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D6.16 (B15, ACTIVITY 6.10, CNR-IPSP-FI) GUIDELINES ON GOOD PHENOTYPING PRACTICES BASED ON THE STRENGTHENING AND INTEGRATION OF EXISTING PHENOTYPING PLATFORMS AND TECHNOLOGIES AIMING AT THE DEVELOPMENT OF PIPELINES TO ASSESS AGRICULTURAL AND FORESTRY RESILIENT TRAITS

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Table of contents

1. INTRODUCTION

The CNR-IPSP in Florence (CNR-IPSP-FI) has been at the forefront of investigating plant responses to both biotic and abiotic stress factors. One of its central research objectives is advancing plant phenomics by enhancing high-throughput phenotyping platforms. Through the application of innovative, non-destructive digital technologies, CNR-IPSP-FI aims to develop improved germplasm with enhanced tolerance to environmental and biological stresses. To accomplish this, the institute has established a range of cutting-edge, environmentally controlled platforms as well as advanced field-based systems, providing an integrated approach to plant phenotyping.

In the controlled environment, CNR-IPSP-FI operates a walk-in phytotron equipped with a state-of-the-art XYZ robotic system, which supports a multi-sensor platform for the automated collection of high-resolution digital data from plants at predefined intervals. The system enables the monitoring of various phenotypic traits over time. Additionally, the facility includes pots placed on scales in which plants are grown individually, allowing precise control of irrigation, weight monitoring, and transpiration dynamics for each plant. This level of precision provides vital insights into water use efficiency and plant stress responses at an individual plant level.

To complement the controlled environments, field-based high-throughput phenotyping platforms, such as fleets of drones, rovers, and a gantry crane system, have been deployed. These platforms are equipped with a variety of non-destructive sensors that are essential for capturing spatial and temporal variability in crop performance across large fields. These sensors include optical devices such as multispectral, hyperspectral, and fluorescence cameras, infrared thermography systems, and LiDAR (Light Detection and Ranging) technology, which are widely used for generating detailed vegetation indices and assessing crop health and vigor.

In addition to these high-throughput technologies, CNR-IPSP-FI employs portable "ground truth" validation tools, such as gas exchange and fluorescence sensors, which serve as critical reference standards. These lean phenotyping tools are used to validate the accuracy of remote and proximal sensing data collected from the drones, rovers, and robotic systems. Furthermore, advanced metabolomics and volatilomics tools enhance the infrastructure, enabling researchers to detect and quantify biomolecules of agricultural and industrial relevance. These integrated platforms enable the precise identification of crop genotypes with superior adaptation to changing environmental conditions, contributing to climate change mitigation strategies.

The high-throughput phenotyping platforms at CNR-IPSP-FI are designed for the rapid, high-frequency screening of a large number of crop varieties across different environments. This allows for the detailed analysis of plant structure, function, productivity, and interactions with the environment, fostering crop improvement efforts. By leveraging the genetic diversity of crops, the platforms play a pivotal role in enhancing plant productivity and supporting innovation in plant breeding programs.

However, the advanced automated data collection capabilities of these platforms generate vast amounts of data, introducing significant challenges in data management, metadata collection, and data annotation. To address these challenges, the CNR-IPSP-FI plant phenotyping laboratory is developing a comprehensive computational infrastructure tailored to manage this complexity. This hybrid infrastructure combines local computing resources for preliminary analysis with a cloud-based platform for sharing, processing, and publishing research outputs, from raw datasets to practical applications.

The architecture of the computational system is designed to ensure effective data harmonization and reuse, integrating versatile data pipelines to manage the diverse datasets collected by the phenotyping platforms. These datasets will serve as a foundation for applying machine learning and artificial intelligence (AI) approaches. By leveraging AI and deep learning, researchers will be able to synthesize large, multivariate datasets, facilitating more precise and rapid quantification of key physiological traits across many plant replicates. The integration of AI-based tools will accelerate discoveries related to plant productivity, stress resilience, and trait improvement.

To ensure the long-term usability, transparency, and reproducibility of the data, the phenotyping laboratory adheres to the FAIR principles (Findable, Accessible, Interoperable, and Reusable). By following these best practices in data curation and management, the laboratory supports the broader scientific community in accessing, reusing, and building upon the data generated by the phenotyping platforms. The adherence to FAIR principles ensures that datasets are properly documented, searchable, and available for future research, contributing to the collective efforts in advancing plant science and addressing global agricultural challenges.

