PRO-GRACE

PROMOTING A PLANT GENETIC RESOURCE COMMUNITY FOR EUROPE

DELIVERABLE 4.1

Unified, crop-specific standards and protocols for the evaluation of the phenotypes and agronomic characteristics of PGR, incorporating the ECPGR, MIAPPE, Crop Ontology, EMPHASIS and final user recommendations and methodologies

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(CREA, ENEA, IPGRI, UPV, KIS)

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Project full title	PRO-GRACE – Promoting a plant genetic resource community for Europe

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Deliverable title	**Unified, crop-specific standards and protocols for the evaluation of the phenotypes and agronomic characteristics of PGR, incorporating the ECPGR, MIAPPE, Crop Ontology, EMPHASIS and final user recommendations and methodologies**
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1. Introduction

The **phenotype** is the set of structural, physiological, and performance-related traits of a genotype in a given environment. Plant phenotyping is the act of determining the quantitative or qualitative values of these traits. It is a procedure leading to understanding of structural and functional plant traits and the relationships between them. Plant phenotypes are inherently complex because they result from the interaction of genotypes with a multitude of environmental factors. Until a few decades ago, it was mostly based on visual observations and scoring systems or on simple instrumental measures of the whole plants and their parts. It has a pivotal importance in breeding activities for producing varietal innovations with superior traits such as higher yield, disease and pest resistance and adaptation to abiotic stresses.

Technological advancements in several sectors have produced methodologies for high-throughput phenotyping. This has led to a new branch of biology, **phenomics**, which is the natural complement to genome sequencing as a route to rapid advances in biology towards the full characterization of the complete set of phenotypes encoded by a genome. The explosion of novel non-invasive methods, such as high-throughput imaging, drones, robots, or artificial intelligence (AI) offers unprecedented possibilities, but poses a new problem as well: the standardization of protocols and methods. **Standardization can also support semantic interoperability which is necessary for reusing and comparing data that are obtained through different phenotyping platforms**.

In the context of genetic resources, three types of information must be taken into consideration:

- **Passport data** allow to identify the accessions in their collection: identifiers and name of the accession, the species to which it belongs and information about its origin, who is holding it, etc.
- **Primary descriptors** are generally morphological traits with simple heredity that characterize an accession: e.g. color and shape of the mature fruit, hairy or hairless leaves….
- **Secondary descriptors** are traits with complex heredity that necessitate several years of observation and/or experiments: e.g. flowering time, bud break, yield…

Over time, an ecosystem of resources has been produced, contributing on one side to standardize the way descriptors are measured, and on the other side to make the data collected FAIR (*i.e.* they meet the principles of findability, accessibility, interoperability, and reusability).

This ecosystem has been developed by three distinct communities with different dynamics: 1) the genebank community, intergovernmental networks and international bodies under the auspices of the FAO; 2) UPOV/CPVO (International Union for the Protection of New Varieties of Plants / The Community Plant Variety Office); and 3) the Plant Science research community.

The aim of deliverable D4.1 is to **review and map in more details the current initiatives in plant phenotyping and related ontologies** and propose, in deliverable 4.3, a unified crop-specific standardization of protocols methods for the evaluation and valorization of Plant Genetic Resources (PGRs).

2. Activities

During online meetings between the project participants, we decided to carry out our inventory on 4 groups of species. In this deliverable we consider only Plant Genetic Resources for Food and Agriculture (PGRFA). In particular, we identified:

1) Fruit trees
2) Fruit vegetables
3) Leafy vegetables

4) Grains (cereals and legumes).

For each group, we identified referents as follows:

- Group 1, Ignazio Verde (CREA)
- Group 2, Véronique Lefebvre (INRAE), Maria José Díez (UPV) and Jaime Prohens (UPV)
- Group 3, Filippo Guzzon (CGIAR), Jelka Šuštar Vozlič (KIS)
- Group 4, Filippo Guzzon (CGIAR), Patrizia Vaccino (CREA), Elisabetta Mazzucotelli (CREA).

Concerning the traits, we decided to concentrate on those that are important for breeding rather than traits used for taxonomy or varietal classification (e.g. DUS, Distinctness, Uniformity, Stability), and in particular on:

- Yield
- Quality characteristics (before and after processing)
- Resistance to biotic stresses
- Tolerance to abiotic stresses
- Plant and root architecture.

An important aspect is the mapping and organization of the existing initiatives. In agreement with the proposal of WP1 (D1.1), we decided to **establish criteria for generating a harmonized system of standards and descriptors for phenotypic data and their related ontologies.**

3. Results

3.1 Main sources of information

In the context of genetic resources, passport and phenotypic descriptors for evaluation of genetic resources have been largely developed by several international organizations such as FAO, ECPGR, or IPGRI/BIOVERSITY. In addition to these organizations, UPOV/CPVO prepared technical protocols and guidelines for DUS tests of varieties. In a larger context of research on plants, consortia of researchers, ontologists and research infrastructures have developed a large set of resources (*e.g.* databases, ontologies, metadata standards, guidelines, training materials) supporting FAIR data management in the context of plant phenotyping experiments. Hereafter is presented the list of references to these initiatives with some general information.

3.1.1. The resources developed under FAO auspices

- The List of Multi-Crop Passport Descriptors (MCPD) is a reference tool developed in 2001 jointly by IPGRI and FAO to provide international standards to facilitate germplasm passport information exchange across crops: https://cgspace.cgiar.org/handle/10568/105205. This metadata standard has been updated twice:
    - MCPD V.2: it is the result of a thorough revision in 2012: https://cgspace.cgiar.org/handle/10568/91224
    - MCPD V.2.1: it is an update to MCPD V.2, released in 2015, and expanded in order to accommodate emerging needs, such as the broader use of GPS tools, or the implementation of the International Treaty on Plant Genetic Resources for Food and Agriculture's Multilateral System for access and benefit-sharing (Alercia et al 2015): https://cgspace.cgiar.org/handle/10568/69166.
- The history and usefulness of Bioversity International's descriptor lists: https://cgspace.cgiar.org/handle/10568/73450. Catalogs of descriptors have been developed by Bioversity International for many species or species groups (see **Annex 1**). In these catalogs, the naming of the descriptors is standardized as well as their scoring methods and scales. These catalogs are a precious resource; however, they are often not machine actionable.

- Genebank Standards for Plant Genetic Resources for Food and Agriculture: prepared under the guidance of the FAO Commission on Genetic Resources for Food and Agriculture, it lays down the procedures that need to be followed for conserving, characterizing, evaluating and documenting plant genetic resources (FAO 2014). https://www.fao.org/3/i3704e/i3704e.pdf.

In Europe, the inter-governmental network of conservation of plant genetic resources (the European Cooperative Programme for Plant Genetic Resources, ECPGR) (https://www.ecpgr.cgiar.org/) has launched the European Evaluation Network (EVA) for PGRFA: it is an international project involving public and private sector partners, aimed at increasing the use of crop genetic diversity conserved in European genebanks and the diversity of stakeholders in plant breeding. The project uses standardized protocols and data collection templates to facilitate comparison of phenotypic data collected in multilocation trials across Europe (https://www.ecpgr.cgiar.org/eva).

ECPGR also supports EURISCO (https://eurisco.ipk-gatersleben.de/apex/eurisco_ws/r/eurisco/about-eurisco), the web-based catalogue that provides information about *ex situ* plant collections maintained in Europe. The EURISCO catalogue contains passport and phenotypic data for more than 2 million samples of crop representing more than 6,700 genera and more than 45,000 species (genus-species combinations including synonyms and spelling variants) from 43 countries (**Figure 1**).

Figure 1. The homepage of the Eurisco web site.

3.1.2. Resources developed in relation to industry needs

- UPOV/CPVO has developed Technical Protocols (TP) or Guidelines to support the process of variety registration: they contain a list of descriptors for several crops. The main aim of this list is to provide directions for cultivar identification, mainly for the assessment of DUS tests. Many traits analyzed have little importance for evaluation and valorization in breeding, however, they can be useful for establishing standard protocols and methods for genetic resources evaluation. The TPs for the crops in the CPVO list can be downloaded at https://cpvo.europa.eu/en/applications-and-examinations/technical-examinations/technical-protocols/cpvo-technical-protocols while the UPOV guidelines can be reached at https://www.upov.int/test_guidelines/en/list.jsp.

- The Agrochemistry industries sponsored the development of a standardized description of plant phenological stages: the BBCH-scale (Meier 2001; downloadable version: https://www.reterurale.it/downloads/BBCH_engl_2001.pdf.
-
- The International Organization of Vine and Wine, OIV, has developed a catalog of descriptors for grapevine, which was then transferred into a crop ontology format (see **Annex 1** and below).

3.1.3. The ecosystem of resources developed by the plant research community

The international plant science community has actively developed a set of complementary ontologies. **Ontology** is a way to represent the entities with all their interdependent properties and relationships, according to a system of categories by defining a set of terms and relational expressions that represent the entities in a specific subject area (Jacquette 2002). The objective is to enable machine actionable consistent data reuse and comparison across projects and locations. In ontologies, well-defined terms associated with unique identifiers and a set of relationships, are the core for data reusability. In the context of plant phenotyping, a set of ontologies have been created to describe in a standardized way the entities of a plant, their properties and the traits targeted by a phenotyping experiment (see https://planteome.org/; https://agroportal.lirmm.fr/,https://agroportal.lirmm.fr/)

- **Plant Ontology** aims to establish a structured vocabulary that links plant anatomy, morphology, growth and development to plant genomics data. It extends the concepts set up by the Gene Ontology Consortium to facilitate the annotation of gene products and gene-associated phenotypes (Avraham *et al.* 2008).
- **Trait Ontology** describes phenotypic traits. Each trait is a distinguishable feature, characteristic, quality or phenotypic feature of a developing or mature plant (Cooper *et al.* 2018).
- **Crop Ontology** aims at capturing the phenotyping practices following a conceptual model that defines **a phenotypic variable as a combination of a trait, a method and a scale** (Shrestha *et al.* 2010). The guidelines for creating crop-specific ontologies to annotate phenotypic data can be downloaded at https://cgspace.cgiar.org/handle/10568/110906 (Pietragalla *et al.* 2022). Moreover, the ontologies prepared for several crops by the Crop Ontology Initiative can be downloaded (https://cropontology.org/) (**Figure 2**).
- These general ontologies have been completed by another ontology aiming at describing in a semantic and standardized way phenotypic experiments: **the Plant Phenotyping Experiment Ontology** (Papoutsoglou *et al.* 2020); https://fairsharing.org/1234).

The **Planteome Project** developed resources aiming at mapping different complementary ontologies relevant to plant phenotyping and corresponding required metadata: The Plant Trait Ontology, The Plant Ontology (description of plant tissue/organ and developmental stages), the Plant Environment Ontology (EO) to describe the experimental conditions, the Plant Stress Ontology (PSO) to describe the treatments with pathogens, stress conditions, some of the Crop Ontologies. The Planteome database has the objective to link the phenomics to the other omics experiments through comparative analysis experiments on transcriptome, proteomics, phenomics and genome annotation projects (https://browser.planteome.org/amigo/term/TO:0000387#display-lineage-tab). The Planteome project brings an integrated approach of adopting common annotation standards / reference vocabularies (ontologies) that can be queried in real time using common query words and a set of reference ontologies for plants to solve conflicting descriptions. Two other central portals allowing to search for ontologies and ontology terms are listed below:

- **The Ontology Lookup Service** (OLS) of EMBL-EBI: https://www.ebi.ac.uk/ols/ontologies/to

- **The Bioportal** (https://bioportal.bioontology.org/ontologies/PTO?p=classes) and its portal dedicated to ontologies relevant to agriculture sciences: https://agroportal.lirmm.fr/.

