyped and genotyped in detail in order to determine marker-trait associations or quantitative trait loci (QTL). After markers are identified and validated, they can be employed in Marker-assisted selection (MAS) to accelerate the pre-breeding process and enhance its precision (Sukumaran et al. 2022; Varshney et al. 2012).

The EU H2020 (https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-2020_en) program has dedicated substantial funding to projects enhancing genetic resource conservation and pre-breeding, particularly in Europe, and this commitment continues under the Horizon Europe program for the 2021–2027 period (https://agriculture.ec.europa.eu/system/files/2023-05/factsheet-agriresearch-genetic-resources-and-breeding_en.pdf). These initiatives require collaboration between public research institutions and private breeding companies. The goal is to analyze genetic variability in the different germplasm collections and breeding programs, and identify ways to broaden it through knowledge, technology (genotyping, phenotyping), and material exchange. The BreedingValue project is highlighted as one of these initiatives, focusing on developing new breeding strategies for resilient and high-quality berries, such as strawberries, blueberries, and raspberries. The project's goal is to maintain genetic diversity while meeting consumer preferences for quality and sensory characteristics (Senger et al. 2022; https://cordis.europa.eu/project/id/101000747). In the implementation of these projects, the question emerged as to how to define the value and, above all, the ownership of the advanced pre-breeding materials derived from cultivated or wild germplasm, which require extensive effort for trait identification and development. Private breeding programs, driven by rapid cultivar development, may lack resources for long-term introgression involving germplasm they do not possess or have not fully characterized (Finn and Knight 2002). This highlights the need for partnerships with public research bodies, which can support the conservation and improvement of germplasm by generating new pre-breeding material. Such material is critical for developing competitive new cultivars with traits not commonly found in commercial ones. However, it is equally important to ensure proper recognition of ownership for those who have contributed to the conservation of germplasm and the development of new pre-breeding resources. In 2023, the BreedingValue consortium organized a workshop that brought together key representatives from the European Cooperative Programme for Plant Genetic Resources (ECPGR), FAO, Community Plant Variety Office (CPVO), and the European Commission (EC) to discuss international regulatory frameworks and the management of intellectual property (IP) for breeding and pre-breeding materials. Building on the outcomes of this workshop, this paper offers an overview of the regulatory frameworks that govern the exchange and use of genetic resources, alongside the systems for plant cultivar regulation and evaluation in both the EU and the USA. We also present a case study focused on berry genetic resources, given their growing economic importance to EU agriculture. With global consumption of berries rising, several EU countries now rank among the top 20 producers of strawberries, raspberries, and blueberries. We review efforts to conserve berry germplasm in the EU and provide a detailed analysis of trends in the registration of new berry cultivars—strawberry, blueberry, raspberry, and blackberry—in the EU over the past 20 years.

Methodology

To compile the information presented in the section entitled "Regulatory Frameworks for the Exchange and Use of Genetic Resources", we consulted the full texts of the Convention on Biological Diversity (CBD) and its Nagoya Protocol, as well as the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA), accessible through the FAO website. These documents were essential to describe the overarching legal frameworks governing access and benefit sharing (ABS) at the international level. At the European level, we reviewed the official documentation and web resources of the European Cooperative Programme for Plant Genetic Resources (ECPGR), including its core initiatives: AEGIS, EURISCO, EVA networks, and the Plant Genetic Resources Strategy for Europe. To understand how ABS regulations are implemented within the EU, we referred to Regulation (EU) No 511/2014, Implementing Regulation (EU) 2015/1866, and supporting guidance documents provided by the European Commission.

To develop section “Different Levels of Plant Variety Regulation and Evaluation: From UPOV to USA and EU Regulations”, a qualitative review of legal texts, institutional sources, and international frameworks governing plant cultivar protection was conducted. For the EU, the analysis focused on key regulations including Council Regulation (EC) No 2100/94 establishing the Community Plant Variety Rights (CPVR) system, as well as Commission Regulations (EC) No 874/2009 and 1768/95 (as amended by EC 2605/98), which detail implementation rules and the farmers’ exemption. Directive 2001/18/EC was also reviewed in relation to the regulation of genetically modified cultivars. For the United States, the legislative framework was examined through the Plant Variety Protection Act (PVPA) of 1970 and the Plant Patent Act of 1930, along with provisions relevant to utility patents under U.S. patent law (35 U.S.C. §101–103 and §161).

Application procedures, examination processes, and enforcement mechanisms were analyzed using publicly available information from the CPVO, the U.S. Plant Variety Protection Office (PVPO), and the U.S. Patent and Trademark Office (USPTO). The UPOV Convention (1991 Act) was consulted to understand harmonized international criteria, particularly for DUS (Distinctness, Uniformity, and Stability) testing.

Data on granted Plant Variety Rights (PVRs) and ongoing applications for section “Berry genetic resources in Europe: current state of PVRs” was extracted from the CPVO Register (v. 4.20.5) in May 2024 (https://online.plantvarieties.eu/publicSearch). The search was conducted using the genus Latin names of the four berry crops. The data extracted from the CPVO Register for granted and active applications was further refined to emphasize:

- Year of application. Even for granted PVRs, the year indicates when the application has been submitted, and not when the PVR has been granted.
- Public/private status of the organizations holding/applying PVRs
- EU/non-EU status of the organizations holding/applying PVRs (based on the location of the legal entity at the time the application was filed). In the framework of this analysis, the “EU” status includes the member states of the European Union as well as countries on the European continent associated to the Horizon Europe research funding programme (e.g. UK, Norway, Switzerland, Moldova).

Regulatory frameworks for the exchange and use of genetic resources

Overview of existing international agreements

International law provides mechanisms to ensure the fair and equitable exchange between providers of genetic resources and the users of these resources. This concept is known as ‘access and benefit sharing’ (ABS) and applies to both academic research and commercial research and development. The CBD is the international legal instrument for “the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources” that has been ratified by 196 nations (United Nations 1992). To advance in the implementation of the third objective, the CBD developed a supplementary agreement called the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization (2010), which sets out core obligations for its contracting Parties to take measures in relation to access to genetic resources, benefit-sharing and compliance. It came into force in 2014. Benefits arising from the utilization of genetic resources can be monetary, such as royalties from commercial products developed using the resources, or non-monetary, such as technology transfer, participation in research, and recognition of country of origin. The Nagoya Protocol also addresses traditional knowledge associated with genetic resources and recognizes the sovereignty of States over natural resources under their jurisdiction. Likewise, it establishes that Contracting Parties should create conditions to facilitate access to genetic resources.

The Nagoya Protocol applies to all biodiversity, including animals, plants, and microbes. In the specific case of PGRFA and their specific types of use, specialized ABS are required. PGRFA are essential for global food security and provide traits and diversity for breeding. No country is entirely self-sufficient in terms of PGRFA, and there has been a colonial history of exploitation of these resources. Until the mid-twentieth century, when the first UN agreements on sovereign rights of own genetic resources were signed, PGRFA were generally considered as global public goods that could be freely collected and exchanged. The first attempt to regulate access to PGRFA at the international level resulted in the adoption of the International Undertaking of PGRFA (IUPGRFA) by the FAO Conference in 1983 (Sirakaya 2022). This IUPGRFA was a voluntary agreement based on the principle that PGR were a "heritage of mankind and consequently should be available without restriction". However, there were concerns over the sovereign rights of the countries, the free availability and compatibility with plant breeders' rights and regarding the system's inequality, as it failed to recognize contribution over time of farmers (farmer's rights). The culmination of efforts to develop a fair system for PGRFA exchange was the adoption of the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA; https://www.fao.org/plant-treaty/overview/texts-treaty/en/), which came into force in 2004. A key objective of CBD, Nagoya Protocol and ITPGRFA was facilitating access to PGRFA (Ebert et al. 2023). However, due to bureaucratic implementation procedures that can vary depending on the country, especially under the bilateral regulations of the Nagoya Protocol, their implementation might be hampering the exchange and use of biodiversity. The Treaty's truly innovative solution to access and benefit sharing was the Multilateral System (MLS). MLS is a cooperative system that allows all contracting parties to have access to the most important PGRFA for their agricultural development-specifically, 64 of the most essential crops, which together account for 80% of the food derived from plants. Access is granted under standardized, multilaterally agreed terms, eliminating the need for bilateral negotiations for each exchange. The exchange of materials is governed by the Standard Material Transfer Agreement (SMTA), which regulates access and benefit-sharing under the MLS. This ensures that benefits are shared multilaterally among Contracting Parties. Furthermore, the Treaty acknowledges the invaluable contribution of farmers to global crop diversity and aims to ensure that the benefits derived from the use of these genetic resources are shared equitably.

The European Cooperative Programme for Plant Genetic Resources (ECPGR)

The European Cooperative Programme for Plant Genetic Resources (ECPGR—www.ecpgr.cgiar.org) was founded in 1980 in response to global policy frameworks such as the FAO Commission on PGRFA and the United Nations' Sustainable Development Goals. During the last decades, this programme has served as the primary European coordinating instrument for technical activities related to the conservation and sustainable use of PGRFA. The ECPGR has endorsed the 'Plant Genetic Resources Strategy for Europe' (PGR Strategy), a comprehensive document outlining goals, necessary actions and step changes to rationally and effectively conserve PGRFA ex situ and in situ, provide access and increase its sustainable use. This document, presented in 2021, resulted from a collaborative effort involving ten National Coordinators and a wide range of experts and stakeholders who provided comments and revisions throughout the drafting process.

Matching with PGR Strategy goals, the objectives of ECPGR are:

(i) Ex situ conservation and provision of access through the European Genebank Integrated System (AEGIS).