2. ENHANCING THE CAPACITY OF THE ITALIAN PHENOTYPING PLATFORMS

CNR-IPSP-FI can play a pivotal role in advancing national integration by leveraging its advanced high-throughput phenotyping platforms to achieve two primary scientific goals at the national level: (1) optimizing biodiversity resources to enhance soil health by improving nutrient cycling, water retention, and organic matter content, and (2) identifying and selecting genotypes that are tolerant to both abiotic and biotic stresses. These genotypes will be specifically chosen for their ability to thrive in harsh environments and contribute to sustainable food production, with the long-term goal of restoring degraded lands. This approach emphasizes the integration of cutting-edge phenotyping technologies to address critical environmental challenges, particularly in Mediterranean dryland ecosystems. By combining innovative technological approaches with sustainable, nature-based strategies, CNR-IPSP-FI aims to improve soil fertility, rehabilitate degraded environments, and enhance the resilience of ecosystems to climate change-induced stresses. Through this multidisciplinary strategy, the institution can contribute significantly to both national and global efforts to promote sustainable agriculture and ecosystem restoration.

High-throughput phenotyping platforms will be central to this effort, as they enable the rapid and accurate assessment of plant traits associated with soil fertility, resilience to environmental stresses, and symbiotic relationships with root-associated microbes. The identification of superior genotypes and beneficial microbial consortia can significantly improve agroforestry systems, particularly in drylands. By enhancing soil structure, increasing organic carbon content, and improving water and nutrient retention, these solutions contribute to both agricultural productivity and ecosystem health.

The advanced platforms for digital agriculture and high-throughput phenotyping (HTP) developed at the CNR-IPSP-FI have been acquired since 2022 through funding from the following projects:

- **ENI-IPSP Joint Research Center "Acqua - Ipazia d'Alessandria" 2019-2024**, dedicated to promoting innovative solutions and technologies for efficient water management aimed at enhancing water resource utilization.
- **Infrastructure Development Project - CNR Biennial Intervention Program 2021-2022**: Phenotyping platforms.
- **Infrastructure Development Project - CNR Biennial Intervention Program 2022-2023**: Metabolomics platforms.
- **PO FESR Basilicata 2014-2020 PHENOLAB 4.0**: A project focused on strengthening the high-efficiency plant phenotyping research infrastructure within the national node of the ESFRI EMPHASIS Project, 2021-2023. Lead proponent: ALSIA; Co-proponent: CNR; Duration: 2022-2025.
- **PNRR ITINERIS - Italian Integrated Environmental Research Infrastructures System (2022-2025).**

These platforms support work at various scales, ranging from cellular (in the lab) to full-crop analysis (in the field).

3. Cell and Tissue, Metabolomics and Volatilomics Phenotyping Platform:

The cell and tissue phenotyping platform is equipped with:

- **Fourier Transform Infrared (FTIR) spectrometer** (IRXross AIM 9000, Shimadzu) for metabolite profiling.
- **Laser Microdissector (LMD6, Leica)** paired with a **microtome (RM2125, Leica)** for gene expression studies in response to different genotype-environment interactions.
- State-of-the-art metabolomics (**HPLC-Q-TOF**) and volatilomics (**GC-MS**, **PTR-Aim-TOF-MS**) equipment to generate high quality platforms for selecting crop genotypes to mitigate the effects of climate change;
- A fully automated phenotype microarray system (**Biolog OmniLog)** performing 1,920 phenotypic assays simultaneously to measure physiological responses in diverse microbial cells.

This primary equipment has been supplemented with additional laboratory equipment, including chemical fume hood, centrifuges, freeze dryers, LED panels, analytical and precision scales, and other specialized instruments. These technologies are essential for studies ranging from metabolic profiling to gene expression analysis across various environmental and genetic scenarios.

