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The INGV Spectral Library: a georeferenced, metadata-rich platform for spectral data management, exploration, and preprocessing

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Abstract

The management, analysis, and reuse of spectral data remain challenging in multidisciplinary contexts, where records often derive from heterogeneous instruments, campaigns, and scientific domains and require consistent metadata, geospatial context, and efficient consultation workflows. This paper presents the INGV Spectral Library, a web-based geoinformatic platform developed for the organisation, exploration, and preliminary analytical use of spectral data in domains including geology, mineralogy, environmental studies, and cultural heritage. The system is based on a modular frontend–backend–database architecture designed to integrate structured metadata organisation, browser-based consultation, geospatial exploration, and basic analytical tools within a single operational environment. The platform supports metadata-driven and map-based access to records, spectrum visualisation and comparison, and preprocessing functions including first derivative, continuum removal, and spectral resampling based on sensor spectral response functions or user-defined wavelength grids. A controlled ingest and harmonisation workflow ensures that spectra and associated metadata are validated and standardised before exposure to the interface. The paper describes the conceptual design of the platform, its architecture, metadata model, data organisation workflow, user-facing functionalities, current limitations, and future development directions. Overall, the INGV Spectral Library provides a geoinformatic environment for structured spectral data management and operational reuse in multidisciplinary research contexts.

1 Introduction

The management, analysis, and reuse of spectral data are essential across several scientific and applied domains, including geophysics, geology, mineralogy, environmental studies, and cultural heritage conservation. These fields frequently rely on non-invasive techniques to determine the chemical and physical composition of materials, and surface spectroscopy has become a key methodology for investigating rocks, minerals, archaeological artefacts, and artworks while preserving sample integrity (Clark and Roush 1984; Yogurtcu et al. 2024). In Earth sciences, spectral data integrated with remote-sensing techniques enable the monitoring of large areas and provide detailed characterisation of surface features (Liao et al. 2023). In cultural heritage conservation, surface spectroscopy is crucial for identifying constituent materials and assessing conservation state in a non-invasive manner (Ruello et al. 2022). In parallel, previous studies have shown that spectral libraries, when combined with machine-learning approaches and derivative-based analyses, can further enhance the interpretation of complex datasets (Zhang et al. 2019).

However, the effective use of spectral data depends not only on the availability of spectra, but also on the possibility of organising, querying, comparing, and reusing them within a coherent operational framework. Existing spectral libraries and spectral databases have made major contributions to the field, but they are often specialised by material class, disciplinary scope, or analytical context, and do not always provide an integrated environment for metadata-rich consultation, geospatial access, and preliminary analytical interaction with the data. In the remote-sensing domain, representative examples

include SPECCHIO, developed as a spectral database for remote-sensing applications and later extended toward improved long-term usability and metadata-driven data sharing, the ASTER Spectral Library, and the Arizona State University thermal emission spectral library (ASU) (Bojinski et al. 2003; Hueni et al. 2009; Baldridge et al. 2009; Christensen et al. 2000). In the cultural heritage domain, spectral resources such as the FORS spectral database of historical pigments in different binders and the Pigments Checker free spectra database have demonstrated the value of open and reusable reference collections for pigment identification workflows (Cosentino, 2014; Larsen et al. 2016).

This limitation becomes particularly evident in multidisciplinary settings, where records may derive from different campaigns, instruments, and research traditions, and where their scientific usefulness depends strongly on the quality and interoperability of associated metadata. In such contexts, sample identity, geographic provenance, spectroscopy type, domain-specific descriptors, and spectral signatures need to remain linked within a unified environment to support reliable retrieval and reuse. The importance of metadata-rich spectral databases and long-term data sharing has already been emphasised in the spectral database literature (Hueni et al. 2009), while other studies have highlighted the need for interoperable metadata standards and structured approaches for heterogeneous Earth observation and field spectroscopy datasets (Rasaiah et al. 2015; Jiménez et al. 2014). In this respect, the integration of heterogeneous datasets acquired with techniques such as Raman (Yogurtcu et al. 2024), FTIR (Walker et al. 2021), and FORS (Cosentino, 2014) across multiple spectral ranges (e.g., VNIR, SWIR, TIR) remains a significant challenge for multidisciplinary analyses.