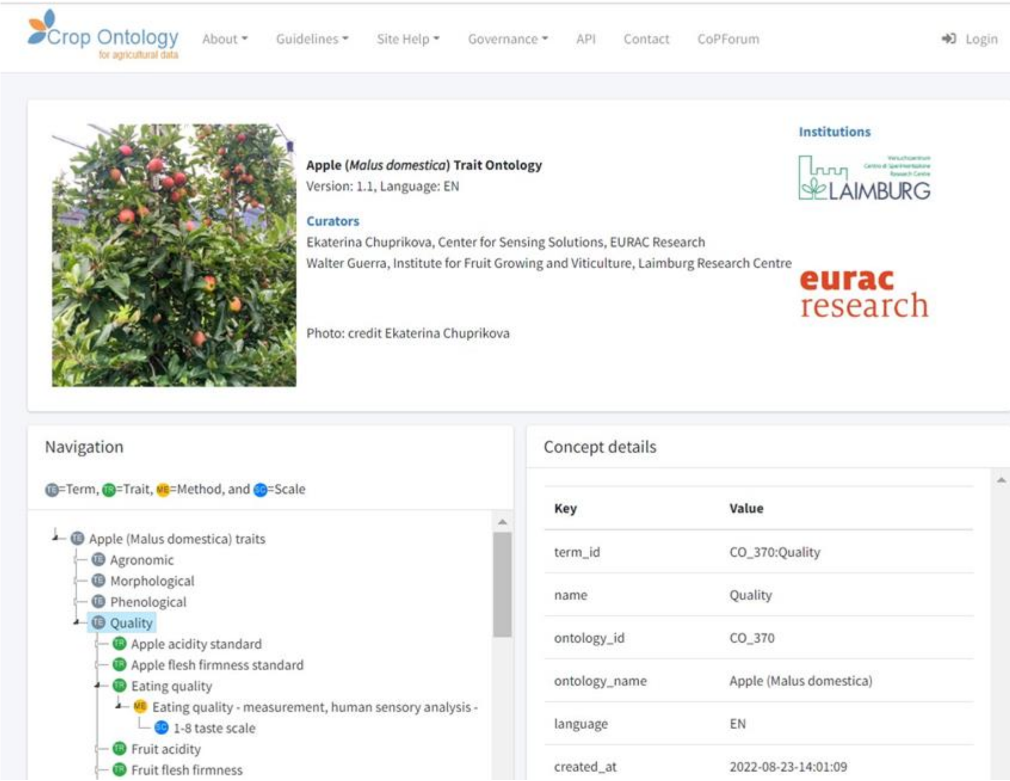


Figure 2. Example of crop ontology for apple. In addition to Crop Ontology, a series of initiatives such as the Minimum Information about a Plant Phenotyping Experiment (MIAPPE), the Planteome database, EMPHASIS, have proposed minimum information, ontologies, and data exchange/database formats to enhance the FAIRness of phenotypic data.

Building on existing resources, the European infrastructures EMPHASIS (https://emphasis.plant-phenotyping.eu/) and ELIXIR (https://elixir-europe.org/), in conjunction with the Wheat Initiative (https://www.wheatinitiative.org/), Bioversity international and the international consortia MIAPPE (www.miappe.org) and the BrAPI (www.brapi.org), have developed a set of coherent resources to support **the FAIR data management of data from plant phenotyping experiments**.

This work was supported by several EU-funded projects (FP7 TranPLANT, H2020 ELIXIR Excelerate, H2020 ELIXIR CONVERGE). The set of tools consists of a set of ontologies (the Plant Phenotyping Experiment Ontology and the Crop Ontologies), aligned with a set of metadata standards (MCPD, MIAPPE) and a standard web service for data exchange (BrAPI). These resources were completed with training resources and dedicated pages in ELIXIR's collaborative gateway supporting FAIR data management (https://rdmkit.elixir-europe.org/plant_sciences).

- **MIAPPE** is an open, community driven, data standard designed to harmonise data from plant phenotyping experiments and provides specifications including a checklist and a data model of metadata required to adequately describe plant phenotyping experiments (https://www.miappe.org/) (Papoutsoglou *et al.* 2020). MIAPPE has developed a checklist in Excel format that includes all the guidelines for each category of information (https://github.com/MIAPPE/MIAPPE/blob/master/MIAPPE_Checklist-Data-Model-v1.1/MIAPPE_Checklist-Data-Model-v1.1.tsv).

- A collaborative gateway of guidelines and resources supporting FAIR Data management in Life Sciences based on GitHub is managed by **ELIXIR: the RDMkit**. It contains guidelines, linked to resources (training, databases, tools, data management related recipes, etc.). The Plant Science domain pages (https://rdmkit.elixir-europe.org/plant_sciences) are currently focussing on best practices to ensure FAIR and interoperable phenotyping and genotyping data (**Figure 3**).

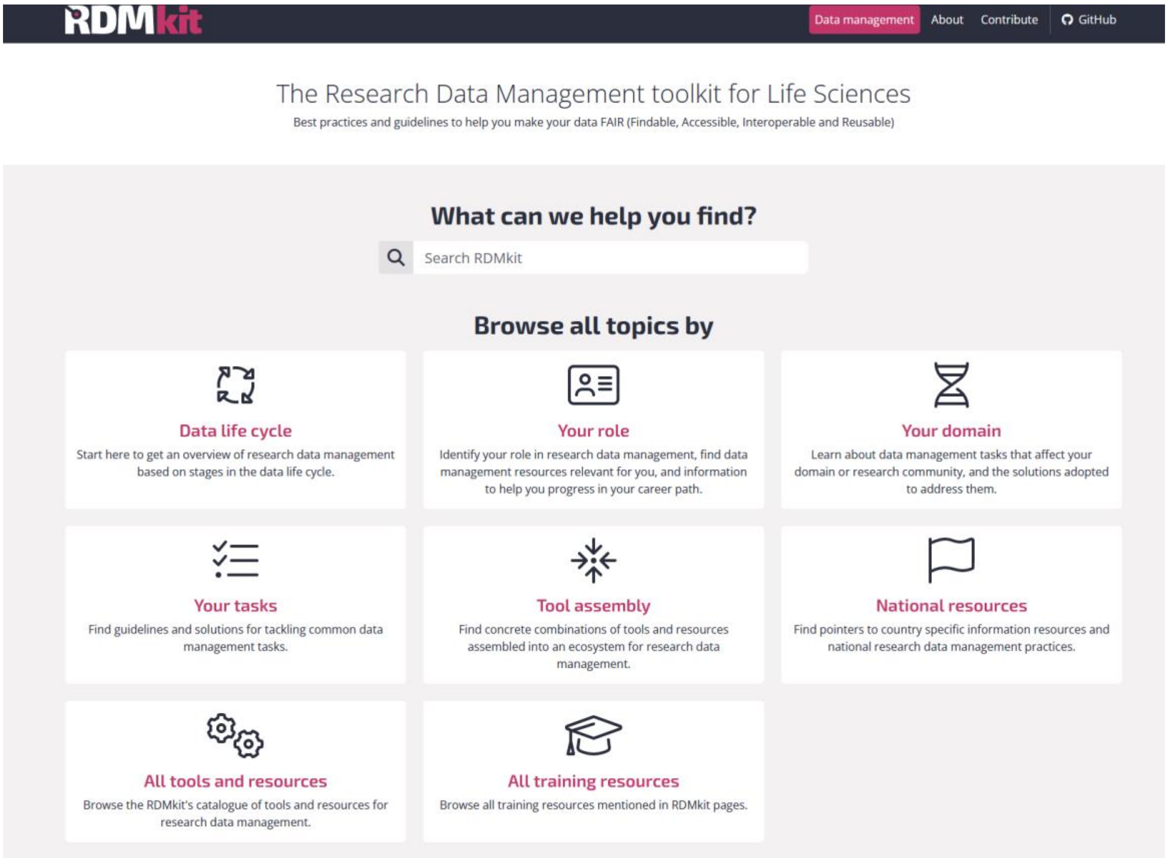


Figure 3. ELIXIR's RDMkit gateway allows to get support on data management from different perspectives and roles.

ELIXIR's RDMkit gateway links with other central catalogues of resources such as FAIRsharing. **FAIRsharing** gives access to a comprehensive view on standards, ontologies, community of practices, policies and databases implementing these policies (*e.g.* in the context of plant ontologies: https://fairsharing.org/search?q=plant%20ontology). FAIRsharing reports for instance 54 initiatives for Plant Ontology, 51 for Trait Ontology and 41 for Crop Ontology (**Figure 4**).

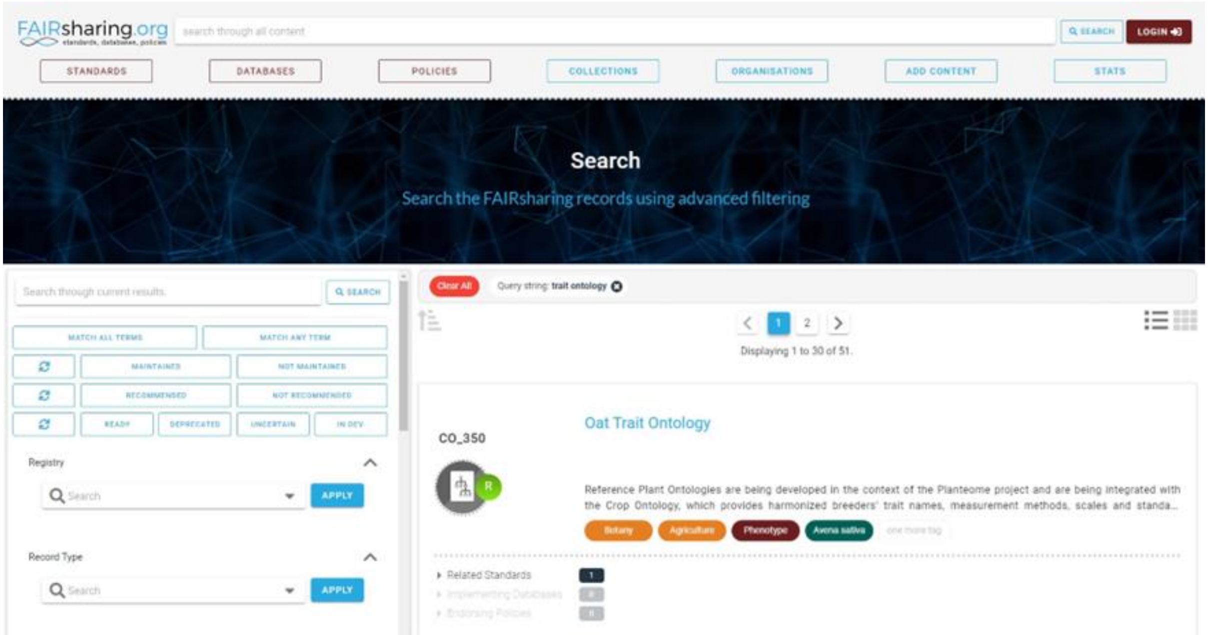


Figure 4. Trait ontology initiatives surveyed in the FAIRsharing website.

The H2020 project **AGENT** is a project that aims to establish a global genebank network to sustainably unlock the genetic diversity of food crops for future generations and make them intuitively accessible for modern breeding programs. It involves 13 genebanks and 5 bioinformatic centres, focusing on wheat and barley (https://www.agent-project.eu/). AGENT contributed to testing and improving the guidelines for FAIR data management in collaboration with the ELIXIR Plant Science community, to ensure interoperability between phenotyping and genotyping data (https://rdmkit.elixir-europe.org/plant_sciences). AGENT also completed or improved the set of tools and databases necessary to support FAIR data collection.