4. Field-Based and Precision Agriculture Phenotyping Platforms:

The platforms for field phenotyping and precision agriculture include:

- **Portable equipment for "ground truth" validation**
- **Instruments equipped with proximal and remote sensing technologies.**

The "ground truth" portable instrumentation provides point-based measurements that serve as reference standards to evaluate the accuracy of biometric and vegetation indices derived from proximal/remote sensing data. The portable equipment includes:

- **Infrared Gas Analyzers (IRGA)** for gas exchange and photosynthesis fluorescence analysis (Ciras 3-4, PP Systems; Li-6800, LICOR),
- **Porometers-fluorometers** (Li-600, LICOR),
- **Chlorophyll, flavonoid, anthocyanin, and nitrogen content analyzers** (Dualex, Force-A),
- **Canopy analyzers** for indirect estimation of Leaf Area Index (LAI) (LAI-2200c, LICOR),
- **Portable sensors for soil moisture monitoring** (TDR, TR85, Handy-TRASE) coupled with fixed meteorological sensors including radiometers, thermohygrometers, leaf wetness sensors, and soil moisture and temperature sensors at three depths, with real-time data available on a web platform.
- Sun induced fluorescence

5. **Proximal and Remote Sensing Platforms:**
   - **A rover equipped with a fluorescence camera (Fluorcam FC 1300-R, PSI)** for estimating Photosystem II (PSII) activity in response to abiotic stress.
   - **A rover with a telescopic arm extendable up to 16 meters** equipped with sensor systems (commercially available), including:
     - **Thermal and multispectral cameras** (Altum PT, Micasense) for canopy temperature and vegetation index measurements in the visible and infrared spectrum.
     - **Hyperspectral camera** for studying vegetation indices across a wide range of spectral bands.
     - **LiDAR** for generating 3D models of vegetation. All instruments are remotely controlled for real-time data acquisition.
   - **A gantry crane-pivot prototype**, compatible with the rover sensors, for georeferenced, repeatable monitoring of morphological and physiological parameters over a 4000 m² area.
   - **A fleet of 5 drones** equipped with real-time kinematics systems for centimeter-level accuracy (DJI Matrice 300), fitted with multispectral, hyperspectral, LiDAR, thermal, and RGB cameras.
   - **A MicroScan**, a compact, portable system designed for automating digital plant phenotyping. It is equipped with 3D laser, near-infrared, red, green, blue sensors to capture multispectral plant data, enabling the calculation of over 20 plant parameters.
   - **Two high performance spectroscopy systems** (each instrument consists in two high performance spectrometers contained in a temperature controlled compartment) for the continuous and unsupervised retrieval of passive Sun-Induced-Fluorescence (SIF) and spectrally resolved reflectance.
6. **Walk-in phytotron platform for high-resolution and high-throughput phenomics**, consisting of a growth capsule that is equipped with a RGB morphometric imaging systems and high-sensitivity chlorophyll fluorescence imaging, transported by an automated robotic system, along with software for the management and remote

processing of the generated big data. The growth capsule uses LEDs, as the sole light source, providing excellent spectral quality with high irradiance. The system enables the investigation of plant trait variability in response to well-defined and monitored environmental factors (both abiotic and biotic). The platform has the capacity to accommodate several dozen plants.

These platforms represent state-of-the-art infrastructure for digital agriculture and high-throughput phenotyping, providing an integrated suite of tools designed to monitor plant responses across multiple scales, from cellular processes to field-level analyses. Such advanced resources are pivotal in addressing critical challenges in agriculture, particularly in enhancing crop resilience, promoting precision agriculture, conserving biodiversity, and fostering sustainable farming practices to mitigate the impacts of climate change.

To maximize the utility of this cutting-edge equipment, it will be utilized to bolster the research capacity of the EMPHASIS-PhenItaly research groups in collaboration with CNR-IPSP-FI. The primary goal is to develop innovative, non-destructive phenotyping platforms that optimize the use of natural and biological resources in agriculture. These platforms are expected to advance the understanding of plant-environment interactions, resource-use efficiency, and crop adaptation strategies under diverse environmental conditions. In this context, collaboration agreements have been signed with the following institutions:

1. Dipartimento di Scienze Agrarie, Forestali e Alimentari - Università degli Studi di Torino
2. Department of Agricultural and Food Sciences - Università degli Studi di Bologna
3. Centro Ricerca e Innovazione - Fondazione Edmund Mach
4. Centro di Ricerca Cerealicoltura e Colture Industriali - Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA).

These agreements include the deployment of portable equipment acquired under the ITINERIS initiative to experimental sites managed by these institutions. Collaborative research activities are already underway at these locations in partnership with CNR-IPSP-FI, utilizing this advanced instrumentation. The integration of these platforms into ongoing experiments will facilitate the collection of high-resolution phenotypic data, supporting cutting-edge research in crop science and sustainable agricultural development. Such collaborations exemplify a unified effort to leverage advanced technologies in addressing the pressing demands of modern agriculture while promoting scientific innovation and sustainable resource management.