AEGIS (https://www.ecpgr.org/aegis) aims to efficiently conserve and provide access to unique PGRFA in Europe by establishing the European Collection, an integrated network connecting European genebanks under a unified system. This system focuses on the long-term conservation of genetically unique accessions important to Europe, also making them readily available and easily accessible for breeding and research purposes. Ex situ conservation of those accessions, known as European Accessions and collectively forming the European Collection, will adhere to common agreed quality standards, independently of where the accessions are physically located. Access can be granted in accordance with the terms and conditions set out by the ITPGRFA through a Standard Material Transfer Agreement (SMTA). Annex I of the Treaty lists the crops and forages—35 crops and 29 forages-included in the Multilateral System. Additionally, members of the ECPGR have opted to treat all the plant genetic resources accessions formally included in the European Collection (either belonging to Annex I of the Treaty or not) in the same way as Annex I materials. With this decision, > 70,000 accessions of all crops in the European Collection will be distributed under a SMTA when they are intended for research, breeding and training for food and agriculture (such purposes shall not include chemical, pharmaceutical and/or other non-food/feed industrial uses), with an explanatory note clarifying how the SMTA should be interpreted when it is used for distribution of non-Annex I material.

(ii) Documentation of PGRFA passport and phenotypic information through the European Search Catalogue for Plant Genetic Resources (EURISCO).

EURISCO provides the scientific community and plant breeders with information about more than 2 million accessions of crop plants and their wild relatives, preserved ex situ by approximately 400 collections from 43 member countries. EURISCO also assists its member countries in fulfilling legal obligations and commitments, e.g. with respect to the ITPGRFA, the FAO Second Global Plan of Action for PGRFA, or the CBD (Weise et al. 2017; Kotni et al. 2023).

(iii) In situ conservation and use of CWR.

CWR can be conserved both ex situ (out of place) in genebanks, field collections and botanical gardens, and in situ (in place) in their natural habitat. Whereas ex situ conservation is essential both to prevent the loss of CWR genetic diversity and to facilitate the use of their diversity in crop breeding, the conservation of populations in their natural environment is necessary for the maintenance of the genetic diversity at the population level, also ensuring continued evolution, which could lead to new, adaptive traits. Conservation of genetic diversity of Mesoamerican wild relatives of some of the world's most important crops is particularly urgent, as up to 35% of taxa are threatened with extinction according to the International Union for Conservation of Nature (IUCN) Red List (Tobón-Niedfeldt et al. 2022). This might not currently be as dramatic in the case of berries, although three species have been described at risk in Canada (Migicovsky et al. 2022).

(iv) Promotion of on-farm conservation and management.

On-farm conservation involves the maintenance of traditional crop cultivars by farmers within traditional agricultural, horticultural or agri-silvicultural cultivation systems, resulting in a "conservation by cultivation". Farmers hold an important role in deciding whether to keep maintaining the material/s and provide the knowledge about its/their management and uses. Populations conserved on farms continue evolving in response to changes in local biotic and abiotic interactions as well as a result of the selection by custodian farmers.

(v) Promote the use of the European Network for the Evaluation of PGRFA (EVA).

In collaborative projects involving public and private sector partners and through participatory plant breeding actions EVA (https://www.ecpgr.org/eva) is generating standardized evaluation data (both phenotypic and genotypic data) for numerous crop accessions and landraces available in European genebanks. EVA is implemented through crop-specific networks, covering both cereals (wheat, barley and maize) and vegetable crops (carrot, lettuce, pepper). The EVA crop networks operate in six steps: (1) selection of accessions, (2) experimental and scoring protocols, (3) seeds multiplied and distributed through SMTA, (4) evaluation by partners in different environments across Europe, (5) genotyping and (6) phenotypic data are collected and stored in a EURISCO-EVA database during an embargo period. Cooperation agreements ensure privileged access to data, while material is exchanged through SMTA and can be used for further development and eventual commercial use. So far, there are no ECPGR EVA networks for vegetatively propagated crops or berries, although strawberry could be a good model.

Implementation of Nagoya protocol in the EU

As mentioned earlier, the Nagoya Protocol enforces the third aim of the CBD, which focuses on ensuring fair and equitable sharing of the benefits derived from the use of genetic resources. The CBD recognizes countries' sovereign rights over their natural resources, and ABS under the Nagoya Protocol is built on this principle. The EU, along with 193 countries, is a party to the CBD and legally bound to the Nagoya Protocol. Therefore, as established in the Protocol, access to genetic resources requires obtaining "Prior Informed Consent" (PIC) and negotiating "Mutually Agreed Terms" (MAT). Individual countries regulate access and benefit sharing subjected to confidential contractual agreements. The EU oversees compliance and ensures that benefits from genetic resources are shared fairly and equitably with the country providing these resources according to two ABS Regulations: Regulation (EU) No 511/2014 and Implementing Regulation (EU) 2015/1866. Article 4 of the EU-ABS Regulation requires users to exercise due diligence to verify that genetic resources or traditional knowledge associated with them have been accessed in accordance with the Nagoya Protocol. Users must demonstrate compliance at two key stages: during research funding and at the final product development stage.

The unique nature of PGRFA implies they might be subjected to access rules that are distinct from general ABS regulations applicable in a given provider country. There are various scenarios under which PGRFA can be obtained and utilized, and the applicability of rules depends on whether the country where the genetic resources are accessed is a Party to the Nagoya Protocol and/or to ITPGRFA, and the intended type of use. Table 1 summarizes the conditions for applicability of the EU ABS Regulation. For example, in the case of genetic resources covered by the multilateral system (MLS) of the ITPGRFA (included in Annex I of the Treaty), they are not in the scope of the EU ABS Regulation. However, species listed in Annex I of the ITPGRFA may be in scope if they are not 'under management and control of Parties and in the public domain', but be found in 'in situ-conditions' (e.g. landraces/farmer 's cultivars from farmer 's fields). In those cases, if the provider country is a contracting Party to the Nagoya Protocol, the EU ABS regulation is applicable, and PIC and MAT may be required.

The Nagoya Protocol and the EU ABS Regulation emphasize that their implementation should be mutually supportive with other international agreements, as long as these agreements align with the objectives of the CBD and the Nagoya Protocol. One remarkable such situation might arise when the genetic resource has been registered by the International Union for the Protection of New Varieties of Plants (UPOV). The UPOV Convention grants breeders of new plant cultivars an intellectual property right: the breeder's right, allowing them to control propagation for commercial use and collect royalties. The UPOV also provides a breeders' exemption, ensuring that protected cultivars can be used freely for breeding new cultivars. The EU ABS Regulation respects UPOV obligations, and due diligence requirements do not conflict with the use of material protected under UPOV plant breeders' rights from UPOV member countries.

Different levels of plant variety regulation and evaluation: from UPOV to USA and EU regulations

Intellectual property (IP) protection for new plant cultivars is a critical area of regulation, ensuring that breeders can legally safeguard and monetize their innovations. The EU and the USA have established robust legal frameworks designed to balance the interests of plant breeders, farmers, and the public.

Table 1 Overview of conditions for applicability of the EU access and benefit sharing (ABS) regulation

		Within scope[a]	Outside of scope
Geographic scope (provenance of GenRes[b])	Access in	Areas within a country's jurisdiction	Areas beyond national jurisdiction or covered by Antarctic Treaty System
	Provider country is	Party to the Nagoya Protocol	Not a party to the Nagoya Protocol
	Provider country has	Applicable access legislation	No applicable access legislation
Temporal scope	Access	On or after 12 October 2014	Before 12 October 2014
Material scope	Genetic Resources	Not covered by a specialised international ABS instrument	Covered by a specialised international ABS instrument (e.g. ITPGRFA)
		Non-human	Human
		Obtained as commodities but subsequently subject to R&D	Used as commodities
	Utilisation	R&D on genetic and /or biochemical composition	No such R&D
Personal scope		Natural or legal persons utilising GenRes	Persons only transferring GenRes or commercialising products based on it
Geographic scope (Utilisation)	Research and Development	Within the EU	Exclusively outside the EU

Source: Guidance document on the scope of application and core obligations of Regulation (EU) No 511/2014, p. 31

[a]To be within the scope, all conditions must be fulfilled

[b]GenRes = Genetic Resource; to be read as also including 'traditional knowledge associated with genetic resources', where appropriate

Both the EU and USA follow the guidelines set by the International Union for the Protection of New Varieties of Plants (UPOV) for DUS (Distinctness, Uniformity, and Stability) testing. These guidelines ensure that the testing process is harmonized and consistent with international standards, making it easier for breeders to apply for plant variety protection in multiple countries. While both systems aim to encourage innovation and protect breeders' rights, the mechanisms and scope of protection differ significantly between the two jurisdictions. The EU's Community Plant Variety Rights (CPVR) system, based on the International Convention for the Protection of New Varieties of Plants of the UPOV (1991 Act) offers a unified and straightforward process with a strong emphasis on facilitating further breeding through the breeders' exemption. In contrast, the USA operates under a dual system consisting of (1) the Plant Variety Protection Act (PVPA), which also implements the UPOV treaty, and (2) the Plant Patent Act of 1930 alongside Utility Patents. This dual approach provides breeders with a broader range of options, with varying levels of protection and complexity. Understanding these differences is crucial for breeders operating in or targeting both markets, ensuring they can navigate the regulatory landscape effectively and maximize the protection of their innovations. This section explores the regulatory and legislative differences in IP protection for new plant cultivars in the EU and the USA, providing a comprehensive analysis of each system's features, processes, and implications for breeders.

Historical context and legal frameworks

European Union

In the EU, the rules established specifically in each country for the inclusion of cultivars in national catalogues coexist with a global regulation for the whole of the EU. The EU's approach to plant variety protection (PVP) is primarily governed by the Community Plant Variety Rights (CPVR) system, established under Council Regulation (EC) No 2100/94 and articulated by (EC) 874/2009, and (EC) 1768/95 as amended by EC Regulation 2605/98 that implement rules on the farmers' exemption.