The **INNOBREED** project is developing and applying innovative solutions in the organic fruit tree sector, including shared procedures and protocols for the evaluation and valorization of the genetic resources, for developing varieties tailored for the organic fruit industry (https://innobreed.eu/).

The **InnoVar** project (https://www.h2020innovar.eu/) is improving the efficacy and accuracy of European crop variety testing and decision-making, using an integrated approach incorporating genomics, phenomics and machine learning. It is focused on wheat initially, then the InnoVar approach will be applied to other major crops. Innovative ways to measure DUS characters will be evaluated. Value for Cultivation or Use (VCU) testing procedures will be revised and shaped to comprehensively address variability in growing conditions, stresses and management approaches.

3.2 CROP-SPECIFIC DESCRIPTORS

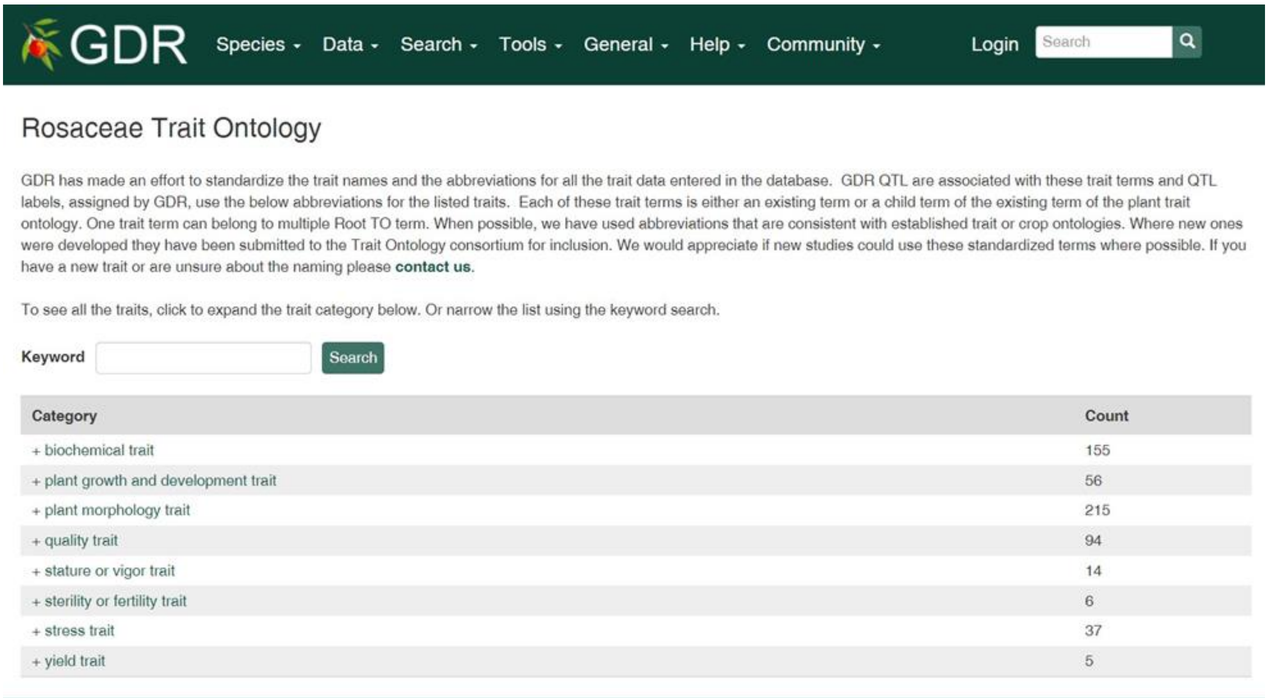
3.2.1 Fruit trees

Fruit Trees are clonally propagated perennial crops. Several initiatives have been conducted so far. **ECPGR** in connection with CGIAR proposed descriptor lists for several temperate and sub-tropical fruit crops. They produced lists of descriptors for the following fruit tree crops:

- Almond (*Prunus dulcis*) https://cgspace.cgiar.org/handle/10568/104209 https://cgspace.cgiar.org/handle/10568/72793

- Anona (*Annona cherimola*) https://cgspace.cgiar.org/handle/10568/104849
- Apple (Malus x domestica) https://cgspace.cgiar.org/handle/10568/72794; https://cropontology.org/term/CO_370:ROOT
- Apricot (*Prunus armeniaca*) https://cgspace.cgiar.org/handle/10568/73447
- Avocado (*Persea spp*) https://cgspace.cgiar.org/handle/10568/72796
- Banana (*Musa spp.*) https://cgspace.cgiar.org/handle/10568/72799; https://cropontology.org/term/CO_325:ROOT
- Cherry (*Prunus avium, P. cerasus*) https://cgspace.cgiar.org/handle/10568/72853
- Citrus (*Citrus spp*) https://cgspace.cgiar.org/handle/10568/72733
- Coconut (*Cocos nucifera L.*) https://cropontology.org/term/CO_326:ROOT
- Coffee (*C. canephora* & *C. arabica*) https://cgspace.cgiar.org/handle/10568/72788
- Durian (*Durio zibethinus*) https://cgspace.cgiar.org/handle/10568/72585
- Fig (*Ficus carica*) https://cgspace.cgiar.org/handle/10568/72691
- Grapes (*Vitis vinifera*) http://www.eu-vitis.de/docs/descriptors/mcpd/Descriptors_EUVitisDB_11Jan12.pdf ; https://cropontology.org/term/CO_356:ROOT
- Hazelnut (*Corylus avellana*) https://cgspace.cgiar.org/handle/10568/72598
- Jackfruit (*Artocarpus heterophyllus*) https://cgspace.cgiar.org/handle/10568/72703
- Litchi (*Litchi chinensis*) https://cgspace.cgiar.org/handle/10568/72694
- Mangaba (*Hancornia speciosa*) https://cgspace.cgiar.org/handle/10568/90693
- Mango (*Mangifera indica*) https://cgspace.cgiar.org/handle/10568/72607
- Papaya (*Carica papaya*) https://cgspace.cgiar.org/handle/10568/72903
- Peach (*Prunus persica*) https://cgspace.cgiar.org/handle/10568/72905
- Pear (*Pyrus communis*) https://cgspace.cgiar.org/handle/10568/72906
- Pistachio and relatives (*Pistacia vera and Pistacia spp*) https://cgspace.cgiar.org/handle/10568/72917 ; https://cgspace.cgiar.org/handle/10568/72916
- Plum (*Prunus domestica, P. salicina, Prunus spp*) https://cgspace.cgiar.org/handle/10568/72940
- Rambutan (*Nephelium lappaceum*) https://cgspace.cgiar.org/handle/10568/72693
- Tropical fruit (various) https://cgspace.cgiar.org/handle/10568/73058
- Grape species https://www.upov.int/edocs/tgdocs/en/tg050.pdf
- Walnut (*Juglans regia*) https://cgspace.cgiar.org/handle/10568/73159

Regarding ontology, the Rosaceae community (Genome Database for Rosaceae, GDR) has made an effort to standardize the names and the abbreviations for all the traits entered in the database. GDR QTLs are associated with these trait terms and QTL labels, assigned by GDR, use the abbreviations for the listed traits. Each of these terms is either an existing term or a child term of the existing term of the plant trait ontology. One term can belong to multiple Root Trait Ontology terms. The trait list can be reached at https://www.rosaceae.org/trait_listing (**Figures 5 & 6**).



GDR Species Data Search Tools General Help Community Login Search

Rosaceae Trait Ontology

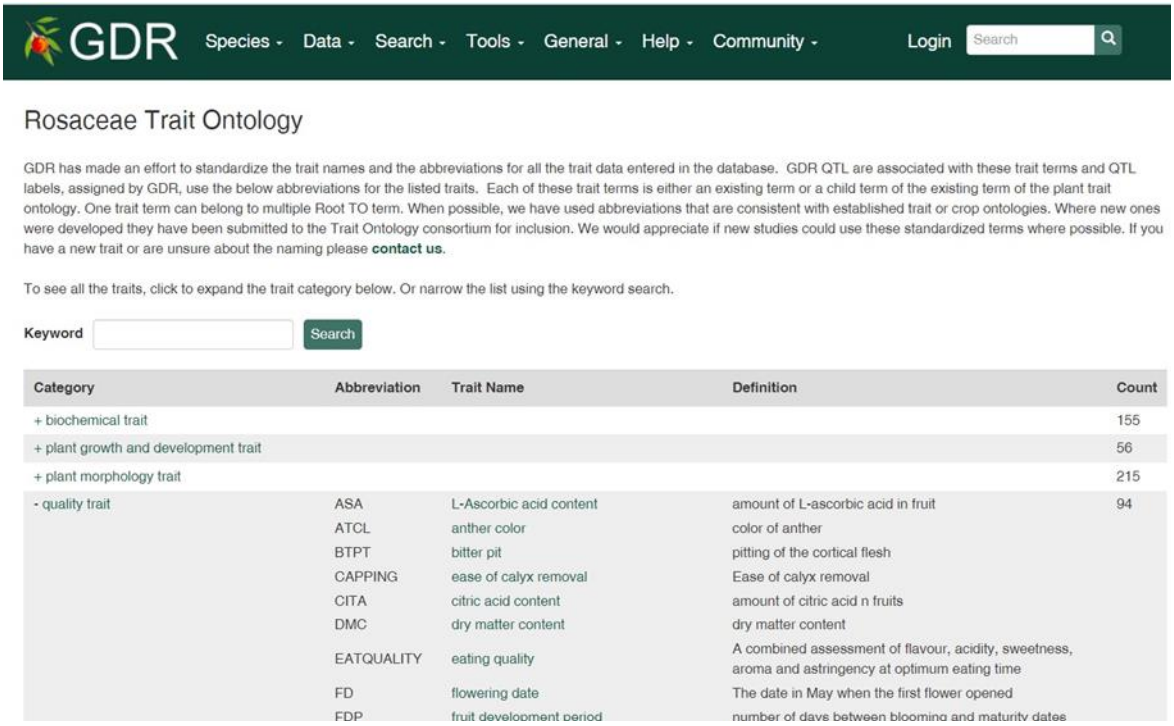
GDR has made an effort to standardize the trait names and the abbreviations for all the trait data entered in the database. GDR QTL are associated with these trait terms and QTL labels, assigned by GDR, use the below abbreviations for the listed traits. Each of these trait terms is either an existing term or a child term of the existing term of the plant trait ontology. One trait term can belong to multiple Root TO term. When possible, we have used abbreviations that are consistent with established trait or crop ontologies. Where new ones were developed they have been submitted to the Trait Ontology consortium for inclusion. We would appreciate if new studies could use these standardized terms where possible. If you have a new trait or are unsure about the naming please **contact us**.

To see all the traits, click to expand the trait category below. Or narrow the list using the keyword search.

Keyword Search

Category	Count
+ biochemical trait	155
+ plant growth and development trait	56
+ plant morphology trait	215
+ quality trait	94
+ stature or vigor trait	14
+ sterility or fertility trait	6
+ stress trait	37
+ yield trait	5

Figure 5. Main Trait Ontology categories on the Genome Database for Rosaceae (GDR).



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Keyword Search

Category	Abbreviation	Trait Name	Definition	Count
+ biochemical trait				155
+ plant growth and development trait				56
+ plant morphology trait				215
- quality trait	ASA	L-Ascorbic acid content	amount of L-ascorbic acid in fruit	94
	ATCL	anther color	color of anther	
	BTPT	bitter pit	pitting of the cortical flesh	
	CAPPING	ease of calyx removal	Ease of calyx removal	
	CITA	citric acid content	amount of citric acid n fruits	
	DMC	dry matter content	dry matter content	
	EATQUALITY	eating quality	A combined assessment of flavour, acidity, sweetness, aroma and astringency at optimum eating time	
	FD	flowering date	The date in May when the first flower opened	
	FDP	fruit development period	number of days between blooming and maturity dates	

Figure 6. Examples of quality traits surveyed in GDR Trait Ontology.