3. CRITERIA LIST USER DEMANDS

The services provided by the high-throughput phenotyping platforms will focus on supporting training and education in plant phenotyping, as well as expanding research networks. These platforms will offer:

- **Training and Education**: Workshops, hands-on training, and educational programs designed to enhance the skills of researchers, students, and professionals in the field of plant phenotyping. The platforms will provide practical experience with cutting-edge phenotyping technologies, data acquisition, and analysis techniques.

- **Access to Installations**: Researchers and institutions will be able to request access to the advanced phenotyping installations for conducting experiments. This will include access to the controlled environment phytotron systems and field-based platforms equipped with proximal and remote sensing technologies.
- **Data Access**: Requests for access to phenotypic data generated by the platforms will be facilitated, enabling researchers to utilize the datasets for their studies. The platforms will support data sharing in alignment with the FAIR principles (Findable, Accessible, Interoperable, and Reusable), ensuring that data is available for reuse in further research.

These services aim to foster collaboration, enhance research capabilities, and promote the integration of advanced plant phenotyping methods within the broader scientific community. CNR-IPSP-FI aims to provide a variety of services that require different access modes to the EMPHASIS-Phenitaly infrastructure. The key focus areas of these services include:

- **ACCESS**: Provision of access to the phenotyping installations for the user community, including controlled environment installations, field installations, networks of field sites, and modeling tools. This ensures broad access to state-of-the-art phenotyping facilities for researchers.
- **QUALITY**: Implementation of quality measures at the research infrastructure, specifically focusing on experimental design, adherence to standards, and sensor calibration to ensure the accuracy and reliability of phenotypic data collection.
- **DATA MANAGEMENT**: Development of approaches to enable data reusability, embedded within a relevant data policy. This will ensure that data generated by the infrastructure is well-documented and reusable, following best practices for data curation and sharing.
- **INNOVATION**: Dissemination and utilization of the technology and results from access and use of the phenotyping installations, promoting advancements in phenotyping methods and agricultural technologies.
- **COMMUNICATION**: Active engagement with all relevant stakeholders, including researchers, policymakers, and industry representatives, to foster collaboration and ensure the widespread impact of the infrastructure's activities.
- **TRAINING**: Support for the next generation of plant scientists through education and training programs, including hands-on experience with the phenotyping platforms, enhancing the skillset of future researchers in plant science.
- **EXPERT ADVICE**: Provision of expert assessments of the plant phenotyping landscape, offering guidance and insights to funders and decision-makers to inform policy and funding strategies related to phenotyping and plant science research.

These services are designed to enhance the accessibility, quality, and impact of the EMPHASIS-Phenitaly infrastructure, while fostering collaboration, innovation, and capacity-building within the global plant phenotyping community.

The goal of CNR-IPSP-FI, as part of an integrated infrastructure, is to optimize access to plant phenotyping facilities and services and to facilitate the seamless use of these infrastructures across the entire phenotyping pipeline. This pipeline includes sensors and imaging techniques, data integration, validation and calibration, data analysis in relation to environmental conditions, data organization and storage, and data interpretation in a biological context, culminating in meta-analysis. The implementation of various services and access modes will provide tangible benefits, particularly in terms of enhancing knowledge exchange and promoting technology transfer. These improvements will streamline the research process, allowing for more efficient and effective use of the infrastructure's capabilities. The following sections provide detailed descriptions of each access mode, illustrating how these infrastructures will support users at every stage of the phenotyping process - from data collection to interpretation and application.

Development access will be implemented at two different levels:

1. **Internal Development Access (IDA)**: This access mode is designed for EMPHASIS-Phenitaly partners and focuses on establishing quality standards to enhance data reusability. Key areas of focus under IDA include:
   - **QUALITY**: Ensuring that quality standards are upheld throughout the phenotyping process to promote consistency and accuracy.
   - **DATA MANAGEMENT**: Implementing robust data management practices to ensure data is organized, annotated, and easily reusable.
   - **TRAINING**: Providing ongoing training opportunities to build capacity in high-throughput phenotyping and data handling.
2. **External Development Access (EDA)**: This access mode is dedicated to external partners and focuses on validating new technologies under realistic conditions. The EDA will be governed by an Access Agreement between external users and service providers. The services provided under EDA include:
   - **ACCESS**: Enabling external partners to access phenotyping installations and infrastructures to validate and test new technologies.
   - **INNOVATION**: Supporting the development and integration of innovative solutions by collaborating with external users and validating them using established methods.
3. **User Access (UA):**
   User access (UA) is designed for researchers who aim to study plant phenotypes to address critical challenges in plant agriculture. UA offers different types of services based on the specific goals of the user, including:
   - **ACCESS**: Providing access to phenotyping installations, project calls for funding, and relevant technologies.
   - **QUALITY**: Offering access to established quality standards for accurate and reproducible phenotyping.
   - **DATA MANAGEMENT**: Ensuring users have access to robust data management systems for efficient handling of their phenotypic data.
   - **INNOVATION**: Providing pathways for translating research into practical applications, including access to market opportunities for innovative technologies.
   - **TRAINING**: Delivering specialized training to enhance the skills of researchers in plant phenotyping.
4. **Dissemination Access (DissA):**
   Dissemination access (DissA) focuses on promoting plant phenotyping knowledge and skills through the following services:
   - **TRAINING**: Offering structured educational programs and workshops to enhance knowledge in plant phenotyping.

- **COMMUNICATION**: Engaging with stakeholders through reports, events, and other dissemination activities to share advancements in phenotyping research.
- **EXPERT ADVICE**: Providing expert guidance and consultation on plant phenotyping to various stakeholders, including policymakers, industry, and academia.

As outlined in Deliverable 3.2, the EMPHASIS-Phenitaly training strategy includes:

- **Coordinating and supporting training activities** across Italy's plant phenotyping community.
- **Guiding European scientists** by offering clarity and orientation on the vast array of training courses available in the phenotyping field.
- **Developing and maintaining an online platform** that catalogs available courses, with quality indicators to ensure a high standard of training.
- **Identifying critical skills** required for plant phenotyping and addressing these through targeted training programs.
- **Coordinating the design and execution of RI (Research Infrastructures) staff training courses**, ensuring that facility staff are equipped with the necessary skills to support phenotyping activities.

The EMPHASIS-Phenitaly community benefits from the presence of leading plant phenotyping experts who promote and coordinate high-quality training initiatives.

5. **Dissemination to a Wide Range of Users:**

Dissemination access to EMPHASIS infrastructures targets a broad audience, including Master and PhD students, postgraduates, junior and senior scientists, and technicians from both industry and academia. Additionally, facility staff across Italy will benefit from these dissemination activities.

Moreover, various stakeholders will gain insights from dissemination efforts, such as reports on the plant phenotyping landscape, which could influence the European research agenda by identifying gaps and emerging needs, supporting the development of new infrastructures or services to address those areas.

User demands will be analyzed based on the type of infrastructure involved and the different access modes available. This approach will ensure that the specific needs of users are met by tailoring access to the appropriate phenotyping installations, whether they are controlled environment systems, field-based platforms, or data management tools. Additionally, the analysis will take into account the various access modes, such as internal development access, external development access, user access, and dissemination access, to ensure that services are aligned with the diverse goals of the user community, ranging from research and innovation to training and data management. This will facilitate a more efficient allocation of resources and optimize the use of phenotyping platforms for addressing agricultural and environmental challenges.

4. ONTOLOGY

We propose here an ontology of objects involved in phenotyping activities, defining the relationships between them and the rationale behind the proposed choices. This ontology is employed within the EMPHASIS-PhenItaly information system and facilitates enhanced communication among EMPHASIS-PhenItaly members and beyond, whether in internal or external documents. The ontology is the result of collaborative discussions within the consortium and will undergo periodic reassessment to ensure its relevance and alignment with ongoing developments in the field. All italicized terms that follow correspond to a controlled vocabulary, meaning they have a specific, defined meaning when first introduced (capitalized). This ensures clarity, consistency, and precision in communication across the consortium and with external stakeholders, promoting a shared understanding of key concepts and processes in plant phenotyping.

Distributed research infrastructures have different levels of organization, and here we follow the general nomenclature provided by the European Commission (EC), adapted to the specific context of plant phenotyping. Additionally, the organization of information systems necessitates precise definitions for terms that are often used interchangeably in everyday language but, in fact, represent distinct concepts and have different practical applications. In this document, we aim to clearly define these terms and explain the relationships between them. This approach ensures that there is a consistent understanding of the terminology used across the phenotyping infrastructure, minimizing confusion and promoting effective communication. By establishing a common vocabulary, we also facilitate better integration of research activities and data management across distributed platforms, ensuring that each concept is applied accurately and uniformly within the broader framework of plant phenotyping.