This regulation created a unified system allowing breeders to obtain PVP across all member states through a single application. The CPVR system is administered by the Community Plant Variety Office (CPVO; https://cpvo.europa.eu/en), which oversees the granting of rights, ensuring consistency and accessibility across all 27 member states of the EU.

United States

In the USA, plant variety protection is governed by the Plant Variety Protection Act (PVPA) of 1970, administered by the Plant Variety Protection Office (PVPO; https://www.ams.usda.gov/services/plant-variety-protection) under the United States Department of Agriculture (USDA) and articulated by the Plant Variety Protection Act and Rules of Practice. Additionally, breeders can also seek protection through the patent system, specifically under Plant Patent Act (PPA), enacted in 1930, (General Information About 35 U.S.C. 161 Plant Patents | USPTO), which apply specifically to asexually reproduced plants, and Utility Patents, both issued and administered by the United States Patent and Trademark Office (USPTO; https://www.uspto.gov/). This dual system offers different levels of protection and requirements, providing breeders with options depending on their needs and the nature of the cultivar.

Scope of protection

European Union

The CPVR system grants breeders exclusive rights to produce and market the protected cultivar within the EU, provided it meets the distinctness, uniformity, and stability (DUS) criteria. These rights extend to:

- Harvested material (plants or parts) obtained through unauthorized use of propagating material.
- Essentially Derived Varieties (EDVs), which differ from the original cultivar by a limited number of traits but retain its essential characteristics. EDVs can arise from natural, chemical, or physical mutations, as well as biotechnological methods like transgenesis, RNAi, and new genetic techniques (e.g., cisgenesis, gene editing). In Europe, however, EDVs produced through biotechnological methods are subject to strict GMO regulations (Directive 2001/18/EC), a significant barrier due to limited public acceptance.
- Cultivars that are not clearly distinguishable from the protected cultivar.

Protection lasts for 25 years from the date of grant, or 30 years for vines and trees.

United States

The PVPA grants breeders exclusive rights to produce, sell, import, and export the protected cultivar. This protection covers:

- Propagating material, such as seeds and cuttings.
- Harvested material from unauthorized propagation.

Additionally, utility patents offer broader protection for any new and useful process, machine, manufacture, or composition of matter, or any new and useful improvement thereof. This includes genetically modified traits and biotechnological innovations. The duration of a PVPA certificate is 20 years (25 years for trees and vines), while utility patents generally last 20 years from the filing date.

Criteria for protection

European Union

To qualify for CPVR, a plant cultivar must meet the following criteria:

- Distinctness: The cultivar must be clearly distinguishable from any other known cultivar.
- Uniformity: The cultivar must be sufficiently uniform in its relevant characteristics.
- Stability: The cultivar must remain true to its description after repeated propagation.
- Novelty: The cultivar must not have been sold or disposed of to others for exploitation more than 1 year before the filing date within the EU, or 4 years outside the EU (6 years for trees and vines).
- Have an appropriate denomination.

United States

Under the PVPA, a cultivar must be:

- New: Not sold or otherwise disposed of for more than 1 year prior to the application in the USA, or more than 4 years abroad (6 years for trees and vines).
- Distinct: Clearly distinguishable from all other publicly known cultivars.
- Uniform: Showing uniformity in its essential characteristics.
- Stable: Remaining true to its essential characteristics after repeated propagation.

For utility patents, the criteria include:

- Novelty: The invention must be new.
- Non-obviousness: The invention must not be obvious to someone with ordinary skill in the relevant field.
- Utility: The invention must be useful.

Application and examination process

European Union

Applications for CPVR are submitted to the CPVO and involve the following steps:

- Submission: Detailed variety description and technical questionnaire.
- Formal Examination: Verification for completeness and compliance.
- Technical Examination: DUS (distinctness, uniformity, and stability) tests conducted by designated offices.
- Objections and Appeals: Applicants can appeal decisions, and third parties can file objections.
- Granting: If all criteria are met, CPVR is granted and published.

Previously taken DUS test reports can be accepted from examination offices in other EU member states.

United States

Applications under the PVPA are submitted to the PVPO and involve:

- Submission: Including a detailed cultivar description and a seed sample.
- Examination: The PVPO evaluates novelty, distinctness, uniformity, and stability. Field trials and comparative tests may be conducted.
- Publication: The application is published, allowing for objections.
- Issuance: A certificate is granted upon approval.

In the USA, it is generally not possible to directly use DUS test reports from other countries for cultivar registration. PVPO requires the DUS tests to be conducted according to their specific guidelines and standards. Field trials can be conducted by the applicant, breeder, agent, or someone contracted by the applicant.

For utility patents, the process involves:

- Submission: Filing a detailed patent application with claims defining the invention.
- Examination: The USPTO examines the application for compliance with patentability requirements.
- Prosecution: Interaction between the applicant and examiner to address any issues.
- Granting: Upon approval, the patent is granted and published.

Both the EU and U.S. systems allow online applications and support the UPOV PRISMA tool for PVP applications (https://www.upov.int/upovprisma/en/index.html).

Enforcement and infringement

European Union

CPVR holders can enforce their rights through national courts in member states. Infringement actions can lead to injunctions, damages, and the destruction of infringing material. The CPVO also provides a central role in coordinating enforcement actions and facilitating cooperation between member states.

United States

Infringement of PVPA rights can lead to civil suits, with remedies including damages and injunctive relief. For utility patents, enforcement is typically through the federal court system, where remedies include damages, injunctions, and, in some cases, treble damages for wilful infringement.

Breeders' exemption and farmers' Privilege

A key distinction between IP protection for new plant cultivars in the EU and the USA lies in the breeders' exemption and the farmer's privilege, both part of the UPOV Convention.

In the EU, the breeders' exemption allows breeders to use protected plant cultivars for further breeding and research without needing the rights holder's permission. This encourages the development of new cultivars by enabling the use of protected cultivars as parent lines, either through direct crossing or by incorporating wild materials. In contrast, in the USA, breeders require the rights holder's consent to use protected cultivars for breeding. According to the International Institute for Sustainable Development (IISD) in its "Sustainability Toolkit for Trade Negotiators," the «Breeders' exemption allows new cultivars to more quickly be developed—cultivars that may be crucial in helping farmers adapt to changing climatic conditions. Plants may be improved or modified, among other objectives, to cope with climate change by enhancing their resistance to environmental stresses such as heat, cold, salinity and drought», contributing to the sustainability of agriculture.

The EU also includes a farmers' privilege, which allows farmers to save and reuse seeds from their own crops under specific conditions, though compensation to the rights holder may be required. This privilege is particularly useful for smallholder farmers who rely on saved seed for the next planting season. In some cases, they may also exchange or resell these seeds locally, enhancing seed security at the community level.

In the USA, the PVPA provides a research exemption similar to the EU, allowing research on protected cultivars but not their use for further breeding without the rights holder's consent. The scope of the farmers' privilege under the PVPA is also more restrictive than in the EU: farmers are permitted to save seeds for replanting only on their own farms, but they cannot sell those seeds for reproductive purposes.

For cultivars covered by utility patents—which offer broader protection for genetically modified traits and other biotechnological innovations—there is no farmers' privilege in the USA. All uses of patented cultivars must comply with the patent holder's terms, which severely limits farmers' ability to save and reuse seeds.

Berry genetic resources in Europe: conservation and utilization

A survey was recently conducted to gather data on global conservation programs for berry crops. The report highlighted the importance of berries as a source of nutrients and antioxidants for indigenous populations worldwide for millennia and the need for the continuation and expansion of berry conservation and germplasm characterization (Hummer et al. 2023a, b). Detailed information on European collections of Berry Genetic Resources (BGR) is available in the European Search Catalogue for Plant Genetic Resources (EURISCO). This section provides an overview of BGR conservation and characterization efforts in Europe.

Berry genetic resources in Europe

In botanical terminology, a berry is a simple fruit with seeds and pulp produced from the ovary of a single flower, in which the entire pericarp remains juicy or at least fleshy when ripe (Kiger et al. 2001). Traditionally, and in everyday language, the term "berry" has different meanings, typically referring to small, sweet fruits. Under both definitions, berries include blueberries, cranberries, lingonberries, and many other fruits of the heather family, as well as gooseberries (*Ribes L.*), goji berries (*Lycium L.*), and elderberries (*Sambucus L.*). Notably, currants (*Ribes L.*), such as blackcurrants, red currants, and white currants, are botanical berries, despite their common names not including the term "berry." Conversely, several fruits commonly called berries are not botanical berries. Blackberries, raspberries, and strawberries are aggregate fruits, containing seeds from different ovaries of a single flower.

Cultivated strawberries, raspberries, and several other berries belong to the Rosaceae family and the Rosoideae sub-family (Potter et al. 2007; Xiang et al. 2017). *Fragaria* (strawberries) and *Rubus* (raspberries) exhibit significant genetic diversity and varying ploidy levels, particularly in *Rubus*, which includes over 500 species. Strawberries (*Fragaria* spp.) are the most economically important berry crop in the EU. Their widespread cultivation has led to their inclusion in the Annex 1 list of the ITPGRFA. Alongside strawberries, the production of other berries, especially raspberries and blueberries, is rapidly increasing in the EU, reflecting a growing market demand.

Domestication of these cultivated species has led to a reduction in both morphological and genetic diversity, with modern cultivars adapted to specific regions being genetically similar (Gil-Ariza et al. 2009; Horvath et al. 2011; Hardigan et al. 2021; Zurn et al. 2022; Hummer et al. 2023a, b). Therefore, maintaining the genetic variability available in genebanks is crucial to prevent the loss of genetic diversity. Several EU projects, including COST Actions 836 and 863, the European AIR project, EU GENBERRY, RIBESCO, EUBerry, and GoodBerry, have surveyed berry genetic resources in genebanks. However, there is still a need to update these resources and promote harmonized characterization and evaluation within AEGIS and EURISCO. In March 2019, the new Berries Working Group was established under the ECPGR, with 51 members from 22 European countries to coordinate activities through long-term network cooperation (https://www.ecpgr.org/working-groups/berries). As a result, documentation on berry genetic resources in Europe was successfully updated and harmonized within the ECPGR Activity Grant Scheme—Phase X. The project documented 4061 berry genetic resource accessions, including 1507 of *Fragaria*, 578 of Rubus, and 213 of *Vaccinium,* which are now available to EURISCO National Focal Points.