For *Vitis* spp., **The European Vitis Database** (http://www.eu-vitis.de/index.php) includes cultivated grapes (*Vitis vinifera* sub. *vinifera*) as well as wild grapes (*Vitis vinifera* sub. *sylvestris*) (**Figure 7**). Ontology considers different descriptors. Descriptors are primary (mainly ampelographic traits), secondary (resistance to disease, traits for wine, table quality) and genetics (SSR markers) as established by Genreso81 and GrapeGen06 projects. The database also reports descriptors for phenotyping (bud swelling, leaf fall and berry enocarpological traits) (**Figure 8**).

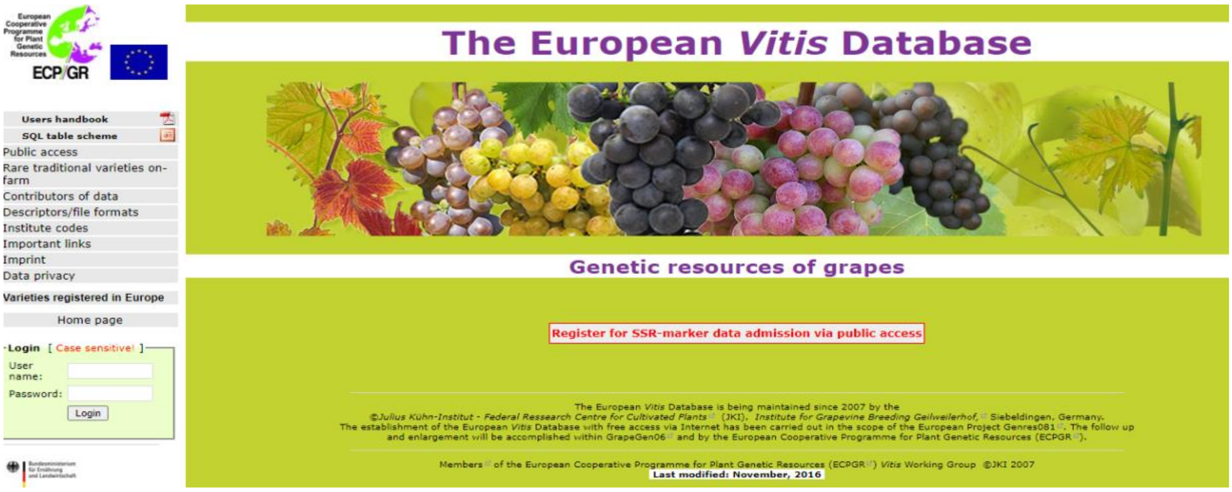

Figure 7. The European Vitis Database.

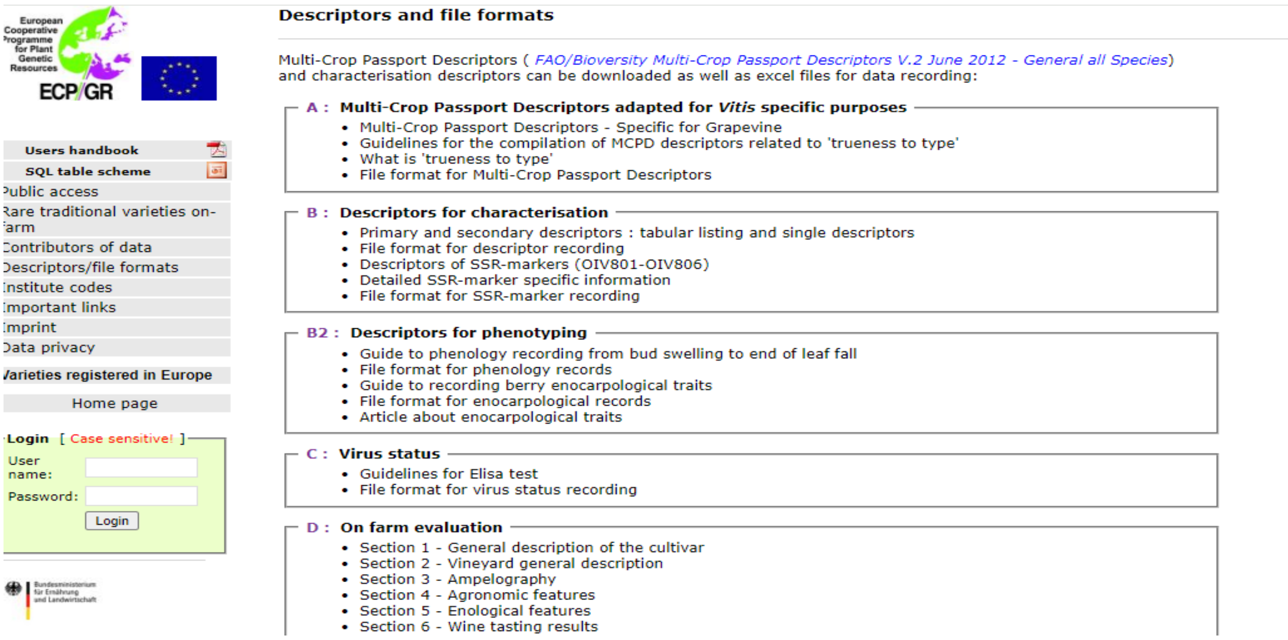

Figure 8. Main Trait Ontology categories on The European Vitis Database

3.2.2 Fruit vegetables

Fruit Vegetables are annual crops mostly of the Cucurbitaceae and Solanaceae families generally propagated by seed, although some such as pepino (*Solanum muricatum*) are vegetatively propagated. In addition, strawberry (*Fragaria x ananassa*), which belongs to the Rosaceae family is commonly considered as a fruit vegetable. Several initiatives have been conducted so far for the development of crop-specific descriptors. In this way, **ECPGR in connection with CGIAR** proposed descriptor lists for the following major crops: melon and other Cucurbitaceae (*Cucumis* spp., *Cucurbita* spp. and *Citrullus* spp.), Capsicum peppers, eggplant and tomato, as well as for a minor Solanaceae crop (pepino), and for strawberry.

The seven produced books of descriptors for these seven fruit vegetable crops are the following.

- Melon (*Cucumis melo*): https://cgspace.cgiar.org/handle/10568/72690

- Cucurbitaceae (*Cucumis* spp., *Cucurbita* spp. and *Citrullus* spp.): https://cgspace.cgiar.org/handle/10568/104810
- Capsicum peppers (*Capsicum* spp.): https://cgspace.cgiar.org/handle/10568/72851
- Eggplant (*Solanum melongena*): https://cgspace.cgiar.org/handle/10568/72874
- Tomato (*Solanum lycopersicum*): https://cgspace.cgiar.org/handle/10568/73041
- Pepino (*Solanum muricatum*): https://cgspace.cgiar.org/handle/10568/72608
- Strawberry (*Fragaria x ananassa*): https://cgspace.cgiar.org/handle/10568/72947

Minimum descriptor lists that encompass the former Solanaceae and Cucurbitaceae crops, as well as other fruit vegetable crops from these families have been produced, respectively by the **ECPGR Solanaceae Working Group and ECPGR Cucurbitaceae Working Group**. These lists of minimum descriptors can be used for crops that have no full descriptors; they are the following.

- Cucurbitaceae: *Cucurbita* spp., cucumber, melon and watermelon: https://www.ecpgr.cgiar.org/fileadmin/templates/ecpgr.org/upload/NW_and_WG_UPLOADS/Cucurbits_DescriptorLists.pdf
- Solanaceae (major fruit crops): Eggplant, *Capsicum* (sweet and hot pepper) and tomato: https://www.ecpgr.cgiar.org/fileadmin/templates/ecpgr.org/upload/NW_and_WG_UPLOADS/Solanaceae_Miscc/Solanaceae_descriptors.pdf
- Solanaceae (minor fruit crops): Pepino, groundcherry and tree tomato: https://www.ecpgr.cgiar.org/fileadmin/templates/ecpgr.org/upload/NW_and_WG_UPLOADS/Solanaceae_Miscc/Descriptors_minor_crops_NEW_for_Web_22022013.pdf

Ontologies of fruit vegetables for Solanaceae have only been developed by the Sol Genomics Network (https://solgenomics.net/). A considerable effort has been made to develop an Ontology Browser (https://solgenomics.net/tools/onto/; **Figure 9**), which allows searching ontologies for phenotypes, as well as for other items such as molecular functions, cellular components, biological processes, plant structure development stages, plant anatomical entities, sequence characteristics, quality and volatile compounds. The various classifications of terms are viewable in a tree display (**Figure 10**). This tree indicates if a trait is a variable of another trait or part of another one.

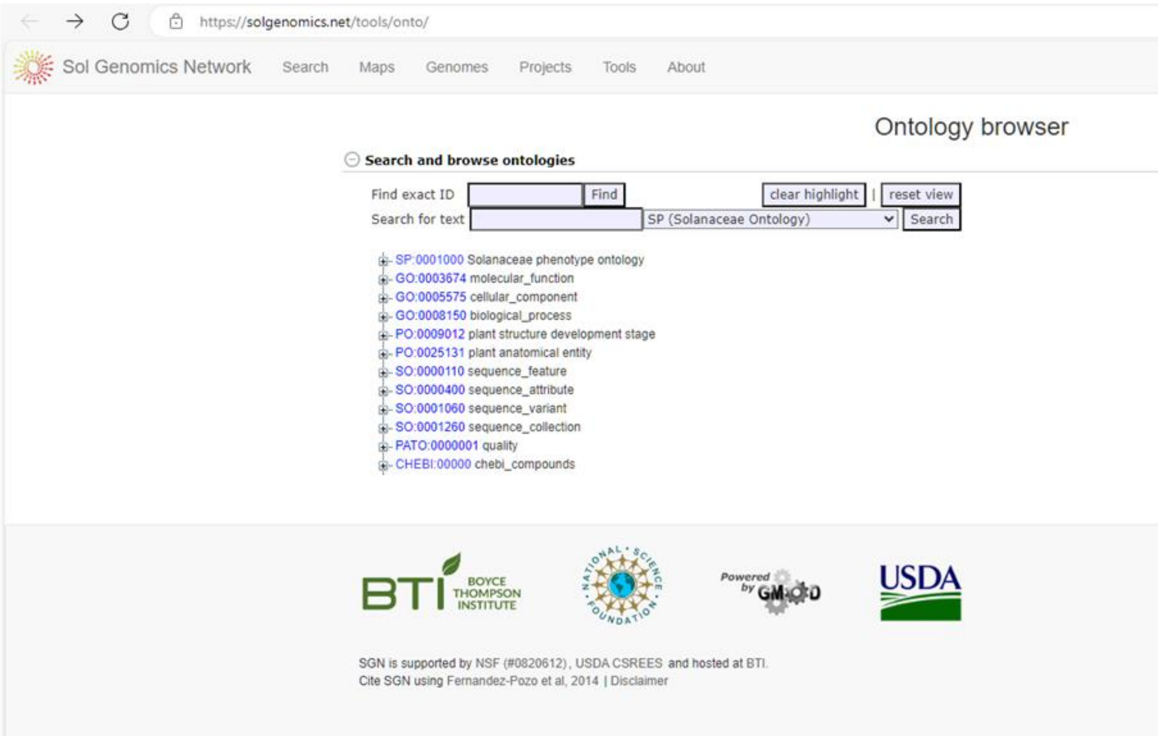

Figure 9. Main categories in the Solanaceae ontology browser (https://solgenomics.net/tools/onto/).

