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THE ROLE OF OPEN SCIENCE INFRASTRUCTURES IN SUPPORTING RELIABLE DIGITAL RESEARCH ECOSYSTEMS

ABSTRACT. *The study focuses on the analysis of a unified information space for European research infrastructures from the perspective of Open Science service integration. The aim is to identify key components of the digital research ecosystem and justify possibilities for their integration into a coherent environment. The research employs system analysis, comparative review, and conceptual modelling of digital research infrastructures. The results indicate that current Open Science platforms are characterized by fragmented APIs, heterogeneous metadata standards, and limited interaction with mobile systems. Key integration points related to researcher identification, data management, and scientific resource aggregation are identified. The findings confirm that the development of a unified information space is essential for improving research efficiency and supporting the advancement of Open Science practices.*

KEYWORDS: *Open Science data; research infrastructures; interoperability; digital platforms; metadata; unified information space.*

INTRODUCTION. Over the last decade, the European research landscape has been changing quite noticeably under the influence of digital technologies and data-driven science. The growth of data-intensive research, together with more distributed and international forms of collaboration, has gradually shifted the focus from individual research facilities toward interconnected digital environments. In this context, research infrastructures are increasingly understood not only as physical installations or specialized laboratories, but as complex socio-technical systems that combine data resources, computing capabilities, instruments, and digital services across institutional and national boundaries. The idea of a common information area for European research infrastructures has become more than just a policy direction. It is, in practice, a response to a very concrete problem: research data and services are still highly fragmented across platforms, disciplines, and countries. In many cases, this fragmentation is not only technical, but also organizational, as different infrastructures use different standards, metadata models, and access rules. As a result, valuable scientific resources remain partially isolated, which limits their reuse and reduces overall research efficiency.

The increasing emphasis on Open Science has made these issues even more visible. Researchers are now encouraged, and in many cases required, to make their outputs more transparent and reusable.

Within the European Research Area, initiatives such as ESFRI and EOSC have emerged as practical attempts to address these challenges and to gradually connect existing infrastructures into a more coherent ecosystem.

At the same time, it is important to recognize that the development of such an ecosystem is not driven only by policy frameworks. In practice, it strongly depends on data quality, metadata standards, and the availability of reliable digital services that support the full research lifecycle — from data creation to preservation and reuse. Without these elements, the idea of a unified information space remains mostly declarative. In this context, the next step is to look more closely at the actual components of the Open Science ecosystem and the way they operate in practice. In particular, it is necessary to examine key platforms, identifiers, repositories, and aggregation services that form the technical foundation of this environment. This allows moving from a conceptual discussion of a unified information space to a more applied analysis of the tools and systems that enable its implementation in real research workflows.

Literature Review and methodology of research. To analyze the potential for integrating mobile systems with scientific ecosystems, a review of key Open Science infrastructure services widely used in contemporary research environments was conducted. The focus was placed on platforms and systems that support research data management, scholarly communication, and researcher identification, as well as on their suitability for integration with mobile software–hardware complexes. One of the core platforms in the Open Science landscape is Zenodo, an open research repository that provides long-term preservation of research outputs and automatic DOI assignment (CERN, 2023). The platform supports a wide range of data types and offers relatively mature mechanisms for data access. However, the analysis shows that direct integration with mobile applications is not fully straightforward and often requires additional middleware layers to mediate between repository services and mobile client requirements, particularly in terms of data caching, offline access, and authentication workflows. Institutional repositories such as DSpace provide established functionality for storing, organizing, and managing scientific materials (Smith, 2002; Tansley et al., 2003). These systems are widely adopted across research institutions due to their flexibility and open-source nature. At the same time, integration with mobile environments remains challenging because of heterogeneous API implementations and limited support for mobile-oriented interaction patterns. This creates a need for standardized service layers that can abstract repository-specific logic and expose unified interfaces for mobile systems.