A limited number of gene banks in Europe maintain large collections of strawberry genetic resources, including cultivars and also a significant number of *Fragaria* wild species. The Fruit Genebank in the JKI Institute for Breeding Research on Fruit Crops in Dresden-Pillnitz, maintains 190 cultivars of *F.×ananassa* and 300 wild accessions of 22 species and hybrids of *Fragaria*. Many accessions were collected during field expeditions or transferred from the significant private collection of "Prof. Staudt" (Olbricht 2017; Wolfsteiner et al. 2021) or the US Department of Agriculture ARS, Corvallis. Another large collection of *Fragaria* wild species can be found at the Andalusian Institute of Agricultural and Fisheries Research and Training (IFAPA), Málaga, Spain. IFAPA's collection is composed of about 500 accessions of old and new cultivated strawberry (*F.×ananassa*), about 300 wild accessions of the genus *Fragaria* (mainly *F. vesca*, *F. chiloensis* and *F. virginiana*) and related genera, as well as other sets of interspecific hybrids and working breeding lines. A subset of this collection representing the diversity of cultivated strawberry has recently been genetically and morphologically characterized (Muñoz et al. 2024). A third large collection can be found at the company Hansabred GmbH & Co.KG., Germany. Hansabred's collection comprises 302 cultivars, 889 wild accessions representing all known *Fragaria* species (Staudt taxonomy), and 74 interspecific hybrids, as well as an additional 26 accessions of related genera (*Potentilla*, *Duchesnea*, *Sanguisorba*, *Alchemilla*). Other *F.×ananassa* collections are maintained by other public and private institutions involved in breeding programs, such as INRAE and Invenio (Prohaska et al. 2024b).

Conservation and accessibility

The primary method for maintaining berry germplasm ex situ is through field plantings or by growing potted plants in protected environments, such as shade houses (Hummer et al. 2023a, b), where they are readily available for thorough characterization, evaluation, and distribution. As most temperate berry species are highly heterozygous, they require vegetative propagation to produce plants genetically identical to the parent plant. Additionally, field preservation entails challenges from pests, diseases, and abiotic hazards, requiring significant input in land, labour, and management. Global warming and warmer summers are one of the most detrimental effects of climate change, affecting the entire plant life cycle (Lippmann et al. 2019). Temperature is inherently challenging to control in open field or shaded conditions while maintenance in controlled environments is even more expensive.

A global conservation strategy for strawberries was developed by an international team of experts based on a worldwide survey of genetic resources (Hummer 2008). Strawberry collections face specific challenges, such as contamination by runners and virus spread through insect vectors. Ideally, these collections should be stored as potted plants under insect-proof screens with an active pest management program. Additionally, backup collections are essential to safeguard against disease outbreaks or environmental disasters. These backups are maintained at various locations in field collections, greenhouses, frigo-conserved in vitro cultures, or through cryopreservation. Notably, the ECPGR Berries WG project demonstrated that only for *Fragaria*, in vitro culture and cryopreservation significantly contribute to creating duplicates. Using a PVS2 vitrification method with cold acclimation, cryopreservation has shown an average recovery rate of 87.23% for strawberry cultivars and 85.34% for wild species, underscoring its advantages for long-term security against disease and environmental loss (Höfer 2016).

Other berry species (*Rubus*, *Ribes*, *Vaccinium*) are typically conserved in ex situ field collections, whereby the growing conditions, and the type and frequency of replanting, depend very much on the genus. The ECPGR Berries Working Group aims to develop berry-specific standards for genebank management.

Utilization of BGR in agricultural research and breeding

Strawberry

Strawberry research and breeding are focused on improving yield, disease resistance, fruit quality, and environmental adaptation. European breeders have made significant strides in developing new strawberry cultivars with enhanced performance. Techniques such as quantitative trait locus (QTL) mapping, marker-assisted selection (MAS) and genome-wide association studies (GWAS) have accelerated the identification of desirable loci underlying important agronomic and quality traits worldwide (Whitaker et al. 2020; Senger et al. 2022).

A primary focus in Europe has been the development of more resilient cultivars to common diseases like powdery mildew and *Verticillium* wilt (Faedi et al. 2002; Sargent et al. 2019; Cockerton et al. 2021; Lynn et al. 2024). QTL mapping and GWAS in strawberry have also resulted in identifying new markers, loci and candidate genes associated with other important agronomic and fruit quality traits (Vallarino et al. 2019; Castillejo et al. 2020; Labadie et al. 2022; Muñoz et al. 2023, 2024; Prohaska et al. 2024b, 2024a; Rehman et al. 2024; Pott et al. 2020). Research also emphasizes sustainable farming practices. Integrated pest management (IPM) and organic farming methods are being explored to reduce the reliance on chemical pesticides. Additionally, breeding programs are developing cultivars that require fewer inputs, such as water and fertilizers, making strawberry cultivation more environmentally friendly (Ariza et al. 2021; Marcellini et al. 2023).

Raspberry

Raspberry (*Rubus idaeus*) is another important berry crop in Europe, valued for its unique flavour and nutritional content. Breeding and research focuses on improving yield and fruit quality, extending the harvesting season, and enhancing pest resistance (Foster et al. 2019).

Traditional raspberry cultivars have a short harvesting window. To overcome this, an important goal of breeding programs is the development of everbearing (primocane-fruiting) cultivars that produce fruit over an extended period (Hernández-Bautista et al. 2018). This not only increases the availability of fresh raspberries but also boosts profitability for growers. Research also focuses on improving tolerance to several pests and diseases, including raspberry beetle and *Phytophthora* root rot (Graham et al. 2011). The incorporation of resistance genes from wild raspberry species has shown promising results (Jones et al. 2000; Hall and Kempler 2011). Additionally, while consumer demand continues to favour raspberries with superior flavour and nutritional content (Kempler et al. 2012), genetic and metabolomic approaches are also being implemented to identify cultivars with enhanced taste and health properties (Paterson et al. 2012; Durán-Soria et al. 2021). Breeding programs prioritize those traits that lead to cultivars rich in antioxidants, vitamins, and minerals. Sensory evaluations and biochemical analyses are integral to these efforts, ensuring that new cultivars meet consumer expectations for both flavour and nutritional value.

Blueberry

Blueberries (*Vaccinium spp*.) have gained popularity in Europe due to their health benefits, particularly their high antioxidant content, and versatility. Research and breeding programs aim at improving fruit quality, yield, and adaptability to European climates (Retamales and Hancock 2018). Originally native to North America, blueberries require acidic soil and specific climatic conditions. European researchers focus on developing cultivars that can thrive in different European regions. Breeding programs explore interspecific hybridization to introduce traits such as cold hardiness and soil adaptability (Lobos and Hancock 2015). Enhancing the yield and quality of blueberries is a primary objective too. This includes developing cultivars with larger fruit size, improved sweetness, and extended shelf life. Advanced phenotyping techniques and molecular markers are used to select these traits efficiently (Babiker et al. 2023; Bhatt and Debnath 2021). Research efforts are also dedicated to uncover the genetic basis of health-promoting compounds accumulation, with the aim of breeding cultivars that offer enhanced nutritional profiles. This work aligns with the growing demand for functional foods. The recent construction and analysis of the first pangenome for both blueberry and cranberry will inform future research and allow the identification of potential targets for breeding (Yocca et al. 2023).

Blackberry

Blackberry (*Rubus* L. subgenus *Rubus* Watson) is a high-value crop appreciated by consumers for its flavour, visual appeal, and health benefits (Nile and Park 2014; Cosme et al. 2022), and by growers for its high market value. Blackberry cultivars are used for fresh market, processing (e.g., freezing, drying, canning), and home gardening. It is the fourth most important berry after strawberry, blueberry, and raspberry, and its significance continues to grow due to the development of new cultivars with improved traits, particularly enhanced fruit quality and the introduction of everbearing (re-flowering) cultivars. Historically Europe and the Americas have been the top blackberry producers (FAOSTAT. http://www.fao.org/faostat/en/?#data/QC 2017). Over the past decade, advances in cultivar types have spurred rapid growth in global blackberry cultivation and consumer demand. The introduction of the new cultivars, such as everbearing cultivars, combined with advanced production methods, has allowed for year-round availability and expansion into new growing regions, including tropical and subtropical environments such as Australia, Southern Europe, Northern Africa, and Central and South America, thus responding to the increasing market demand.

Growing market demand has motivated research groups and companies, previously focused only on raspberries, to invest in new breeding programs aimed at developing innovative blackberry cultivars (Foster et al. 2019; Chauhan et al. 2022). Recently, an international consortium published a chromosome-level genome assembly for blackberry, which is expected to advance genetic and genomic research, further strengthening applied breeding programs (Brůna et al. 2023). The major breeding targets include improving fruit quality and yield, extending the cropping season, enhancing storage and processing properties, increasing resistance to pests and diseases, and ensuring adaptation to various growing environments. Specific traits are also targeted based on whether the berries are intended for fresh markets, processing, or home gardens.