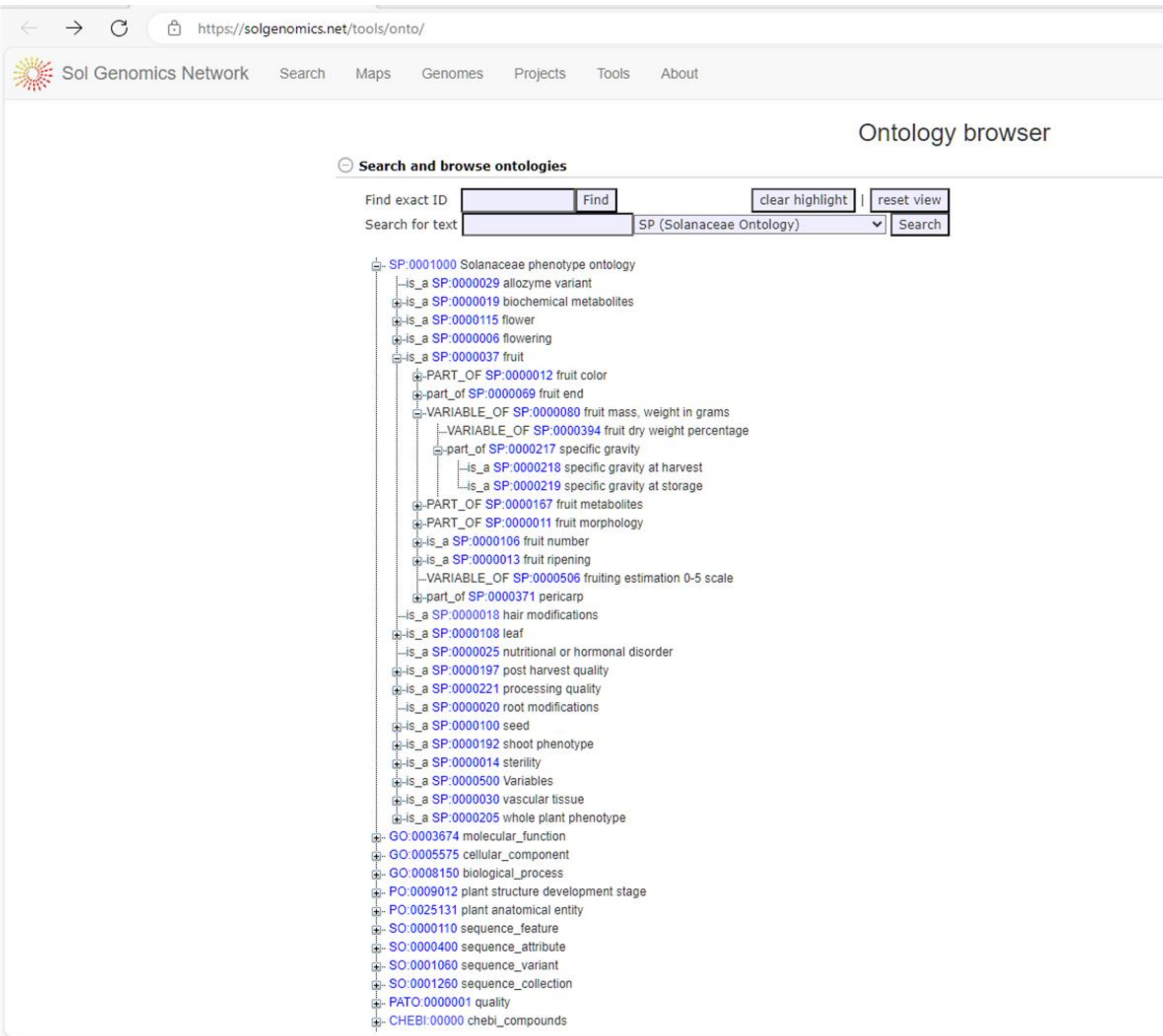

Figure 10. Example of tree display for the fruit mass trait in the Solanaceae ontology browser (https://solgenomics.net/tools/onto/).

Ontologies of strawberry have been developed by the Genome Database for Rosaceae (GDR), which has made significant strides in creating a comprehensive ontology for strawberries, similarly as indicated for Rosaceae fruit trees (Section 3.2.1). This effort is evident in the standardized naming and abbreviation of trait data within the database https://cropontology.org/term/CO_372:ROOT (**Figure 11**). The GDR's trait terms, including those for strawberries, are either existing terms or child terms of existing terms from the plant trait ontology. These terms are associated with GDR's Quantitative Trait Loci (QTL), and the labels for QTL are assigned using these standardized abbreviations. The GDR has submitted new trait terms to the Trait Ontology consortium, aiming to align with established trait or crop ontologies wherever possible. Researchers are encouraged to use these standardized terms in new studies to maintain consistency.

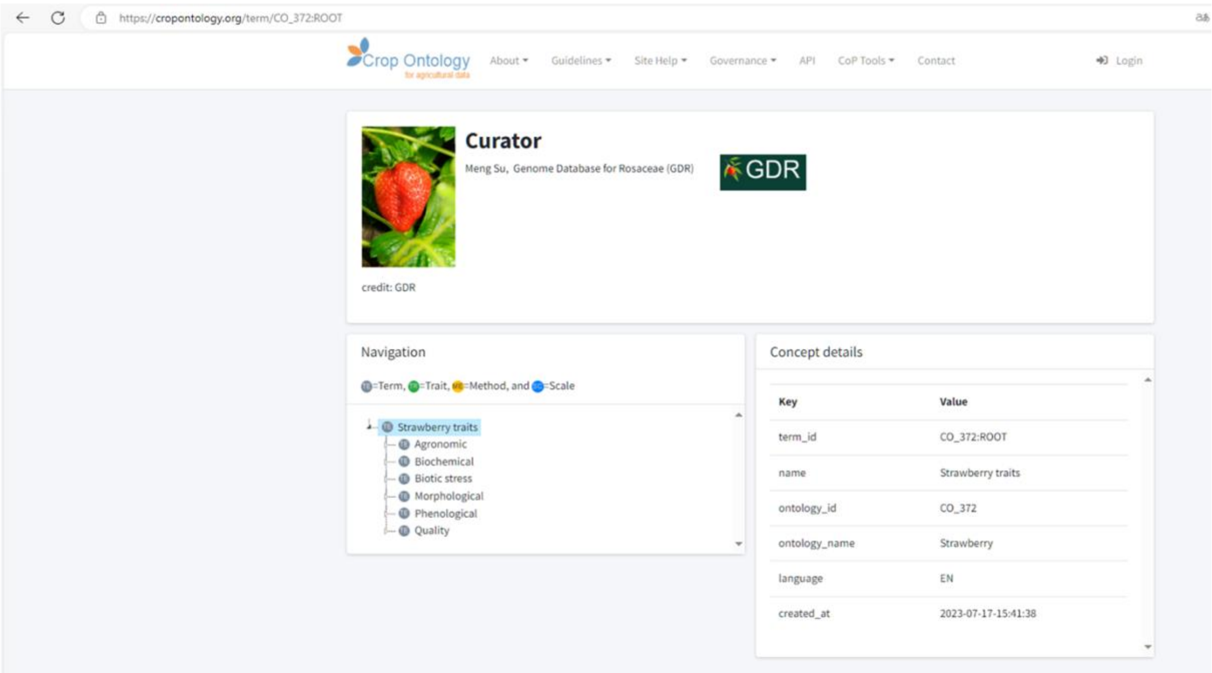

Figure 11. Screenshot of the strawberry ontologies at the Genome Database for Rosaceae (GDR), displaying the main ontology categories.

3.2.3 Grain crops

3.2.3.1 Cereals

Cereal grain crops include rice, wheat, rye, oats, barley, millet, sorghum and maize. Cereals belong to the family Poaceae, commonly known as grasses. **ECPGR in connection with CGIAR** proposed descriptor lists for them, some recently updated in Crop Ontology.

Barley:

1994: Descriptors for barley (*Hordeum vulgare* L.) (cgiar.org)

2009: Key access and utilization descriptors for barley genetic resources (cgiar.org)

2020: CO_323, https://cropontology.org/term/CO_323:ROOT

Wheat:

1978: Descriptors for wheat and Aegilops (cgiar.org)

1985: Descriptors for wheat (Revised) (cgiar.org)

2019: CO_321, https://cropontology.org/term/CO_321:ROOT

Maize

1991: Descriptors for maize/Descriptores para maiz/Descripteurs (cgiar.org)

2009: Key access and utilization descriptors for maize genetic resources (cgiar.org)

2021: CO_322, https://cropontology.org/term/CO_322:ROOT

Rice

2007: Descriptors for wild and cultivated rice (*Oryza* spp.) (cgiar.org)

2009: Key access and utilization descriptors for rice genetic resources (cgiar.org)

2016: CO_320, https://cropontology.org/term/CO_320:ROOT

Sorghum

2010: Key access and utilization descriptors for sorghum genetic resources (cgiar.org)

2018: CO_324, https://cropontology.org/term/CO_324:ROOT

Rye and Triticale

1985: Descriptors for rye and triticale (cgiar.org)

Oat

1985: Oat descriptors (cgiar.org)

2019 : CO_350, https://cropontology.org/term/CO_350:ROOT

Finger millet

1985. Descriptors for finger millet (cgiar.org)

2010: Key access and utilization descriptors for finger millet genetic resources (cgiar.org)

Pearl millet

1993: Descriptors for pearl millet (*Pennisetum glaucum* (L.) R. Br.) (cgiar.org)

2010. Key access and utilization descriptors for pearl millet genetic resources (cgiar.org)

2016: CO_327, https://cropontology.org/term/CO_327:ROOT

A specific focus on wheat is here presented as a case study. A Trait and Phenotype Ontology has been specifically developed for wheat, called **WHEATPHENOTYPE**, since 2010 (Nédellec et al., 2020) and it is accessible through Wheat Trait and Phenotype Ontology | AgroPortal (lirmm.fr). The objective was to answer breeders and scientists' needs for wheat trait and phenotype information management and retrieval at varying abstraction scales. Its supports two objectives: (1) building a formal shared representation of wheat trait whose knowledge organization closely reflects the expert knowledge model, and (2) making phenotypic information extraction from text easier. It has been evaluated in respect to FAIR scores, according to O'FAIRe (an open-source FAIRness assessment methodology and tool for ontologies, vocabularies and semantic resources developed within D2KAB and FooSIN projects). WHEATPHENOTYPE covers a wide range of bread wheat traits (e.g. observable physical plant properties), phenotypes (e.g. trait values) and their related environmental conditions (e.g. disease, extreme temperature) organized in three trees. It has a deep and balanced structure, moreover the classes of the 'Trait' subtree are linked to the corresponding phenotypes by the "Trait_has_value" relationship. For instance, 'ear emergence time' trait class is linked to the 'late heading' phenotype class. This structure can help managing data at different levels of aggregation, and mining data for different objectives with high-level queries. The responses of the plant to biotic stresses are expressed in two ways: either by the disease name or by the causative agent names (their standard names and the other names, because names corresponding to different life stages can be found). A given disease name may have synonyms and a disease may be caused by more than an agent.