The ORCID system plays a critical role in the global research information infrastructure by providing unique and persistent identifiers for researchers (Haak et al., 2012). It enables reliable linkage between researchers and their scholarly outputs across multiple platforms. From an integration perspective, ORCID is particularly important for personalized services; however, effective interoperability still depends on consistent metadata alignment and synchronization mechanisms across heterogeneous systems.

The CORE aggregator provides centralized access to open scholarly publications and offers APIs for content search and analysis (CORE, 2023). Despite its strong aggregation capabilities, variability in metadata structures across sources remains a limiting factor for seamless integration with mobile systems. This heterogeneity affects the consistency of search results and requires additional normalization procedures when building unified mobile interfaces.

National-level systems such as OUCI provide citation analytics for Ukrainian scientific publications (OUCI, 2023), while URIS supports research information management at the institutional and national level (Zharinova et al., 2025). Both systems contribute significantly to the national research infrastructure; however, their integration potential is constrained by limited API standardization and insufficient support for mobile-first interaction models. The literature analysis indicates that the main challenges in integrating Open Science platforms with mobile systems include insufficient API unification, lack of standardized metadata schemas, complexity of authentication mechanisms, and strong dependence on web-oriented interfaces. These limitations create fragmentation at the application layer and increase the complexity of developing scalable mobile solutions.

The analysis identifies several key interaction points between mobile systems and scientific infrastructures, including access to research metadata, management of researcher profiles, aggregation of scientific content, and synchronization of citation data. These interaction points form a conceptual basis for designing integrated mobile software–hardware architectures capable of supporting end-to-end workflows in scientific data environments. Such architectures may contribute to improved accessibility, real-time interaction with research services, and enhanced reliability of distributed scientific systems.

From a methodological perspective, this study is based on a combination of systematic literature analysis and conceptual modelling of research infrastructures as digital ecosystems. The aim is not only to describe existing Open Science services, but also to understand how they interact within a broader information environment and what limitations emerge when these services are considered in the context of integration with advanced digital systems, including mobile and distributed software–hardware complexes.

The Concept of a Unified Information Space for Research Infrastructures. The concept of a unified information space for research infrastructures has gradually taken shape as a response to persistent fragmentation within the European research ecosystem. Rather than emerging as a purely theoretical construct, it reflects a practical attempt to address the reality in which research data, services, and digital resources remain distributed across numerous platforms, often with limited interaction between them. Over the past decade, initiatives such as the European Strategy Forum on Research Infrastructures (ESFRI) and the European Open Science Cloud (EOSC) have made this fragmentation more visible, particularly by demonstrating how difficult it is to align governance models, data practices, and technological solutions across different countries and scientific domains. At a conceptual level, a unified information space assumes that research outputs should not be confined to isolated institutional systems but instead made accessible through shared standards and interoperable frameworks. The idea itself is relatively straightforward: researchers should be able to discover, access, and reuse data regardless of where it is stored or who manages it. However, in practice this principle is difficult to implement consistently, since research infrastructures evolve unevenly and are shaped by different institutional priorities, funding mechanisms, and disciplinary traditions.

A key enabling principle of this environment is interoperability. Research infrastructures typically rely on heterogeneous technologies, domain-specific data models, and independently developed information systems. ESFRI roadmaps repeatedly highlight the need for convergence, yet real implementation remains partial and uneven. Interoperability in this context is therefore not a static technical property but a continuous process of alignment between standards, metadata schemas, identifiers, and exchange protocols that must coexist within a single, increasingly complex ecosystem.

Closely related to this is the FAIR framework, which has become a widely accepted reference point for research data management, including within EOSC-related developments. The principles of making data Findable, Accessible, Interoperable, and Reusable are now broadly endorsed at the policy level. However, implementation remains inconsistent. In many cases, infrastructures adopt FAIR principles selectively, depending on local constraints, institutional capacity, or the maturity of digital services. This creates a noticeable gap between formal commitment and practical realization.