Among existing solutions, SPECCHIO stands out as a particularly relevant example of a spectral database designed for remote-sensing applications, combining structured metadata, relational organisation, and automated mechanisms for data input, retrieval, and long-term usability (Bojinski et al. 2003; Hueni et al. 2009). More broadly, several geoinformatic systems have shown the value of combining structured data organisation, interface design, and user-oriented access within a single operational environment. This is evident in web-based scientific platforms and spatial-data infrastructures that integrate database logic, metadata handling, interface components, and analytical or reporting tools into a coherent framework. Yet there remains room for platforms specifically designed to combine structured metadata organisation, geospatial consultation, and integrated preprocessing tools within a web-based environment for spectral data.

In this perspective, the INGV Spectral Library was developed as a modular platform that combines a frontend for user interaction, a backend for service orchestration, and a database for structured persistence and exposure of spectral records. Its design emphasises metadata-driven exploration, direct GIS integration, and built-in analytical tools for first-derivative analysis, continuum removal, and spectral resampling, thereby supporting a more operational use of archived spectra in multidisciplinary research settings. The platform was conceived to support the organisation, consultation, and preliminary analysis of spectral data across different scientific domains, with particular relevance for geology, Earth sciences, environmental studies, and cultural heritage. At the same time, its modular design leaves room for future developments such as spectral matching, machine-learning-assisted analysis, guided ingest procedures,

and broader interoperability with remote-sensing workflows. A recent study showed that a single spectral library can be adapted to multiple sensors through data simulation based on sensor spectral response functions and radiative-transfer models (Ma et al. 2021), further supporting the relevance of extensible spectral data infrastructures.

This work presents the INGV Spectral Library as a geoinformatics platform for the management, consultation, and preliminary analytical use of spectral data. The paper describes the conceptual design of the system, its general architecture, the organisation of data and metadata, the ingest and harmonisation workflow, the main user-facing functionalities, and the current limitations and future development directions of the platform.

2 Platform concept and general architecture

2.1 Concept and objectives of the INGV Spectral Library

The INGV Spectral Library was conceived as a unified web-based platform for the management, exploration, and preliminary analytical processing of spectral data across multiple application domains, including rocks, minerals, cultural heritage, and survey-based datasets. Its development was motivated by the need to bridge the gap between heterogeneous spectral archives and the operational tools required to consult, compare, and interpret them effectively within a consistent digital environment.

At the conceptual level, the platform was designed not only to store spectra, but also to make them operationally usable through metadata-driven exploration, geospatial contextualisation, and integrated visual inspection tools. This objective is particularly relevant in multidisciplinary settings, where spectral datasets are often distributed across different domains and organised according to different conventions. In this context, the INGV Spectral Library provides a structured environment in which geographic information, descriptive metadata, and reflectance signatures remain linked throughout the consultation process.

A second core objective concerns the creation of a robust technical framework for spectral data organisation and access. This is achieved through a modular FE–BE–DB architecture in which presentation, application logic, and persistence are clearly separated. The frontend, backend, and database layers together provide a scalable and maintainable structure capable of supporting both current consultation needs and future extensions.

Finally, the platform was designed to integrate basic analytical capabilities directly within the consultation environment. Real-time spectrum visualisation, comparison of multiple signatures, first derivative, continuum removal, and spectral resampling based on sensor spectral response functions are intended to make spectral records immediately explorable within the same environment in which they are stored and queried. In this sense, the INGV Spectral Library should be understood as a geoinformatic infrastructure for spectral data rather than as a simple online archive.

2.2 General architecture of the system

The INGV Spectral Library is based on a three-tier web architecture designed to separate presentation, application logic, and data persistence while preserving a coherent end-to-end workflow for spectral data consultation and analysis. At the highest level, the system is organised into a React frontend, a Node/Express backend, and a PostgreSQL database, each of which performs a distinct role within the overall platform (Fig. 1).

Within this architecture, the frontend provides the user-facing environment for navigation and interaction, the backend mediates requests and exposes domain- and filter-oriented REST services, and the database stores spectral records together with their associated metadata. The database also exposes harmonised views that combine geographic, spectral, and sample-specific information for direct use by the interface. This separation of responsibilities ensures modularity and maintainability, while allowing the three layers to evolve independently.

From an operational perspective, the system follows a stateless request–response model. Each view or analytical tool requests only the information required for the current task, and the backend returns outputs already structured for efficient rendering as tables, maps, or plots. A key architectural feature is therefore the use of dedicated database views that reduce transformation logic at the application layer and align database outputs with the needs of the interface.