Berry genetic resources in Europe: current state of PVRs

Berry plant variety rights (PVR) in Europe are managed by the CPVO. Technical examinations (DUS tests) are conducted by designated examination offices specific for each berry crop. For blueberries, there are two offices: one in Portugal for low-chilling cultivars and another in Poland for high-chilling cultivars. For raspberries and blackberries, the offices are in Germany for all types, in Poland for Northern European types, and in Canada for Northern US types. For strawberries, the offices are located in Portugal, Spain, Germany and Poland, covering annual and biannual cultural systems. CPVO applications and titles currently in force are publicly available through the CPVO Register database. When interrogated for the four berry crops—strawberries, raspberries, blueberries, and blackberries—we retrieved all PVR applications at the various stages of the evaluation process (Table 2):

Table 2 Number and status of Plant Variety Rights (PVRs) for each crop extracted from the Community Plant Variety Office (CPVO) Register

Berry	Strawberry	Blueberry	Raspberry	Blackberry
Searched term	*Fragaria*	*Vaccinium*	*Rubus*	*Rubus* subg. *Rubus*
Number of results	Granted: 385	Granted: 151	Granted: 130	Granted: 36
	Active: 101	Active: 126	Active: 77	Active: 53
	Terminated: 265	Terminated: 19	Terminated: 55	Terminated: 11
	Refused: 16	Refused: 7	Refused: 14	Refused: 12
	Withdrawn: 101	Withdrawn: 53	Withdrawn: 58	Withdrawn: 31
	Total: 868	Total: 356	Total: 334	Total: 143
Retrieved species	*Fragaria × ananassa* Duchesne ex Rozier *Fragaria iinumae* Makino x *F. vesca* L *Fragaria vesca*	*Vaccinium corymbosum* L *Vaccinium* L *Vaccinium corymbosum* L. x *V. darrowii* Camp *Vaccinium virgatum* Aiton *Vaccinium angustifolium* Aiton x *V. corymbosum* L *Vaccinium vitis*-idaea L	*Rubus idaeus* L *Rubus occidentalis* L *Rubus chamaemorus* L *Rubus idaeus* L. x *R. parvifolius*	*Rubus* subg. *Rubus*

- Granted Rights: The PVR has been granted and is currently active.
- Active Applications: A PVR has not yet been granted, but the CPVO is in the process of examining the application.
- Terminated Rights: The PVR was previously granted but is no longer active (e.g., due to unpaid renewal fees or reaching the maximum time limit).
- Refused Applications: The CPVO has denied the request for PVR registration.
- Withdrawn Applications: The applicant has withdrawn their PVR request.

The following analysis focuses exclusively on granted rights and active applications for the four berry crops. Though the protection lasts 25 years from the date of grant for strawberries or 30 years for blueberries, raspberries and blackberries (5 years extension to woody small fruits as per Regulation 2021/1873), the analysis of granted rights provided in the next section focuses on the last 20 years (from 2004 onwards). At the time of the analysis, no PVR had been granted yet for 2024, therefore the year 2024 is not shown in the figures.

Strawberry PVRs

After curating the initial 868 results, we detected a total of 385 different strawberry cultivars currently under protection (Fig. 1) and 101 strawberry cultivars with active applications (Fig. 2).

Granted PVRs are held by 73 different organisations, with the majority being from the EU (53 EU vs. 20 non-EU) and private entities (57 private vs. 16 public). In the first decade of the twenty-first century, the number of granted PVRs remained around ten per year, with a prevalence of EU organisations (Fig. 1). Non-EU organisations surpassed EU ones only in 2008, largely due to a significant number of releases by the University of California. A notable increase in the number of granted PVRs occurred in the second decade of the 2000s, from both EU and non-EU organisations. This phenomenon could be explained by the consolidation of several new EU and non-EU strawberry breeding programmes, allowing the diversification of production systems and the introduction of new cultivars with specific characteristics for different environments and cultivation systems. This period marked the end of the dominance of a few cultivars, opening up opportunities for crop diversification through innovations introduced by emerging breeding programs.

The number of granted PVRs shows a peak in 2019 (Fig. 1), particularly due to a higher number of PVRs granted to private organisations based in the EU. It is interesting to note that the majority of these organisations come from Spain and Italy, and have filed applications only in 2019. It reflects the fact that those two countries have more strawberry breeding programs

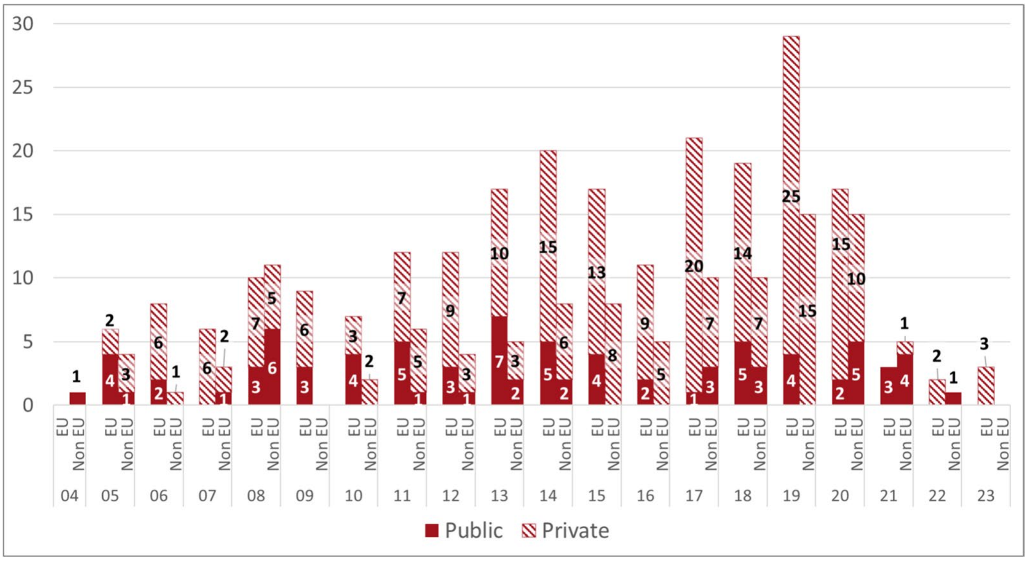

Fig. 1 Granted Plant Variety Rights (PVRs) for strawberries by EU vs. non-EU, and public vs. private organizations over the past 20 years (2004–2023)

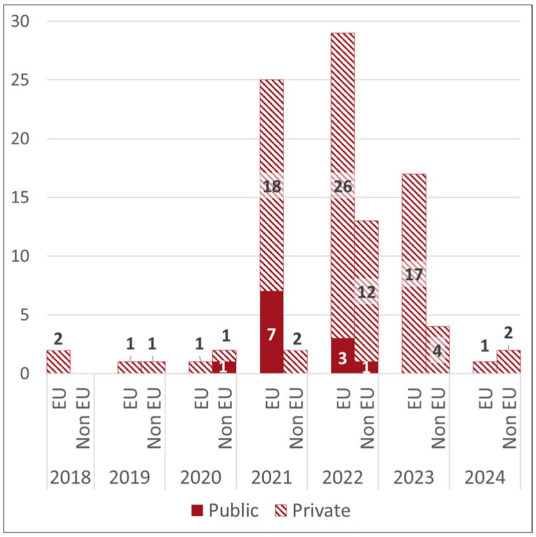

Fig. 2 Active Plant Variety Rights (PVR) applications for strawberries by EU versus non-EU, and public versus private organizations

than other EU countries, including small-scale programs from companies and public institutions.

The number of granted PVRs reaches a total of 136 for the period 2017–2020. Although being very extensive and diversified, only a small number of all these new cultivars might have had an actual penetration in some EU production areas. Differentiation can certainly offer opportunities for farmers but the commercialisation of interesting material is challenging and requires an appropriate nursery and efficient distribution system. About one third of the granted PVRs between 2017 and 2020 belong to Driscoll's (29 PVRs) and Plantas de Navarra, now Planasa (16 PVRs), illustrating a strategy to penetrate the EU market with a high number of new cultivars.

Active PVR applications come from 38 different organizations, reflecting a growing diversification in breeding efforts. Again, most of the active PVR applications have been submitted by EU-based organizations (24 EU vs. 14 non-EU), with a strong predominance of private entities (32 private vs. 6 public). This continues a long-standing trend in the strawberry sector, where private companies have consistently invested in research and held the majority of PVRs for over 20 years. Driscoll's remains the market leader, holding over twice as many PVRs (57) compared to other key players such as Planasa (23), the Consorzio Italiano Vivaisti (C.I.V.) (23), and Flevo Berry Holding (21).

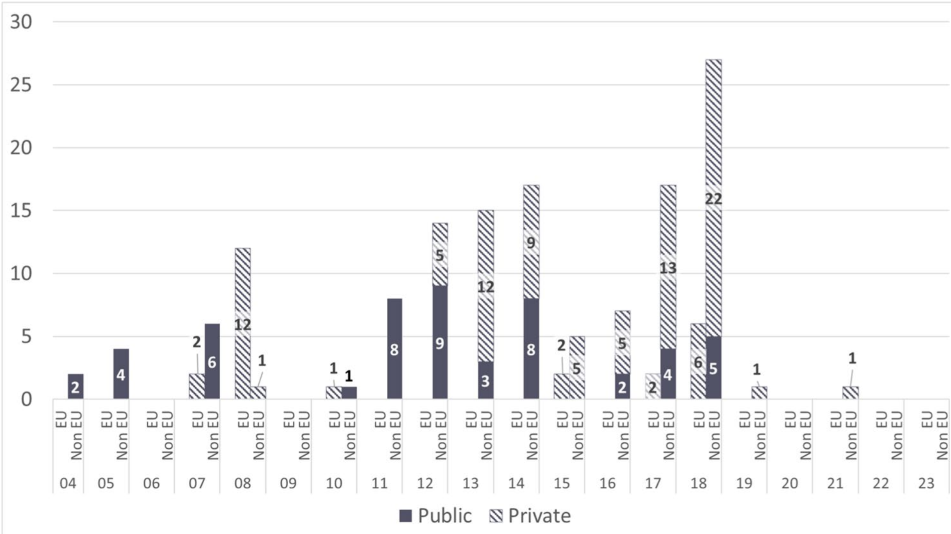

Fig. 3 Granted Plant Variety Rights (PVRs) for blueberries by EU versus non-EU, and public versus private organizations over the past 20 years (2004–2023)

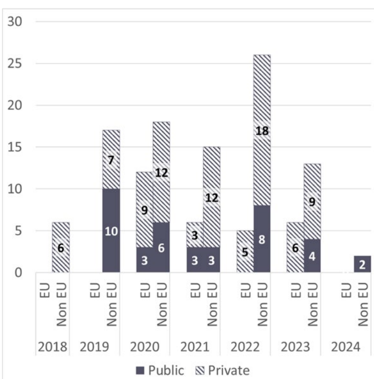

Fig. 4 Active Plant Variety Rights (PVR) applications for blueberries by EU versus non-EU, and public versus private organizations

Blueberry PVRs

From the initial 356 results, data curation yielded 151 distinct blueberry cultivars currently under protection (Fig. 3) and 126 active PVR applications (Fig. 4).