This gap between policy ambitions and operational reality is particularly evident in the European Open Science Cloud. While EOSC promotes a federated and integrated approach to research data and services, the underlying systems are still partially fragmented, especially in terms of metadata harmonization and cross-platform service integration. As a result, the unified information space should be understood less as a completed architecture and more as an evolving ecosystem that is still under active construction. From this perspective, interoperability and FAIR-oriented practices form the conceptual backbone of the emerging European research information environment. They enable more consistent data exchange and support collaboration across institutional and national boundaries. At the same time, the experience of ESFRI and EOSC suggests that integration is not an automatic outcome of policy frameworks. It requires continuous coordination of technical standards, governance approaches, and institutional strategies within the broader European Research Area.

A similar logic is reflected in European coordination mechanisms supporting this transformation. ESFRI plays a central role in strategic planning and prioritization of research infrastructures, providing long-term roadmaps that guide their development and integration. EOSC, in turn, functions as a federated environment that connects existing infrastructures, repositories, and service providers, enabling access to research data and computational resources across borders. Together, these initiatives illustrate both the progress achieved in building a shared European research environment and the structural complexity that still limits full integration. The integration of national and international research infrastructures remains a critical factor in this process. As scientific activity becomes increasingly collaborative and cross-disciplinary, the demand for seamless access to data and services continues to grow. European initiatives encourage the

adoption of shared standards and interoperable systems at national level, which helps reduce fragmentation and improves the visibility and usability of research outputs. However, the overall picture remains one of gradual convergence rather than full unification.

Open Science Services as Components of Intelligent Digital Research Ecosystems. The ongoing digital transformation of research infrastructures has led to the emergence of complex software and hardware environments that support data-intensive scientific activities. Modern research infrastructures increasingly rely on distributed digital services, cloud platforms, repositories, persistent identifier systems, and automated data exchange mechanisms. Together, these components form intelligent digital ecosystems that enable efficient management and utilization of scientific resources.

Within this context, Open Science services can be considered an important functional layer of contemporary research infrastructures. Services such as research data repositories, persistent identifier systems, metadata registries, and federated access platforms provide mechanisms for data discovery, sharing, validation, and long-term preservation. Their integration contributes to the transparency and reproducibility of research processes while facilitating collaboration between institutions and research communities. The integration of Open Science services influences the operational characteristics of digital research environments. Standardized interfaces, interoperable data models, and automated workflows reduce the need for manual operations and improve the consistency of information exchange between system components. The use of established standards and shared digital services can increase the robustness of information processes by minimizing data duplication, synchronization errors, and interoperability issues.

The development of intelligent software and hardware complexes capable of interacting with Open Science infrastructures creates additional opportunities for monitoring system performance, collecting operational data, and supporting predictive analytics. These capabilities may contribute to improving system reliability and supporting data-driven decision-making within distributed research environments. Consequently, Open Science services should be viewed not only as instruments for data sharing but also as essential elements of modern digital ecosystems that support the sustainable operation and future development of research infrastructures.

Digital Tools and Standards Supporting Research Infrastructure Integration. The effective functioning of a unified information space depends on the availability of digital tools and standards that enable the identification, discovery, exchange, and reuse of research resources. These instruments provide the technical foundation for interoperability and support the implementation of Open Science principles across research infrastructures. Persistent identifiers play a particularly important role in ensuring the traceability and reliability of scientific information. Systems such as ORCID, DOI, and ROR provide unique and persistent references to researchers, research outputs, and organizations. ORCID facilitates the unambiguous identification of researchers and supports the integration of scholarly profiles across multiple information systems. DOI identifiers ensure permanent access to publications, datasets, software, and other research products, while ROR enables the standardized identification of research organizations. Together, these identifiers improve information quality, support automated data exchange, and strengthen connections between researchers, institutions, and research outputs.