This general architecture also supports the analytical role of the platform. Because consultation and preprocessing are built on the same frontend–backend–database framework, users can move from record discovery to spectrum visualisation and basic transformation within a single environment. In this way, the architecture serves not only as a technical implementation scheme, but as the structural basis of a reliable geoinformatic platform for spectral data.

2.3 Access model and operational logic

The access model of the INGV Spectral Library was designed to support a coherent transition from data discovery to spectral inspection while preserving continuity between thematic domain, geographic context, metadata, and analytical outputs. The platform is accessed through a browser-based interface and is currently intended primarily for internal, read-oriented use, allowing authorised users to consult, explore, and process spectral data without direct interaction with the underlying database structure or ingest procedures. This operational model is implemented through the interaction between the user-facing frontend, the backend service layer, and the database layer that supports retrieval and consultation workflows (Fig. 2).

Access begins with domain selection. The Home page presents the main thematic areas of the library as domain-based categories, such as rocks, minerals, cultural heritage, surveys, and other material classes. This initial choice establishes the consultation context that is then propagated through the subsequent stages of navigation, ensuring consistency in labels, filters, interface elements, and retrieval logic.

After domain selection, users enter the main exploration environment, which offers two complementary access modes. The first is geographic and relies on map-based consultation, enabling users to move from territorial context to record-level spectral detail. The second is metadata-driven and relies on a filtered table, allowing targeted searches through criteria such as class, subclass, sample name, location, survey name, or spectroscopy type. Although these two modes differ in approach, they converge on the same analytical workspace, where individual spectra can be visualised, compared, and processed.

The operational logic of the platform is therefore based on a progressive narrowing of context: from thematic domain, to exploration through map or filters, to detailed record-level analysis. This design reduces the fragmentation that often characterises spectral archives and supports a continuous consultation workflow in which metadata, geography, and spectral signatures remain connected.

A further aspect of this model is its controlled nature. The system is not publicly exposed and is currently configured for authorised internal access on a dedicated machine. Within this framework, the browser interface exposes consultation-oriented functions only, while ingestion and validation are handled through separate controlled workflows. This separation reinforces the reliability of the consultation environment and keeps platform use aligned with its current institutional and operational scope.

3 Spectral data organization and metadata structure

3.1 Source data and current scope of the library

The current scope of the INGV Spectral Library is defined by its role as a multidisciplinary platform for the organisation, exploration, and preliminary analytical processing of spectral data across several scientific and applied domains. At its present stage, the library supports records associated with rocks, minerals, cultural heritage materials, surveys, and other domain-specific categories, providing a common environment in which heterogeneous datasets can be explored through shared descriptive, geospatial, and spectral criteria.

From the data perspective, the library stores spectral records together with the metadata required to make them searchable, interpretable, and reusable within the platform. Each record is associated with information such as sample identity, thematic domain, class and subclass, spectroscopy type, geographic provenance, and other domain-specific descriptors. This organisation enables not only direct spectrum visualisation, but also the construction of meaningful comparison sets based on metadata and location.

A defining aspect of the current scope of the library is the integration of spectral information with geographic context. The platform supports georeferenced access to samples and allows users to move from locality-based exploration to record-level spectral analysis within the same consultation framework. Interoperability between the spectral database and a GIS environment is therefore a central aspect of the

system, since it preserves the relationship between sample location, metadata, and reflectance information in a unified environment (Cardoso-Fernandes et al. 2023).

The current content of the library is managed through a controlled ingest workflow in which spectral files and associated metadata are collected, checked, normalised, and inserted into the operational data structure of the system. This ensures that the records exposed by the platform are already pre-validated for consultation and analysis, reducing inconsistencies at the stage of user interaction.

At the present stage, the library should therefore be understood as an evolving but already operational resource whose value lies not only in the spectra themselves, but also in the way they are contextualised and exposed. Examples mentioned in the current platform content include contexts such as the kaolinite quarry at Sasso di Furbara and the salt pond of Sal'e Porcus, which illustrate the range of materials and environments currently represented in the archive. Overall, the current scope of the INGV Spectral Library is defined by its multidomain nature, its integration of spectra with structured metadata and geographic information, and its role as an operational platform for spectral consultation and preliminary analysis.