Analogously, the **Wheat Trait Ontology** (CO-WHEAT, https://bioportal.bioontology.org/ontologies/CO-WHEAT) defines traits of several information systems such as the International Wheat Information System (**IWIS** database from CIMMYT, https://orderseed.cimmyt.org/iwin-results.php) and the Wheat Information System (**WheatIS**, http://www.wheatis.org/) endorsed by the Wheat Initiative. The WheatIS released guidelines on the best practices, tools, recommendations, and examples to create, manage and share data related to wheat, including phenotypes (https://ist.blogs.inrae.fr/wdi/). About phenotype data formats, it refers to MIAPPE recommendations; for observation variables, which include trait and environment variables, WheatIS refers to the Crop Ontology, especially the Wheat Trait Ontology for phenotypes (http://agroportal.lirmm.fr/ontologies/CO_321), and the FAO-IPGRI Multi-CropPassport Ontology (http://agroportal.lirmm.fr/ontologies/CO_020) for germplasm.http://genome.jouy.inra.fr/bibliome/WheatPhenotypeOntology/WheatPhenotypeOntology-v2.0

3.2.3.2 Pseudocereals

Pseudocereal are crop species grown to produce starchy grain suitable for human food, excluding the cereals, legumes, oilseeds and nuts (Fletcher 2016). The major pseudocereals are grain amaranth (*Amaranthus*), quinoa (*Chenopodium quinoa*, both belonging to the Amaranthaceae family), and buckwheat (*Fagopyrum*, belonging to the Polygonaceae family).

Descriptors have been developed by **IPGRI** / **Bioversity International** for:

- **Quinoa**: descriptors first developed in 1981, and updated in 2013, HYPERLINK "https://cgspace.cgiar.org/handle/10568/69165" including also descriptors for crop wild relatives (CWR): https://cgspace.cgiar.org/handle/10568/69165,

- **Buckwheat**, developed by IPGRI in 1994: https://cgspace.cgiar.org/items/f708e2a7-f40d-4e43-82df-547265e10696.

A list of descriptors for **amaranth** is provided by the **US National Plant Germplasm System**: https://npgsweb.ars-grin.gov/gringlobal/cropdetail?type=descriptor&id=159.

Ontology for quinoa was prepared by the **Crop Ontology Initiative:** https://cropontology.org/term/CO_367:0000048.

3.2.3.3 Grain Legumes

Grain legumes are plants of the family Fabaceae whose dry seeds are consumed by humans for food (Michaels 2016). They include several crops, *e.g.* common bean, runner bean, lima bean, tepary bean, pea, chickpea, faba bean, lentil, pigeon pea, peanut, *Lathyrus* species, *Vigna* species, grass pea, horse gram, soybean and lupin. **ECPGR** in connection with CGIAR proposed descriptor lists for most of them.

Characterization and evaluations descriptors were developed by the International Board for Plant Genetic Resources (**IBPGR**), followed by the International Plant Genetic Resources Institute (**IPGRI**).

These include descriptors for several species of the genus *Phaseolus*, as following:

- **Common bean** (*Phaseolus vulgaris*; IBPGR, 1982): https://cgspace.cgiar.org/handle/10568/72698
- **Runner bean** (*Phaseolus coccineus*; IBPGR, 1983): https://cgspace.cgiar.org/handle/10568/72914
- **Tepary bean** (*Phaseolus acutifolius*; IBPGR, 1985): https://cgspace.cgiar.org/handle/10568/73381
- **Lima bean** (*Phaseolus lunatus*; IBPGR, 1982): https://cgspace.cgiar.org/handle/10568/91220

Moreover, IBPGR and IPGRI developed descriptors for several other grain legumes, including:

- **Chickpea** (*Cicer arietinum*; IBPGR, 1993): https://cgspace.cgiar.org/handle/10568/72855
- **Cowpea** (*Vigna unguiculata*; IBPGR, 1993): https://cgspace.cgiar.org/handle/10568/72871
- **Faba bean** (*Vicia faba*; IBPGR, 1985): https://cgspace.cgiar.org/handle/10568/72876
- **Peanut** (*Arachis hypogaea*; IBPGR and ICRISAT, 1992): https://cgspace.cgiar.org/handle/10568/72881
- **Pigeon pea** (*Cajanus cajan*, IBPGR and ICRISAT, 1981 updated in 1990):

https://oar.icrisat.org/8138/1/RP%201147.pdf, https://alliancebioversityciat.org/publications-data/descriptors-pigeonpea-cajanus-cajan-l-millsp

- ***Lathyrus*** **spp.** (IPGRI, 2000): https://cgspace.cgiar.org/handle/10568/72702
- **Lentil** (*Lens culinaris*; IBPGR and ICARDA, 1985): https://cgspace.cgiar.org/handle/10568/72887

- **Lupin** (*Lupinus* spp.; IBPGR, 1981): https://cgspace.cgiar.org/handle/10568/73417
- **Mung Bean** (*Vigna radiata*; IBPGR, 1980): https://cgspace.cgiar.org/handle/10568/73435
- **Soybean** (*Glycine max*; IBPGR, 1984): https://cgspace.cgiar.org/handle/10568/72944

A series of **key access and utilization descriptors** were subsequently developed for several legumes species by **Bioversity International** in collaboration with several other institutions, comparing and harmonizing existing descriptors lists. These key descriptors aim at establishing minimal descriptors sets i.e. priority sets of descriptors to describe, access and utilize genetic resources. Key access and utilization descriptors were developed for:

- **Bean** (Bioversity International and CIAT, 2009): https://cgspace.cgiar.org/handle/10568/73356. This list is based on the aforementioned IBPGR descriptors (1982), the descriptors list was subsequently compared and harmonized with a number of sources such as:
  - 'Descriptors for Phaseolus' (USDA, ARS, GRIN, https://npgsweb.ars-grin.gov/gringlobal/cropdetail?type=descriptor&id=83),
  - UPOV technical guidelines (2005, https://www.upov.int/en/publications/tg-rom/tg012/tg_12_9.pdf),
  - 'Handbook on evaluation of Phaseolus Germplasm' (PHASELIEU, 2001; https://digital.csic.es/bitstream/10261/103897/1/Cuadra_Handbook_evaluation.pdf),
  - 'Standard System for the Evaluation of Bean Germplasm' (CIAT, 1987, https://cgspace.cgiar.org/handle/10568/69557).
- **Chickpea** (Bioversity International, ICARDA, ICRISAT and IARI 2010): https://cgspace.cgiar.org/handle/10568/73371. This list is based on the aforementioned IBPGR descriptors (1993), the descriptors list was subsequently compared and harmonized with a number of sources such as:
  - UPOV technical guidelines for Chickpea (2005, https://www.upov.int/en/publications/tg-rom/tg143/tg_143_4.pdf),
  - 'Descriptors for CHICKPEA' (USDA, ARS, GRIN, https://npgsweb.ars-grin.gov/gringlobal/cropdetail?type=descriptor&id=54),
  - 'Core Collection of Chickpea as a Means to Enhance Utilization of Genetic Resources in Crop Improvement' (ICRISAT, https://oar.icrisat.org/4178/1/Web_Art_2000_Core_Collection_of_Chickpea.pdf),
  - 'Global Strategy for the *Ex situ* Conservation of Chickpea (*Cicer* L.)' (Global Crop Diversity Trust, 2008.
- **Cowpea** (Bioversity International, ICARDA, ICRISAT and IARI 2010): https://cgspace.cgiar.org/handle/10568/73346. This list is based on the aforementioned IBPGR descriptors (1983), the descriptors list was subsequently compared and harmonized with a number of sources such as:
  - 'Descriptors for VIGNA' (USDA, ARS, GRIN, https://npgsweb.ars-grin.gov/gringlobal/cropdetail?type=descriptor&id=188)
  - 'Cowpea (*Vigna unguiculata* (L.) Walp.) core collection defined by geographical, agronomical and botanical descriptors' (Mahalakshmi *et al.* 2007)
  - 'Descriptors for Characterization and Evaluation of Cowpea' (National Institute of Agrobiological Sciences, Genebank of Japan, see: https://www.gene.affrc.go.jp/manuals-plant_characterization_en.php).

- **Faba bean** (Bioversity International, NBPGR and IITA 2010): https://cgspace.cgiar.org/handle/10568/73351. This list is based on the aforementioned IBPGR descriptors (1985), the descriptors list was subsequently compared with a number of sources such as:
  - ‘Descriptors for Faba bean’ (USDA-ARS, https://npgsweb.ars-grin.gov/gringlobal/cropdetail?type=descriptor&id=103),
  - UPOV Technical guidelines (2003, https://www.upov.int/edocs/tgdocs/en/tg206.pdf),
  - Minimal descriptors of Faba bean (IBPGR),
  - ‘Global Strategy for the *Ex Situ* Conservation of Faba Bean’ (GCDT, 2009, https://www.genebanks.org/resources/publications/faba-strategy-2009/).
- ***Lathyrus* spp.** (Bioversity International and ICARDA 2009): https://cgspace.cgiar.org/handle/10568/73328
- **Lentil** (Bioversity International, ICARDA and NBPGR 2010): https://cgspace.cgiar.org/handle/10568/73368 This list is based on the aforementioned IBPGR descriptors (1985), the descriptors list was subsequently compared with a number of sources such as:
  - ‘UPOV technical guidelines for Lentil’ (2003,see here the 2015 version: https://www.upov.int/edocs/tgdocs/en/tg210.pdf),
  - ‘Descriptors for LENTIL’ (USDA, ARS, GRIN, https://npgsweb.ars-grin.gov/gringlobal/cropdetail?type=descriptor&id=107),
  - ‘Methodology to establish a composite collection: case study in lentil’ (Furman et al. 2007),
  - ‘Global Strategy for the Ex Situ Conservation of Lentil’ (GCDT, 2008, https://www.genebanks.org/resources/publications/lens-strategy-2008/).
- **Pigeon pea** (Bioversity International, ICRISAT and ICAR 2010): https://cgspace.cgiar.org/bitstream/handle/10568/73367/brief.pdf?sequence=3&isAllowed=y This list is based on the aforementioned IBPGR descriptors (1990), the descriptors list was subsequently compared with a number of sources such as:
  - ‘Descriptors for PIGEON-PEA’ (USDA, ARS, GRIN, https://npgsweb.ars-grin.gov/gringlobal/cropdetail?type=descriptor&id=134),
  - ‘Development of a Strategy for the Global Conservation of Pigeonpea Genetic Resources’ (GCDT, 2006).

Moreover, ontologies were prepared for several grain legumes by the **Crop Ontology Initiative**, including:

- **Common bean**: https://cropontology.org/term/CO_335:ROOT
- **Soybean**: https://cropontology.org/term/CO_336:ROOT, Soybean onthology can also be found as part of **SoyBase**: https://soybase.org/ontology.php.
- **Mung bean**: https://cropontology.org/term/CO_346:ROOT.
- **Lentil:** https://cropontology.org/term/CO_339:ROOT
- **Peanut**: https://cropontology.org/term/CO_337:ROOT
- **Chickpea**: https://cropontology.org/term/CO_338:ROOT
- **Cowpea**: https://cropontology.org/term/CO_340:ROOT
- **Pigeon pea**: https://cropontology.org/term/CO_341:ROOT
- **Bambara groundnut**: (*Vigna subterranea*): https://cropontology.org/term/CO_366:ROOT.

3.2.4 Leafy Vegetables

Leafy vegetables are a wide group of plant species that includes: "vegetables cultivated for the edible part constituted of foliar and flower structures, comprising lamina, petiole, midrib and veins" (Alvino and Barbieri 2016). This crop group includes several species belonging to different plant families (*e.g.* Apiaceae, Asparagaceae, Asteraceae, Boraginaceae, Brassicaceae, Chenopodiaceae, Lamiaceae, Polygonaceae, Portulaceae, Valerianiaceae). Lettuce, spinach and chicory are generally considered the main leafy vegetables because of the worldwide human consumption and economical importance (van Treuren et al. 2012), while the minor leafy vegetables include, amongst others, rocket salad, lamb's lettuce, asparagus, artichoke and rhubarb (Lebeda and Boukema, 2001).