Research repositories and infrastructure catalogues constitute another essential component of the digital research ecosystem. They provide mechanisms for storing, preserving, and disseminating scientific resources, including publications, datasets, software, and research services. Infrastructure catalogues further enhance resource visibility by offering structured information about available facilities, services, and research capabilities. Through centralized discovery mechanisms, these platforms facilitate access to distributed resources and support collaboration among research communities. Metadata standards and information exchange protocols are equally important for achieving interoperability between research infrastructures. Metadata provide structured descriptions of scientific resources, enabling their discovery, interpretation,

and reuse across different systems and disciplines. The adoption of common metadata schemas and standardized exchange protocols supports seamless communication between repositories, databases, and digital services. As a result, research infrastructures can efficiently share information, reduce duplication of effort, and improve the overall accessibility and usability of scientific resources.

The combined use of persistent identifiers, repositories, catalogues, and metadata standards forms the technological basis of the European research information ecosystem. These tools support the integration of heterogeneous resources and contribute to the development of a sustainable, interoperable, and researcher information space.

Prospects for Ukraine. The integration of Ukraine into the European research information space is currently characterized by a mixed landscape, where active digital transformation coexists with structural fragmentation of research information systems. On the one hand, there is a clear strategic movement toward alignment with the European Research Area and adoption of Open Science principles. On the other hand, many national systems still operate in isolation or only partially comply with interoperability requirements, which limits full integration into European infrastructures such as EOSC-based services.

A key example of existing fragmentation is the National Research Foundation of Ukraine's information environment, which remains only partially interoperable with European research information systems. In practice, its data exchange mechanisms are not fully aligned with standards used in EOSC-related services or research information aggregators such as URIS-compatible infrastructures. This results in additional manual processing of research outputs and limits automated integration of funding data, project results, and researcher profiles across systems.

Similar challenges can be observed in institutional repositories. For instance, the repository of the Ukrainian Institute of Scientific and Technical Expertise and Information-type repository ecosystem for dissertations and academic outputs is still largely based on scanned documents in PDF format. While this ensures long-term preservation, such an approach does not fully meet FAIR principles, particularly in terms of machine readability and data reuse. As a consequence, large volumes of Ukrainian scientific knowledge remain difficult to process automatically, which reduces their visibility in international aggregation systems and limits their reuse in data-driven research environments.

Issues related to metadata quality further complicate integration. A significant number of Ukrainian journals still produce inconsistent or incomplete metadata records, which leads to incorrect indexing or partial representation in global databases. These inconsistencies affect citation tracking, institutional analytics, and the visibility of Ukrainian publications in international research infrastructures. At the same time, gradual improvements can already be observed, particularly among journals that are transitioning toward DOAJ inclusion standards and adopting more structured metadata practices.

A similar duality exists in researcher identification systems. While ORCID adoption in Ukraine is widespread, in many cases it remains formal rather than functional. Researchers often create ORCID identifiers due to institutional requirements, but do not actively maintain or integrate them with publications, repositories, or funding systems. However, institutional-level integration is gradually improving, especially through participation in the ORCID Ukraine consortium and the increasing connection of repositories and journal platforms to ORCID APIs.

At the same time, positive developments are clearly visible. Many Ukrainian research institutions are transitioning toward repository systems with open APIs, enabling partial integration with international aggregators such as CORE and other Open Science services. There is also a gradual shift toward machine-readable metadata, especially in leading universities and research organizations that align their systems with European interoperability practices. These developments indicate that technical readiness exists, even if it is not yet uniformly implemented across the national system. The current state of Ukrainian research

information infrastructure can be described as transitional. Fragmentation and legacy approaches still limit interoperability, but at the same time there is a clear and measurable movement toward integration with European standards. The main driver of this transformation is not only technological modernization, but also increasing participation in European research initiatives and alignment with the requirements of the European Research Area.

From this perspective, deeper integration into the European unified research information space is not merely an external opportunity, but a necessary condition for systemic modernization. Alignment with FAIR principles, standardized metadata models, persistent identifiers, and interoperable APIs would significantly improve the quality, visibility, and usability of Ukrainian research outputs. In the long term, such integration would allow Ukrainian institutions to shift from fragmented digital solutions toward a coherent, networked research information ecosystem fully compatible with European infrastructures.