Granted PVRs belong to 26 different organisations, the majority of them being non-EU (19 non-EU vs. 7 EU) and private organisations (18 private vs. 8 public). Blueberry innovation is clearly dominated by organisations from the US and Australasia, with key players such as the Florida Foundation of Seed Producers, Fall Creek Farm and Nursery, Driscoll's, The New Zealand Institute for Plant and Food Research, and Costa. The 7 EU organisations—all private entities from Spain or the Netherlands—have been granted PVRs, accounting for only 25 out of the 151 protected cultivars. This suggests a need for more blueberry breeding programs within Europe. Notably, the peaks in EU blueberry PVRs in 2008 and 2018 were due to single organizations successfully submitting multiple PVRs in a single year, specifically eleven by Royal Berries in 2008 and six by Planasa in 2018.

The active PVR applications are held by 27 different organisations. As with granted PVRs, the majority of applications have been submitted by non-EU entities (20 non-EU vs. 7 EU), and most come from private organisations (19 private vs. 8 public). However, as shown in Fig. 4, there has been a noticeable increase in applications from EU organisations. This growth is attributed to a rising "blueberry fever" across Europe, with new breeding programs such as Fruit Vision in the Netherlands, Agromolinillo in Spain, and Fondazione Edmund Mach in Italy. Historically, blueberry cultivation was largely limited to northern regions, focused on 'Northernbush' cultivars. However, the development of cultivars adapted to warmer climates ('Southernbush') and the adoption of more efficient soilless cultivation systems have expanded blueberry production to areas where it was previously non-existent. In some regions, blueberries are now partly replacing strawberries and even raspberries, contributing to a diversification of berry cultivation. Looking ahead, despite this recent growth in EU-based breeding programs, the market is expected to remain primarily driven by non-EU organisations, which have continued to submit a significantly higher number of PVR applications in recent years.

The public/private ratio of PVR holders indicates a prevalence of private actors. However, unlike the strawberry market, this situation in the blueberry market was the opposite 20 years ago, with private market players innovating less and innovation largely tied to public institutions. The analysis of active PVR applications confirms this shift, with private institutions becoming the main drivers of innovation and are likely to continue leading for the next upcoming years (Fig. 4).

The limited importance of blueberry in the EU market in the past, confined to a few European regions, has certainly circumscribed the interest to develop specific breeding programs and public initiatives focused on searching, characterizing, conserving, and improving the genetic resources available for this species. As a result, the genetic diversity of blueberries in Europe remains particularly narrow. This lack of early interest by most EU companies also explains why, when the demand for blueberry cultivation in Europe increased, priority was given to the diffusion of cultivars developed by international companies that had long recognized the potential for the species' global expansion.

Public and private consortiums, such as the Horizon 2020 project BreedingValue, play a crucial role in addressing this gap. These initiatives allow the characterization of the available germplasm, but above all, the development of new genotyping and phenotyping technologies. Such advancements are essential for boosting the breeding capacity of EU organisations, enabling them to develop competitive new cultivars in the near future that can hold their own on the global stage.

Raspberry PVRs

From the 334 initial results, we isolated after data curation a total of 130 different raspberry cultivars

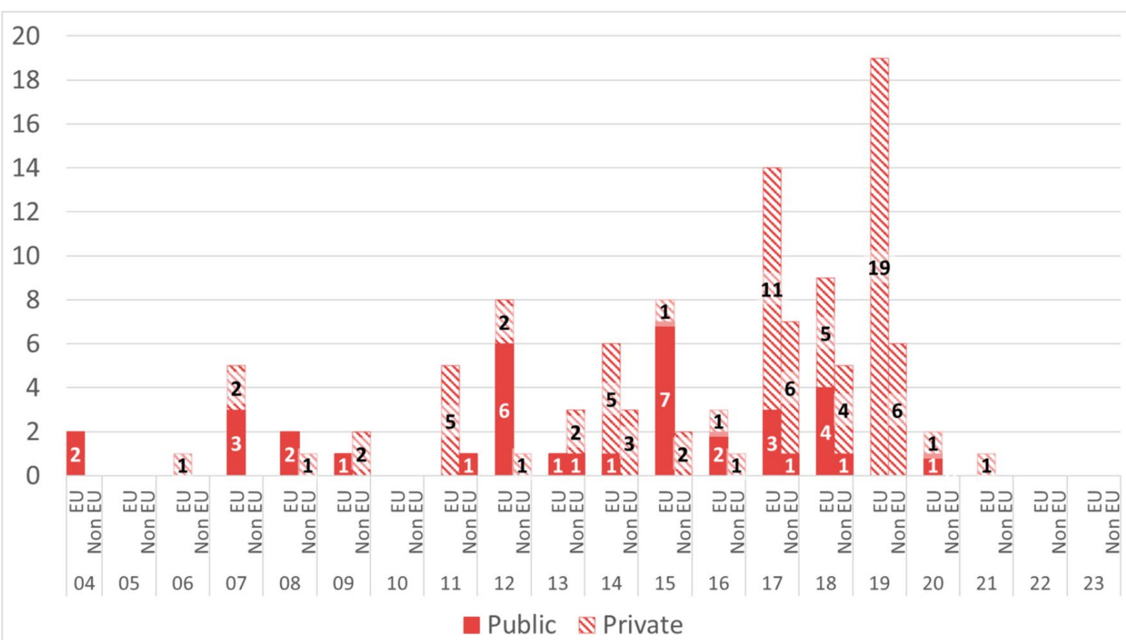

Fig. 5 Granted Plant Variety Rights (PVRs) for raspberries by EU versus non-EU, and public versus private organizations over the past 20 years (2004–2023)

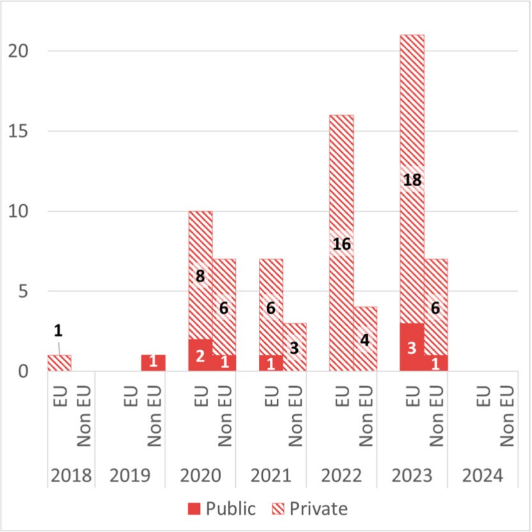

Fig. 6 Active Plant Variety Rights (PVR) applications for raspberries by EU versus non-EU, and public versus private organizations

currently under protection (Fig. 5) and 77 raspberry cultivars as active applications (Fig. 6).

Granted PVRs belong to 38 different organisations, the majority of them being from EU (27 EU vs. 11 non-EU) and private organisations (24 private vs. 14 public). Figure 5 shows an increase in the number of granted PVRs in the late 2010's with peaks in 2017 and 2019, recording both more than 20 granted PVRs which is more than doubled compared to previous years. This trend, already observed for strawberry and blueberry, most likely corresponds to the market release of most of the new genetic material emerging from the different breeding programmes, also in this case, driven by an increasing consumer demand.

Most of the key players are EU organisations, private entities such as Allberry (part of Advanced Berry Breeding in the Netherlands), "Centre de Recherche et d'Innovation Végétale" (C.R.I.V.), Marionnet label in France, Sant' Orsola in Italy and Planasa in Spain; but also, public entities such as the National Institute of Horticultural Research (INHORT) in Poland, the James Hutton Institute and the National Institute of Agricultural Botany (NIAB) in UK. Nevertheless, the US companies Driscoll's and Plant Sciences also have very strong positions and belong to the top 5 innovators.

Active PVR applications belong to 37 different organisations (Fig. 6), the majority of which are from the EU (27 EU vs. 10 non-EU) and primarily private entities (32 private vs. 5 public). Notably, half of the organisations with active applications have not yet secured PVRs for raspberries. Most of these "newcomers" are based in the EU, particularly in Spain (6 organizations), suggesting that the EU may increasingly dominate this market, in contrast to what can be observed for blueberry, and it will not be as evenly distributed as it has been previously. Unlike the strawberry market—historically dominated by private entities—the raspberry market 20 years ago was largely driven by public institutions (Fig. 5). This shift in dominance is evident today, as the higher number of active PVR applications from private organisations suggests that private entities will increasingly lead innovation in the raspberry sector.

The 77 active PVR applications will probably lead to many new granted PVRs that will compete in the market in the coming years. However, only a few are expected to stand out for their potential for broad market penetration, while others may remain of local interest or have limited distribution.

Blackberry PVRs

From the 143 initial results, we isolated after data curation a total of 33 different blackberry cultivars currently under protection (Fig. 7) and 53 blackberry cultivars as active applications (Fig. 8).

There are 11 organizations holding granted PVRs, with the majority being private (8 private vs. 3 public). The organizations are evenly distributed geographically, with six based in the EU and five outside. Notably, all EU-based organizations are private entities.