The International Board for Plant Genetic Resources (**IBPGR**), followed by the International Plant Genetic Resources Institute (**IPGRI**), developed descriptors for leafy vegetables of the family Brassicaceae, including:

- Descriptors for *Brassica* and *Raphanus* (IBPGR, 1990). This document includes descriptors for several **leafy brassicas**: https://cropgenebank.sgrp.cgiar.org/images/file/learning_space/descriptors_brassica_raphanus.pdf
- Descriptors for **rocket** (*Eruca* spp; IPGRI 1999): https://cgspace.cgiar.org/handle/10568/72775

The **ECPGR Leafy Vegetables Working Group** has developed several descriptors for different leafy vegetables, including:

- Minimum descriptors for **cultivated lettuce** (*Lactuca sativa*), **wild lettuce** species (*L. serriola*, *L. saligna*, *L. virosa*), **spinach** (*Spinacia* spp.), leaf and root **chicory** (*Cichorium intybus*), witloof (*Cichorium intybus* var. *foliosum*) and **endive** (*Cichorium endivia*). These descriptors were published in 2009 and can be found here: https://www.ecpgr.cgiar.org/fileadmin/templates/ecpgr.org/upload/NW_and_WG_UPLOADS/LeafyVeg_misc/LeafyVeg_MinDescr.pdf
- Minimum descriptors for **asparagus** (*Asparagus* spp.; 2014): https://www.ecpgr.cgiar.org/fileadmin/templates/ecpgr.org/upload/WG_UPLOADS_PHASE_IX/LEAFY_VEGETABLES/Minimum_descriptors_for_asparagus_.pdf
- Minimum descriptors for **rocket** (*Eruca* spp.) developed with the EU GENRES project: https://www.ecpgr.cgiar.org/fileadmin/templates/ecpgr.org/upload/NW_and_WG_UPLOADS/LeafyVeg_misc/Eruca_descriptor_list.pdf
- Minimum descriptors for **corn salad** (*Valerianella* spp.) developed with the EU GENRES project: https://www.ecpgr.cgiar.org/fileadmin/templates/ecpgr.org/upload/NW_and_WG_UPLOADS/LeafyVeg_misc/Valerianella_descriptor_list.pdf .

It is important to highlight that internationally agreed descriptors for many leafy vegetables are, to the best of our knowledge, still not available (e.g. celery (*Apium graveolens*) and fennel (*Foeniculum vulgare*)).

A recent initiative (**LettuceGDP**, Guo *et al.* 2023) was launched to provide an omics data hub for lettuce. Moreover, as part of the aforementioned ECPGR European Evaluation Network (**EVA**) for Plant Genetic Resources for Food and Agriculture (PGRFA, https://www.ecpgr.cgiar.org/eva), a Lettuce Evaluation

Network was established, this included the development of a standard ontology to collect metadata and evaluation data.

4. Gap and redundancy analysis

Within the PRO-GRACE WP4, devoted to evaluation and valorisation of Plant Genetic Resources (PGRs), the deliverable D4.1 gathers a set of available documents, websites and initiatives aiming at listing catalogues of descriptors of PGR phenotypic and agronomic characteristics. This deliverable helps us to **highlight several gaps in** proposing unified, crop-specific standards and protocols for the evaluation of the phenotypes and agronomic characteristics of PGRs.

We focused our first analysis for D4.1 on Plant Genetic Resources for Food and Agriculture (PGRFA) dedicated to agronomy. We first organised the gathered information into four groups of crop species: Fruit trees, Fruit vegetables, Leafy vegetables, Grains (cereals and legumes). In future, **other groups of crop species should be considered as well**, such as tuber and root crops, woody plants, fibre plants, forage crops, medicinal plants, and so on. It is also important to highlight that internationally agreed descriptors for many species are, to the best of our knowledge, still not available.

We aimed at listing descriptors used for PGRs. **A standard descriptor is a combination of a specific trait name, a method used for assessing the trait value, and the scale of the measurement, as well as the protocol used**. Trait names, methods, scales and protocols need to be harmonized between catalogues of descriptors. D4.1 emphasizes the **heterogeneity of phenotypic descriptors** between the 4 groups of crop species and even between the crop species belonging to the same group of crop species, as well as **the redundancy of descriptor catalogues for some crop species**. PRO-GRACE project partners and ECPGR, MIAPPE, Crop Ontology, EMPHASIS organisations use different phenotypic traits, methods and scales and denominations for each one. However, most of the descriptor catalogues are **not necessarily interoperable**. They can lack common vocabulary and scales, even for the same species. In addition, the catalogues are **not machine-actionable** and difficult to access, due to availability in pdf format for example. These drawbacks hinder the comparison between phenotyping projects for a specific crop species or for multiple crops, and the reuse of phenotypic data. Furthermore, the fact that these catalogues are not machine-actionable **limits the possibility of easily constructing a unified catalogue of standardized descriptors for each specific crop**.

We observed that some descriptor catalogues date back to the last century or the beginning of the current one, such as the IPGRI and UPOV descriptors for Apple. More generally, most descriptor catalogues are **not easily upgradeable**, as they are fixed at a specific date. However, in today's era of rapid development of new technology tools used in phenomics, such as image analysis, NIRS (near infrared spectroscopy), etc., it is **crucial to be able to add novel descriptors derived from new technologies**.

Several descriptor catalogues **do not include the collection of metadata** of where and in which conditions the phenotypic trial was carried out. According to the increasing interest in environmental effects on phenotypes (that we summarize as the Genotype by Environment (GxE) effect), it is crucial to systematically collect the environment information for each phenotyping trial (e.g. controlled vs. natural conditions, crop location, climatic curves during the plant development, agronomic itinerary, soil type, biotic and abiotic stresses, etc.). The MIAPPE protocols aim at generalizing this information for each phenotypic trial.

So far, **guidelines for harmonizing phenotyping trait names, methods, and scales as well as the minimum metadata information describing each specific phenotypic trial, are lacking** from all catalogues of descriptors for PGRs. These guidelines would help genebanks and international organizations, such as ECPGR, EMPHASIS, Crop Ontology, and others, to develop novel catalogues of descriptors for orphan crops and to improve existing ones. It could facilitate comparative analysis between crop species. Comparisons will also need to consider the environmental parameters, that would help researchers to evaluate the GxE effects on phenotype expression. For example, old descriptor lists, such as apple, pear and *Prunus*, lack information on management, site and weather conditions that are crucial for analysing GxE interactions.

In addition, **an official list of reference scientists responsible for up-to-date unified crop-specific guidelines for phenotyping PGRs** (preferably in pairs to anticipate sudden or expected absence) is lacking. These scientists would have recognised skills either in each crop, in each category of traits, or in each category of phenotypic methods (visual, image analysis, plant product processing...) including the recommended scales, as well as in experimental design. That would guarantee confidence in the evaluation of the phenotypic performance of PGRs. This list of reference scientists would help scientists and genebank curators in charge of describing genetic resources, to design new descriptor catalogues or adapt old ones, to include new traits to be considered or new phenotyping methods. These reference scientists would act as guardians of the up-to-date unified crop-specific guidelines for phenotyping PGRs, following general rules established by the GRACE-RI in collaboration with other relevant European Research Infrastructures, such as EMPHASIS and ELIXIR.

Finally, we suggest that the unified guidelines per crop species should also **address the issues of data management, including their FAIR character** (guaranteeing that they will be findable, accessible, interoperable and reusable). This has not been considered until now.

To conclude, to propose unified, crop-specific standards and protocols for the evaluation of the phenotypes and agronomic characteristics of PGRs, further catalogues of descriptors need to include first the recommended checklist of metadata required to adequately describe the plant phenotyping experiment as recommended by the MIAPPE (Minimum Information About Plant Phenotyping Experiments) requirement. Second, descriptors need to be harmonized according to trait ontology and crop ontology, requiring a panel of reference scientists responsible for up-to-date unified crop-specific guidelines for phenotyping PGRs. Third, scientists and curators involved in phenotypic assessment must ensure the correct storage of phenotypic data to ensure that the data are FAIR and follow a certified data management plan. These preliminary requirements will help to build the standards and protocols adopted by the future GRACE-RI.

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Deviations

D4.1 aiming at producing a unified, crop-specific standards and protocols for the evaluation of the phenotypes and agronomic characteristics of PGR, incorporating the ECPGR, MIAPPE, Crop Ontology, EMPHASIS and final user recommendations and methodologies is a preliminary version. This first version is thus incomplete and does not include all crops. D4.3 dealing with the same goal will be an improved version.

Annex 1

FRUIT VEGETABLES

Crop common name	scientific name	urls	date of publication	main descriptor classes
Capsicum peppers	*Capsicum* spp.	https://cgspace.cgiar.org/handle/10568/72851	1995	(plant, inflorescence and fruit, seed), Evaluation (plant, abiotic
Cucurbitaceae	*Cucumis spp., Cucurbita spp. and Citrullus spp.*	https://cgspace.cgiar.org/handle/10568/104810	1983	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed), stress susceptibility, disease and pest susceptibility
Cucurbitaceae	*Cucumis spp., Cucurbita spp. and Citrullus spp.*	https://www.ecpgr.cgiar.org/fileadmin/templates/ecpgr.org/upload/NW_and_WG_UPLOADS/Cucurbits_DescriptorLists.pdf	2008	Minimum characterization descriptors
Eggplant	*Solanum melongena*	https://cgspace.cgiar.org/handle/10568/72874	1990	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed), stress susceptibility, disease and pest susceptibility
Melon	*Cucumis melo*	https://cgspace.cgiar.org/handle/10568/72690	2003	Passport, Management, Environment and Site, Characterization (plant, inflorescence and fruit, seed), Evaluation (plant, abiotic stress susceptibility, biotic stress susceptibility)
Pepino	*Solanum muricatum*	https://cgspace.cgiar.org/handle/10568/72608	2004	Passport, Management, Environment and Site, Characterization (plant, inflorescence and fruit, seed), Evaluation (plant, abiotic stress susceptibility, biotic stress susceptibility)
Solanaceae (major fruit crops)	*Solanum melongena, Capsicum* spp., *Solanum lycopersicum*	https://www.ecpgr.cgiar.org/fileadmin/templates/ecpgr.org/upload/NW_and_WG_UPLOADS/Solanaceae_Misc/Solanaceae_descriptors.pdf	2008	Minimum characterization descriptors
Solanaceae (minor fruit crops)	*Solanum muricatum, Physalis peruviana, Solanum betaceum*	https://www.ecpgr.cgiar.org/fileadmin/templates/ecpgr.org/upload/NW_and_WG_UPLOADS/Solanaceae_Misc/Descriptors_minor_crops_NEW_for_Web_22022013.pdf	2013	Minimum characterization descriptors
Tomato	*Solanum lycopersicum*	https://cgspace.cgiar.org/handle/10568/73041	1996	Passport, Management, Environment and Site, Characterization (plant, inflorescence and fruit, seed), Evaluation (plant, abiotic stress susceptibility, biotic stress susceptibility)
Strawberry	*Fragaria x ananassa*	https://cgspace.cgiar.org/handle/10568/72947	1986	Passport, Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
		https://cropontology.org/term/CO_372:ROOT	-	Crop Onotology