CONCLUSIONS. The formation of a unified information space for research infrastructures in Europe represents a key direction in the ongoing transformation of the European Research Area. It reflects a gradual shift from fragmented, domain-specific systems toward an integrated digital ecosystem that enables data sharing, interoperability, and cross-border scientific collaboration. This evolution is primarily driven by the increasing role of data-intensive research and the growing need for coordinated management of distributed scientific resources.

European coordination mechanisms, in particular ESFRI and the European Open Science Cloud (EOSC), play a central role in shaping this environment. ESFRI provides long-term strategic planning for research infrastructure development, while EOSC offers a federated framework for access to research data, services, and digital resources. Together, they establish both the governance and technological foundations for integrating heterogeneous national and international infrastructures into a more coherent research ecosystem.

At the technological level, the implementation of persistent identifiers (ORCID, DOI, ROR), interoperable research repositories, infrastructure catalogues, and standardized metadata frameworks remains a critical prerequisite for effective integration. These instruments ensure consistent identification of researchers, organizations, and research outputs, while also improving the quality, discoverability, and reusability of scientific information. In this context, FAIR principles serve as a key methodological reference, although their practical implementation still varies significantly across infrastructures.

The analysis also shows that, despite substantial progress in Europe, full integration is still an ongoing process rather than an achieved state. Fragmentation at the level of metadata standards, service interoperability, and governance models continues to limit seamless data exchange. This indicates that the unified information space should be understood as an evolving ecosystem, shaped by continuous alignment rather than a finished infrastructure.

For Ukraine, integration into the European research information space represents both a strategic opportunity and a structural necessity. The current national landscape is characterized by a combination of positive digital developments and persistent fragmentation. While many institutions have already adopted repository systems with open APIs, joined international initiatives such as ORCID consortiums, and begun integration with global aggregators, systemic issues remain. These include limited interoperability of national funding and research information systems, uneven metadata quality in journals, and partial machine readability of scholarly outputs, particularly in legacy repositories of dissertations.

At the same time, these challenges are accompanied by clear progress trends, including gradual alignment with European metadata standards, increasing adoption of DOAJ-oriented publishing practices, and expanding participation in international research information infrastructures. In this sense, deeper integration with the European unified information space is becoming a key driver for modernization of the Ukrainian research ecosystem, rather than only an external policy objective.

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ChatGPT-5 was used as an auxiliary tool for language support, including proofreading, editing, and stylistic refinement of the English-language text. The use of this tool was limited exclusively to improving linguistic quality, coherence, and academic style. It did not contribute to the formulation of ideas, research concepts, analysis, or scientific content of the work. All intellectual contributions, including the development of the structure, methodology, and conclusions, remain fully attributable to the author.

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РОЛЬ ІНФРАСТРУКТУР ВІДКРИТОЇ НАУКИ У ПІДТРИМЦІ НАДІЙНИХ ЦИФРОВИХ ДОСЛІДНИЦЬКИХ ЕКОСИСТЕМ

АНОТАЦІЯ. Дослідження присвячене аналізу єдиного інформаційного простору дослідницьких інфраструктур Європи з позиції інтеграції сервісів відкритої науки. Метою є визначення ключових компонентів цифрової наукової екосистеми та обґрунтування можливостей їх інтеграції в єдине середовище. Використано методи системного аналізу, порівняльного огляду та концептуального моделювання цифрових дослідницьких інфраструктур. Результати показують, що сучасні платформи відкритої науки характеризуються фрагментованістю API, неоднорідністю метаданих та обмеженою взаємодією з мобільними системами. Виявлено ключові точки інтеграції, пов'язані з ідентифікацією дослідників, управлінням даними та агрегацією наукових ресурсів. Висновки підтверджують, що формування єдиного інформаційного простору є критично важливим для підвищення ефективності наукових досліджень та розвитку відкритої науки.

КЛЮЧОВІ СЛОВА: відкриті наукові дані; дослідницькі інфраструктури; інтероперабельність; цифрові платформи; метадані; єдиний інформаційний простір.