The blackberry innovation market is the smallest among the berry crops analysed in this study and remains dominated by a few traditional cultivars. However, in recent years, there has been a noticeable increase in varietal innovation, largely driven by non-EU organizations. Key players include three US organisations (University of Arkansas, Driscoll's and the US Secretary of Agriculture), Black Venture Farm from Mexico, and two Spanish companies (Berryneo and Agricola El Bosque). Interestingly, many PVRs were successfully submitted in 2017 with a

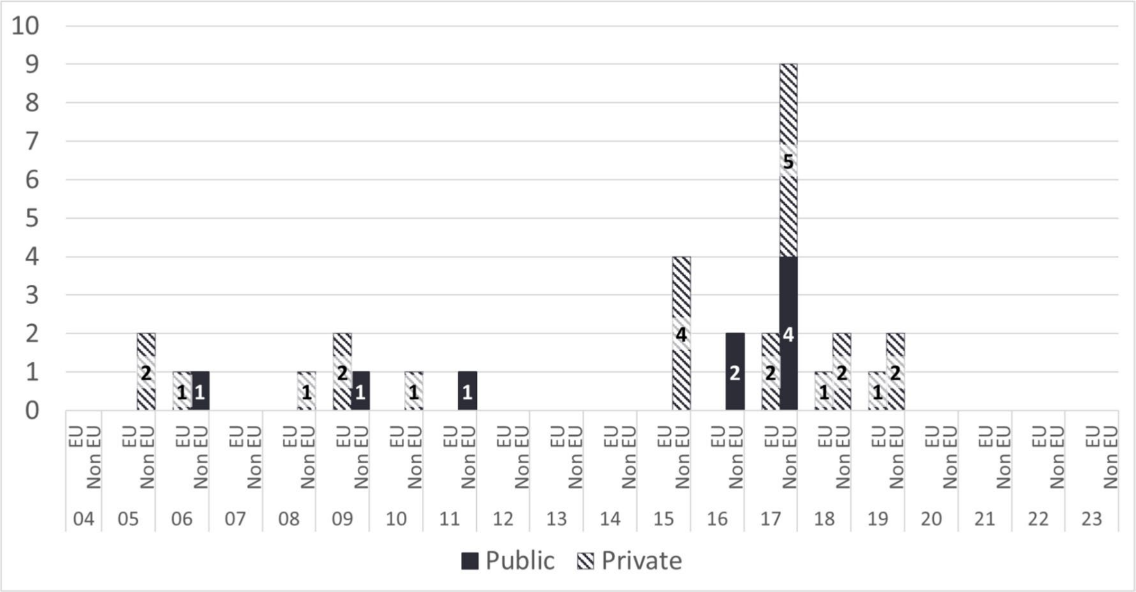

Fig. 7 Granted Plant Variety Grants (PVRs) for blackberries by EU versus non-EU, and public versus private organizations over the past 20 years (2004–2023)

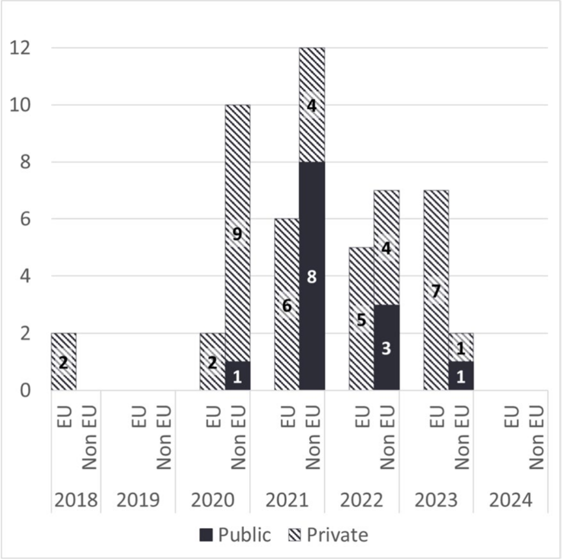

Fig. 8 Active Plant Variety Rights (PVR) applications for blackberries by EU versus non-EU, and public versus private organizations

total of 11 granted PVRs, which represents one third of all granted PVRs.

With currently 53 active PVR applications, the blackberry innovation is the most dynamic. It is the only berry with more PVR applications than already granted PVRs. It indicates that the market is poised for significant growth.

The 53 active applications belong to 21 different organisations, the majority of which are private organisations (19 private vs. 2 public). Again, all EU organisations are private entities. Although more EU (13) than non-EU (8) organisations have open PVR applications, non-EU entities account for about two thirds of the applications, with the three US leaders alone holding 20 active applications. Only one-third of the organizations with active applications already hold granted PVRs for blackberries, signalling a surge in new breeding programs, particularly in Spain (4) and Mexico (3). Public organizations, such as the University of Arkansas and the U.S. Secretary of Agriculture, are leading in blackberry breeding, with 13 active PVR applications. Considering the overall smaller size of the blackberry market, this figure is particularly significant when compared with the number of active PVR applications coming from public organisations for strawberry (12 PVRs) and raspberry (9 PVRs). This trend may be a consequence of the relatively recent history of blackberry breeding and the limited availability of suitable germplasm, which poses challenges for private companies.

Discussion

A regulatory system for germplasm safety and accessible breeding

The complexity of the regulatory framework affecting genetic resources, particularly due to the lack of cohesion between different regulations, makes it challenging for public and private organisations involved in germplasm conservation, improvement, and breeding programs, to understand and interpret them. In this context, it is hoped that continuous dialogue will be promoted between the various institutions involved (e.g. CBD, ECPGR, FAO, Nagoya protocol, CPVO, national patent authorities) in order to clarify and simplify procedures, facilitate the exchange of genetic material, promote its enhancement, including in breeding programs, with due recognition to all the actors who have contributed to achieving the result, in particular by ensuring support for genetic resource conservation centres, as the main repositories of fundamental genetic sources for future breeding initiatives.

Public research projects, including those in the EU, play a crucial role in advancing knowledge and building technical and scientific expertise transferable to breeding programs, including the use of genomic technologies. At the same time, it is equally important to promote the effective management of intellectual property rights associated with the new genetic material developed through these efforts.

Within the current funding program Horizon Europe (2021–2027), cluster 6 (Food, Bioeconomy, Natural Resources, Agriculture and Environment) aims, among other objectives, at halting the further loss of genetic diversity as well as tapping into the vast genepool of plant and animals and making it available for breeders, farmers, foresters, and ultimately consumers. The strategy to achieve these results is based on the need for an increasingly important close collaboration between breeding programs of private companies, with a strong capacity for penetration and varietal management on the market, and public institutions that possess germplasm, including CWR, and the ability to develop new genotyping and phenotyping technologies useful for better characterizing the new pre-breeding material obtained, so as to better use it for the rapid production of new competitive cultivars.

The complexity of varietal protection and the valorisation of genetic resources and pre-breeding material

In this article we aimed to highlight the different levels of regulation and evaluation processes for plant cultivars, comparing the three most important systems: UPOV, the USA and the EU. Our goal was to highlight the differences between these three systems, which have a strong impact on the protection and valorisation of genetic resources worldwide. Despite evolving in different historical contexts, all three systems share similarities, particularly in how plant material is evaluated. However, their approaches to protecting and using genetic material, as well as the resulting cultivars, differ significantly. The most relevant difference probably lies in the protection of patented cultivars also as breeding lines, a feature recognized by the American system that impacts the release of new commercial cultivars obtained using patented parental cultivars in countries following this system. This approach also restricts the exchange of material across breeding programs, leading to its centralization within large companies. Conversely, the EU Patenting System aligned with the UPOV Convention, provides both the breeders' exemption and the farmers' privilege. The breeders' exemption allows breeders to freely use protected plant cultivars for further breeding and research without needing the rights holder's permission, and the farmers' privilege allows farmers to save and reuse seeds from their own crops under specific conditions, though compensation to the rights holder may be required. These provisions leave a large space for the use of genetic resources in breeding programs, promoting the exchange of material and the creation of new variability. However, this more open system raises important questions about the relationship between public institutions, which invest significant resources into developing pre-breeding material, and private companies that may exploit this material for commercial breeding. If not carefully defined, pre-breeding material could remain in a "grey zone," difficult to protect, making it vulnerable to large companies that may freely use it to develop new, competitive cultivars with high market potential—without fairly compensating the original creators for their efforts. This calls for a precise framework to ensure that public institutions can recover the costs of their work and that genetic resources are used responsibly and equitably.

The role of genres for reorienting genetics and breeding programs

'Genetics and breeding' constitute one of the three fundamental pillars identified by the Nobel Prize winner Norman Borlaug in his definition of the 'Green revolution', which enabled substantial growth and improvement of agricultural systems worldwide, ensuring access to quality food for a rapidly increasing global population. In the latter half of the twentieth century, these advances were primarily seen in staple crops essential for food security; however, the benefits of these advancements later extended to specialty crops such as fruits and vegetables. During this period, breeding programs prioritized increasing yield, often at the expense of biotic and abiotic resistance and fruit quality. Unfortunately, this focus favoured the spread of high-yield but less resilient and lower-quality cultivars, impacting genetic resources by neglecting the conservation and use of germplasm crucial for these valuable traits. In the twenty-first century, awareness has grown around the need to steer genetic improvement programs toward addressing new global challenges, such as enhancing resilience to climate change, reducing water and chemical inputs, and meeting consumer demands for better flavour and nutritional content. These emerging priorities underscore the crucial role of genetic resources, including CWR, along with new genomic and phenomic technologies, in restoring and transferring traits lost in earlier breeding programs to future cultivars.

The berry market is constantly growing and so is the availability of new cultivars

Berries, known for their consumer-friendly traits, are experiencing a continuous rise in market demand. Until the 1990s, strawberry was the most well-known and widely consumed berry. While strawberries remain the dominant player in the global market, the early twenty-first century has seen the growing popularity of other small fruits, starting with raspberries, followed by blueberries, and more recently, a particular increase of interest has been observed also for blackberries, with forecasts predicting a continued global growth in the coming years.