FRUIT TREES

Crop common name	scientific name	urls	date of pubblication	main descriptor classes
Almond	*Prunus dulcis*	https://cgspace.cgiar.org/handle/10568/104209	1981	Passport, Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
		https://cgspace.cgiar.org/handle/10568/72793	revision 1985	
Anona	*Annona cherimola*	https://cgspace.cgiar.org/handle/10568/104849	2008	Passport, Management, Site (soil, wheather), Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Apple	*Malus x domestica*	https://cgspace.cgiar.org/handle/10568/72794; https://cropontology.org/term/CO_370:ROOT	1982	Passport, Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Apricot	*Prunus armeniaca*	https://cgspace.cgiar.org/handle/10568/73447	1991	Passport, Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Avocado	*Persea spp.*	https://cgspace.cgiar.org/handle/10568/72796	1995	Passport, Management, Site (soil, wheather), Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Banana	*Musa spp.*	https://cgspace.cgiar.org/handle/10568/72799	1996	Passport, Management, Site (soil, wheather), Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
		https://cropontology.org/term/CO_325:ROOT	-	Crop ontology
Cherry	*Prunus avium, P. cerasus*	https://cgspace.cgiar.org/handle/10568/72853	1985	Passport, Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Coffee	*C. canephora & C. arabica*	https://cgspace.cgiar.org/handle/10568/72788	1996	Passport, Management, Site (soil, wheather), Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Citrus	*Citrus spp*	https://cgspace.cgiar.org/handle/10568/72733	1999	Passport, Management, Site (soil, wheather), Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Durian	*Durio zibethinus*	https://cgspace.cgiar.org/handle/10568/72585	2007	Passport, Management, Site (soil, wheather), Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Fig	*Ficus carica*	https://cgspace.cgiar.org/handle/10568/72691	2003	Passport, Management, Site (soil, wheather), Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Grapevine	*Vitis spp.*	https://cropontology.org/term/CO_356:ROOT	2017	Transposition in the Crop Ontology format of the OIV descriptors: Morphological, physiological, Abiotic stress, biotic stress, quality, Agronomic morphological, physiological, Abiotic stress, biotic stress, quality, Agronomic
Hazelnut	*Corylus avellana*	https://cgspace.cgiar.org/handle/10568/72598	2008	Passport, Management, Site (soil, wheather), Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Jackfruit	*Artocarpus heterophyllus*	https://cgspace.cgiar.org/handle/10568/72703	2000	Passport, Management, Site (soil, wheather), Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Litchi	*Litchi chinensis*	https://cgspace.cgiar.org/handle/10568/72694	2002	Passport, Management, Site (soil, wheather), Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Mangaba	*Hancornia speciosa*	https://cgspace.cgiar.org/handle/10568/90693	2018	Passport, Management, Site (soil, wheather), Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Mango	*Mangifera indica*	https://cgspace.cgiar.org/handle/10568/72607	2008	Passport, Management, Site (soil, wheather), Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Papaya	*Carica papaya*	https://cgspace.cgiar.org/handle/10568/72903	1988	Passport, Site (soil, wheather), Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease

Peach	*Prunus persica*	https://cgspace.cgiar.org/handle/10568/72905	1984	Passport, Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Pear	*Pyrus communis*	https://cgspace.cgiar.org/handle/10568/72906	1983	Passport, Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Pistachio and relatives	*Pistacia vera and Pistacia spp*	https://cgspace.cgiar.org/handle/10568/72917	1997	Passport, Management, Site (soil, wheather), Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
		https://cgspace.cgiar.org/handle/10568/72916	1998	
Plum	*Prunus domestica, P. salicina, Prunus spp*	https://cgspace.cgiar.org/handle/10568/72940	1984	Passport, Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Rambutan	*Nephelium lappaceum*	https://cgspace.cgiar.org/handle/10568/72693	2003	Passport, Management, Site (soil, wheather), Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Walnut	*Juglans regia*	https://cgspace.cgiar.org/handle/10568/73159	1994	Passport, Management, Site (soil, wheather), Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease
Tropical fruit (various)		https://cgspace.cgiar.org/handle/10568/73058	1980	Passport, Site (soil, wheather), Vegetative, Fenological, Yield, Quality, Susceptibility to stress, pest and disease.

LEAFY VEGETABLES

Crop common name	scientific name	urls	date of publication	main descriptor classes
Leafy brassicas	Brassica spp.	https://cropgenebank.sgrp.cgiar.org/images/file/learning_space/descriptors_brassica_raphanus.pdf	1990	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed), stress susceptibility, disease and pest susceptibility
Rocket	Eruca spp.	https://cgspace.cgiar.org/handle/10568/72775	1999	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed), stress susceptibility, disease and pest susceptibility
Cultivates lettuce, wild lettuce, spinach, chicory, endive	Lactuca sativa, L. serriola, L. saligna, L. virosa, Spinacia spp., Cichorium intybus, Cichorium endivia	https://www.ecpgr.cgiar.org/fileadmin/templates/ecpgr.org/upload/NW_and_WG_UPLOADS/LeafyVeg_misc/LeafyVeg_MinDescr.pdf	2009	Minimum characterization descriptors
Asparagus	Asparagus spp.	https://www.ecpgr.cgiar.org/fileadmin/templates/ecpgr.org/upload/WG_UPLOADS_PHASE_IX/LEAFY_VEGETABLES/Minimum_descriptors_for_asparagus_.pdf	2014	Minimum characterization descriptors
Rocket	Eruca spp.	https://www.ecpgr.cgiar.org/fileadmin/templates/ecpgr.org/upload/NW_and_WG_UPLOADS/LeafyVeg_misc/Eruca_descriptor_list.pdf	NA	Minimum characterization descriptors
Corn salad	Valerianella spp.	https://www.ecpgr.cgiar.org/fileadmin/templates/ecpgr.org/upload/NW_and_WG_UPLOADS/LeafyVeg_misc/Valerianella_descriptor_list.pdf	NA	Minimum characterization descriptors

GRAINS

Grain type	Crop common name	scientific name	urls (most recent guideline)	date of publication	main descriptor classes
Cereal	Wheat	Triticum sp. (durum, aestivum, dicoccum, spelta)	Crop Ontology Curation tool	2018	phenological, physiological, morphological, agronomic, quality, abiotic stress, biotic stress
Cereal	Barley	Hordeum vulgare	Crop Ontology Curation tool	2020	phenological, physiological, morphological, agronomic, quality, abiotic stress, biotic stress
Cereal	Rice	Oriza sativa	Crop Ontology Curation tool	2016	phenological, physiological, morphological, agronomic, quality, abiotic stress, biotic stress, biochemical, fertility
Cereal	Maize	Zea mays	Crop Ontology Curation tool	2016 (2023 updated)	phenological, physiological, morphological, agronomic, quality, abiotic stress, biotic stress, postharvest
Cereal	Finger Millet	Eleusine coracana	Key access and utilization descriptors for finger millet genetic resources (cgiar.org)	2010	phenological, morphological, agronomic, biotic stress
Cereal	Oat	Avena sativa	Crop Ontology Curation tool	2019	phenological, physiological, morphological, agronomic, quality, abiotic stress tolerance, biotic stress resistance, biochemical
Cereal	Sorghum	Sorghum bicolor	Crop Ontology Curation tool	2019	phenological, morphological, agronomic, biotic stress, quality
Cereal	Rye	Secale cereale	Descriptors for rye and triticale (cgiar.org)	1985	phenological, morphological, agronomic, quality, abiotic stress, biotic stress
Cereal	Pearl millet	Pennisetum glaucum	Crop Ontology Curation tool	2016	phenological, morphological, agronomic, biotic stress, fertility
Legume	Common bean	*Phaseolus vulgaris*	https://cgspace.cgiar.org/handle/10568/72698	1982	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed, grain quality), stress susceptibility, disease and pest susceptibility
Legume	Runner bean	*Phaseolus coccineus*	https://cgspace.cgiar.org/handle/10568/72914	1983	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed, grain quality), stress susceptibility, disease and pest susceptibility
Legume	Tepary bean	*Phaseolus acutifolius*	https://cgspace.cgiar.org/handle/10568/73381	1985	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed, grain quality), stress susceptibility, disease and pest susceptibility
Legume	Lima bean	*Phaseolus lunatus*	https://cgspace.cgiar.org/handle/10568/91220	1982	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed, grain quality), stress susceptibility, disease and pest susceptibility
Legume	Chickpea	*Cicer arietinum*	https://cgspace.cgiar.org/handle/10568/72855	1993	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed, grain quality), stress susceptibility, disease and pest susceptibility
Legume	Cowpea	*Vigna unguiculata*	https://cgspace.cgiar.org/handle/10568/72871	1993	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed, grain quality), stress susceptibility, disease and pest susceptibility
Legume	Faba bean	*Vicia faba*	https://cgspace.cgiar.org/handle/10568/72876	1985	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed, grain quality), stress susceptibility, disease and pest susceptibility
Legume	Peanut	*Arachis hypogaea*	https://cgspace.cgiar.org/handle/10568/72881	1992	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed, grain quality), stress susceptibility, disease and pest susceptibility

Legume	Pigeon pea	*Cajanus cajan*	https://oar.icrisat.org/8138/1/RP%201147.pdf	1981	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed, grain quality), stress susceptibility, disease and pest susceptibility
Legume	Pigeon pea	*Cajanus cajan*	https://alliancebioversityciat.org/publications-data/descriptors-pigeonpea-cajanus-cajan-l-millsp	1990	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed, grain quality), stress susceptibility, disease and pest susceptibility
Legume	*Lathyrus* spp.	*Lathyrus*	https://cgspace.cgiar.org/handle/10568/72702	2000	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed, grain quality), stress susceptibility, disease and pest susceptibility
Legume	Lentil	*Lens culinaris*	https://cgspace.cgiar.org/handle/10568/72887	1985	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed, grain quality), stress susceptibility, disease and pest susceptibility
Legume	Lupin	*Lupinus*	https://cgspace.cgiar.org/handle/10568/73417	1981	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed, grain quality), stress susceptibility, disease and pest susceptibility
Legume	Mung Bean	*Vigna radiata*	https://cgspace.cgiar.org/handle/10568/73435	1980	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed, grain quality), stress susceptibility, disease and pest susceptibility
Legume	Soybean	*Glycine max*	https://cgspace.cgiar.org/handle/10568/72944	1984	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed, grain quality), stress susceptibility, disease and pest susceptibility
Legume	Common bean	*Phaseolus vulgaris*	https://cgspace.cgiar.org/handle/10568/73356	2009	Minimum characterization descriptors
Legume	Chickpea	*Cicer arietinum*	https://cgspace.cgiar.org/handle/10568/73371	2010	Minimum characterization descriptors
Legume	Cowpea	*Vigna unguiculata*	https://cgspace.cgiar.org/handle/10568/73346	2010	Minimum characterization descriptors
Legume	Faba bean	*Vicia faba*	https://cgspace.cgiar.org/handle/10568/73351	2010	Minimum characterization descriptors
Legume	*Lathyrus* spp.	*Lathyrus*	https://cgspace.cgiar.org/handle/10568/73328	2009	Minimum characterization descriptors
Legume	Pigeon pea	*Cajanus cajan*	https://cgspace.cgiar.org/bitstream/handle/10568/73367/brief.pdf?sequence=3&isAllowed=y	2010	Minimum characterization descriptors
Pseudocereals	Quinoa	*Chenopodium quinoa*	https://cgspace.cgiar.org/handle/10568/69165	2013	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed, grain quality), stress susceptibility, disease and pest susceptibility
Pseudocereals	Buckwheat	*Fagopyrum*	https://cgspace.cgiar.org/handle/10568/72849	1994	Passport, Site, Characterization and preliminary evaluation (plant, inflorescence and fruit, seed, grain quality), stress susceptibility, disease and pest susceptibility
Pseudocereals	Amaranth	*Amaranthus*	https://npgsweb.ars-grin.gov/gringlobal/cropdetail?type=descriptor&id=159	na	Characterization