5. CONCLUSIONS

The establishment of a novel phenotyping infrastructure represents a major achievement in enhancing the research capacity of PhenItaly, positioning it as a leader in plant science and agricultural innovation. Plant phenotyping is increasingly acknowledged as a cornerstone for the future of crop breeding and selection, offering critical tools to confront pressing global challenges such as food security, environmental sustainability, and climate resilience. The phenotyping community faces the complex task of accurately assessing a growing diversity of plant traits across an expanding range of genotypes and ecotypes. Addressing these challenges requires far more than simply improving crop yields: it necessitates the selection of resilient plant varieties capable of thriving in resource-limited environments, resisting biotic and abiotic stresses, and supporting the transition to low-input, sustainable agricultural systems.

In response to these needs, the infrastructure developed through this project integrates advanced, non-destructive imaging technologies, compact and high-precision phenotyping equipment, cutting-edge metabolomics and volatilomics platforms, sophisticated data management systems, and innovative modeling approaches. This comprehensive technological portfolio enables high-throughput and high-resolution monitoring of plant phenotypes under both controlled and field conditions. The ability to simultaneously capture photosynthetic efficiency, thermal and multispectral indices, three-dimensional canopy structures, and gas exchange parameters significantly enhances the scope and precision of plant research.

The infrastructure has been specifically designed to foster a deep understanding of plant responses to environmental conditions, elucidating the mechanisms of resistance, tolerance, and adaptation to a wide array of stress factors. High-throughput phenotypic data acquisition is instrumental in driving innovation in precision agriculture, the optimization of crop management practices, and the development of climate-resilient varieties. The collected data and research outputs will be made available through the ITINERIS Hub, promoting open and collaborative research based on the growing demand for innovation and interdisciplinary approaches.

Moreover, this platform extends its applications beyond abiotic and biotic stress studies. It supports research aimed at enhancing natural biocontrol strategies against pests and weeds, improving water use efficiency, restoring degraded ecosystems, optimizing agri-food quality and yield, and promoting the selection and valorization of plant germplasm. Additionally, it contributes to the production of agro-industrially relevant biomolecules and to global efforts to mitigate the impacts of climate change, reinforcing the role of agriculture and forestry in environmental stewardship.

The integration of phenotyping technologies with ecological research addresses fundamental questions in plant biology and ecosystem dynamics. By advancing scientific understanding at the intersection of plant sciences and environmental sciences, the infrastructure enables novel strategies for the sustainable management of agricultural and forestry systems. These efforts are aligned with a broader vision of digital agriculture and ecological restoration, paving the way for transformative advancements in food security, biodiversity conservation, and sustainable development.

Importantly, this initiative also responds to the evolving needs of the plant phenotyping community. Designing new crop and forestry varieties, characterizing plant responses to complex environmental stimuli, and enhancing breeding programs are central objectives that require the continuous evolution of phenotyping technologies. Functional traits, linking genotype to phenotype, will remain a central focus in future phenotyping activities. The platform, therefore, provides essential tools to overcome the bottlenecks that currently limit the translation of genomic knowledge into practical breeding outcomes.

However, the successful implementation of high-throughput phenotyping also highlights areas requiring further development. Among the most urgent needs identified by the community are improvements in data analysis, the expansion of modeling capabilities, and the seamless integration of novel technologies into user workflows. Furthermore, there is a clear demand for expanded access to multiscale infrastructures, offering opportunities for controlled environment experiments, field-based studies, and computational modeling across a diverse range of plant species, extending beyond the major crops to include underutilized and ecologically significant species.

To fully realize the potential of the infrastructure and the vision of PhenItaly, future efforts must prioritize the expansion of capacity, the development of comprehensive and interoperable data management systems, and the establishment of integrated workflows that promote collaboration among researchers, technology providers, and end-users. Ensuring interoperability and data exchange across installations, experimental sites, and research projects will be essential to fostering innovation and maximizing the scientific impact of phenotyping activities.

In conclusion, the creation of this novel phenotyping infrastructure represents a strategic investment that significantly strengthens PhenItaly’s role within the EMPHASIS research infrastructure and, more broadly, within the global research landscape. It establishes a solid foundation for addressing some of the most pressing scientific and societal challenges of our time, while promoting the development of a more resilient, sustainable, and productive future for agriculture and forestry.