The growing market demand for berries has been matched by a significant public and private commitment to the development and dissemination of new cultivars. In fact, in this study, we observed a notable increase in the number of applications and granted rights over the past 30 years for all four berries. Strawberries lead in the total number of registered cultivars, followed by blueberries and raspberries, with blackberries showing relatively lower figures. Interestingly, in 2018, the number of granted cultivars for blueberries even surpassed that of strawberries, highlighting the rapid expansion and importance of this emerging market (Fig. 9). The number of granted PVRs after 2018 are biased by the fact that applications are still under evaluation. Indeed, the examination process at the CPVO typically takes 2–4 years, depending on the crop. When we analyse the total number of applications filed for the four berries over the last 6 years (Fig. 10), we still find very high numbers. Strawberry maintains a lead position, but raspberry and especially blueberry have seen significant growth. This trend reflects the ongoing activity of breeding programs, always active in the release of new cultivars. Particularly in the case of strawberries, this abundance of new cultivars will ensure a broad selection for the market, though not all will succeed commercially. Nonetheless, part of this new material will contribute to broadening the genetic base, ensuring the continuity of breeding programs, especially private ones. Among the four berries, blueberry stands out for having a high number of new applications per year, while strawberry showed a peak in applications in 2021 and 2022, raspberry in 2023, while blackberry maintained an average of 10 applications per year over the last 4 years (Fig. 10), which represents a large increase compared with granted PVRs over the last 20 years (Fig. 7).

There seems to be a correlation between the number of applications and granted rights, and the market size of each berry. Indeed, strawberries are the most economically important berry crop in the EU, and in general it has stood out for a greater number of varietal releases, with a notable increase in recent years. In contrast, the other berries have seen a more substantial growth especially over the past 20 years, starting with raspberries, followed by blueberries, and, in the near future, blackberries will surely experience

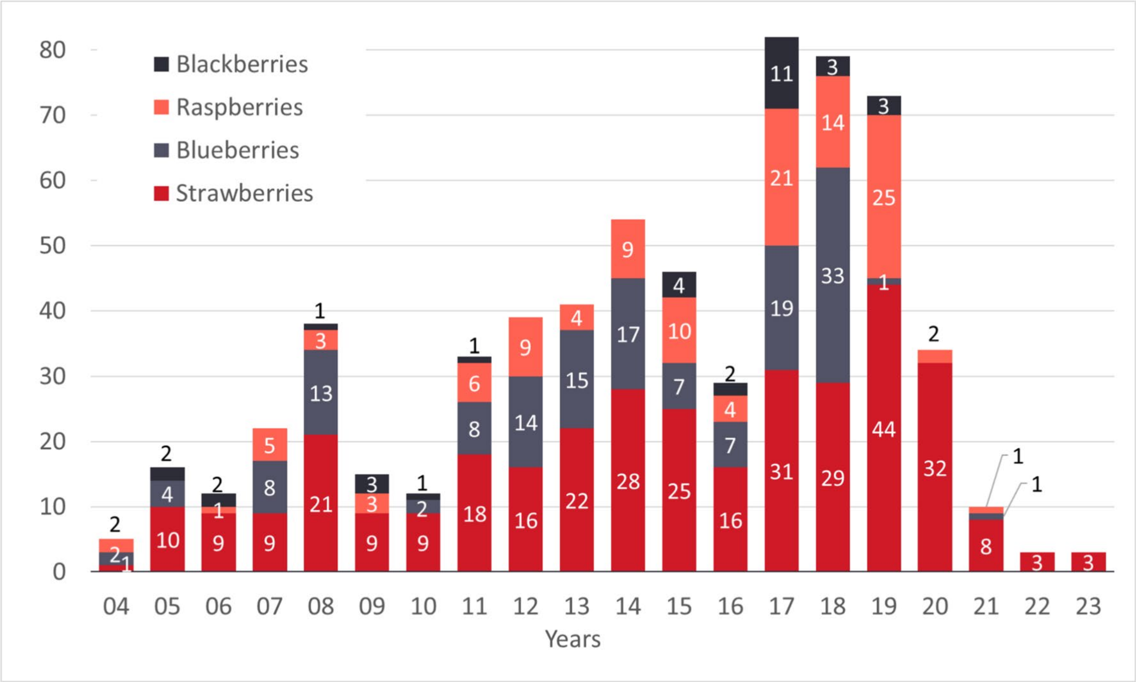

Fig. 9 Number of Plant Variety Rights (PVRs) granted for the four berry crops over the past 20 years (2004–2023)

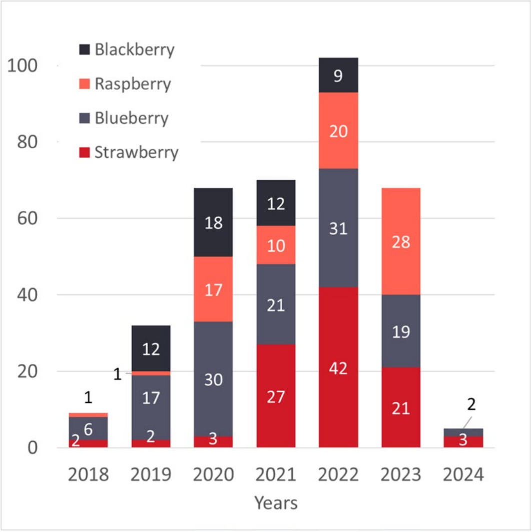

Fig. 10 Number of active Plant Variety Rights (PVR) applications for the four berry crops from 2018 to May 2024

similar expansion, reflecting the increasing market demand and a broad diversification within the berry industry.

For all four berries, the majority of cultivars are granted to private organisations, demonstrating the enormous commitment of companies to develop cultivars of high commercial interest, which is essential for maintaining their market spaces in different areas and cultivation systems. At the same time, this fact reinforces reported conclusions that it might be critical to reinvest in public breeding programs that provide pre-breeding and other diversifications to commercial systems (Khoury et al. 2022). Similarly, it seems necessary to foster and consolidate the collaboration between private companies and public institutions, which have wider BGR and new genotyping and phenotyping techniques to facilitate the introgression of improved traits in pre-breeding materials.

The majority of strawberry PVRs are granted to European organisations, while blueberry and blackberry cultivars are predominantly concentrated among non-European entities. This can be attributed to the long-established history of strawberry breeding in Europe, both in the public and private sectors. In contrast, breeding activities in Europe for blueberries, and particularly blackberries, are quite limited. Even globally, blackberry breeding remains minimal.

Considering the strong investments underway on the diffusion of blueberries, it is crucial for the EU to develop robust breeding programs to prevent the European market from becoming dominated by non-EU cultivars. While for blackberries, the introduction of new cultivars improved for fruit quality and adaptability to different growing environments would be key to favour further diffusion of this species and boosting market demands. In the case of raspberries, EU organisations hold a slight majority in granted PVRs, and recent trends in active applications over the last 4 years indicate that the EU may continue to play a leading role in shaping this market. The relationship between current right holders and the leading innovators—represented by the major EU and non-EU applicants—provides valuable insight into how the innovation landscape may evolve in the coming years. For raspberries, there is a relatively balanced distribution of rights between European and non-European holders, with a majority of active applications coming from European organisations. This reflects the heightened activity of both public and private European entities in raspberry breeding programs, indicating that European breeders may continue to play a dominant role in driving innovation in the raspberry market.

Conclusions and future perspectives

Despite progress, challenges remain in breeding and utilization of genetic resources in Europe. Climate change, disease pressure, and market demands continue to pose significant hurdles. Future research needs to focus on understanding the genetic mechanisms of stress tolerance and incorporating these traits into commercial cultivars. Additionally, understanding consumer preferences is key to successful cultivar development. Breeding programs must align with market demands for acceptance and profitability. Sustainability remains critical, requiring innovative agricultural practices, including the use of better adapted cultivars, that reduce environmental impact while ensuring high productivity. To achieve these objectives, it remains essential to continue the conservation and characterization of genetic resources and their use in breeding programs, also integrating the application of genomics and advanced phenotyping technologies. The development of genome editing tools based on the CRISPR/Cas9 system further holds promise for accelerating breeding efforts. It is hoped that in the near future, the EU and other countries around the world will continue to support these strategies, ideally in a coordinated manner, particularly regarding regulations on technologies, and on the exchange and protection of genetic materials. This coordination would help ensure greater sharing of resources and expertise, while avoiding the risk of material loss and the concentration of genetic material ownership in a few companies.

Trends in varietal releases certainly turns out to be an indicator of the significance of different crops in the market and the level of genetic resource utilization. Analysis of Plant Variety Right (PVR) applications shows a dynamic berry breeding sector in Europe. Strawberries, raspberries, blueberries, and blackberries have seen evolving research and investment, with strawberries leading in market maturity and private investment. Blackberries, though lagging, show high growth potential. Strawberry, raspberry, and blueberry breeding followed a trajectory of strong initial public investment, later complemented by private funding, largely due to European policies from the 1990s countering U.S.-dominated markets. However, increased competition has disadvantaged cultivars from smaller companies and public institutions. Blackberries, with fewer registered cultivars, present an opportunity for European breeders before foreign dominance grows, as seen with blueberries. Projects like Horizon 2020 BreedingValue exemplify public–private collaboration, fostering germplasm evaluation and new cultivar development. These initiatives ensure knowledge development, enhance genetic resource utilization, and boost European competitiveness. While blackberries fall outside Breeding Value's scope, its methodologies can be applied to other crops. Public–private partnerships also accelerate pre-breeding, facilitating unique cultivar development. Protecting these under the European CPVO system ensures accessibility and conservation of genetic diversity, offering a crucial resource for future breeding efforts.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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