3.2 Metadata model

The metadata model of the INGV Spectral Library was designed to make spectral records not only storable, but also searchable, interpretable, and reusable across different domains and consultation contexts (Hueni et al. 2009; Rasaiah et al. 2015). Rather than treating spectra as isolated wavelength–reflectance series, the platform organises each record within a broader descriptive structure that links spectral information to geographic provenance, thematic classification, and domain-specific attributes.

At the core of the model, metadata are organised into three main groups: geographic metadata, spectral metadata, and domain-specific metadata. Geographic metadata include locality, site description, acquisition date, and coordinates; spectral metadata describe the measurement itself, including spectroscopy type and acquisition-related information; and domain-specific metadata include classificatory and descriptive attributes that vary according to the represented domain. In this way, the metadata model is both structured and flexible, allowing the platform to preserve a common logical organisation while accommodating heterogeneous content (Jiménez et al. 2014; Rasaiah et al. 2015).

This logic is reflected in the database design, where each thematic domain follows a recurring pattern composed of a main sample table, a dedicated geography table, a domain-specific properties table, and a spectral table storing wavelength–reflectance pairs. The spectrum is therefore only one component of a broader record structure whose scientific meaning depends on its linkage to metadata.

A further strength of the metadata model lies in the way it is exposed to the rest of the system. The platform relies on derived views that combine the relevant portions of metadata and spectral records into forms already adapted to consultation needs. Filters, maps, detail panels, and plots therefore operate on harmonised outputs in which sample identity, geographic provenance, and domain-specific descriptors are already associated with the spectrum.

The metadata model is also closely linked to the ingest workflow. During ingestion, scripts parse spectral files and supporting metadata, map them to the application tables, and standardise labels, units, and textual conventions. As a result, the metadata model acts not only as a schema for storing information, but also as the framework through which harmonisation and downstream usability are ensured (Rasaiah et al. 2015; Jiménez et al. 2014; Innerebner et al. 2017). Because locality and related descriptors are part of the same structured record, samples can be accessed both through semantic filters and through their spatial distribution (Cardoso-Fernandes et al. 2023). Overall, this metadata framework is one of the main elements that allows the library to function as an operational platform rather than as a simple collection of spectra.

3.3 Data ingestion, harmonization, and organization workflow

The ingestion workflow of the INGV Spectral Library was designed as a controlled process aimed at ensuring that spectral files and their associated metadata enter the platform in a form that is already consistent, searchable, and usable for consultation and analysis. Rather than relying on direct upload into the operational environment, the platform adopts an upstream workflow in which spectra and metadata are collected, checked, normalised, and only then inserted into the structured data model of the system.

In practical terms, ingestion is currently performed through Python scripts operating on input directories containing spectral files and, where available, supporting metadata. Spectral data are typically provided in simple tabular formats such as ASCII or CSV, while additional metadata may derive from field campaign sheets, laboratory forms, or other structured descriptions. During ingest, the scripts extract the key attributes required by the platform, including sample name, thematic domain, class or subclass, spectroscopy type, and references to location or survey context.

A central component of this workflow is validation. Before records are inserted into the operational database, the scripts check the presence of mandatory fields, the existence of a non-empty spectral series, the numerical validity and monotonic ordering of wavelength values, the plausibility of reflectance values, and the consistency between metadata identifiers and spectral filenames. In this way, the ingest stage acts not only as a loading mechanism, but also as a first control layer for data quality.

In parallel, the workflow performs harmonisation operations that are essential for downstream usability. Domain labels, class names, units, and other user-facing fields are standardised so that filtering, plotting, derivative computation, continuum removal, and resampling can all rely on a consistent internal basis. Once validated and normalised, records are inserted into the system and exposed through representations already suitable for consultation, filtering, map display, and plotting.

At its current stage, the ingest workflow remains intentionally curator-driven. This choice is appropriate for an operational phase in which data quality and consistency take priority over open self-service submission, while still leaving room for future evolution toward more user-friendly ingest solutions.

Overall, the ingestion, harmonisation, and organisation workflow is one of the elements that makes the INGV Spectral Library an operational platform rather than a simple container of files.

3.4 Database structure and logical organization

The database structure of the INGV Spectral Library provides the relational framework through which spectral records are stored and exposed across multiple thematic domains. Rather than functioning as a simple repository of wavelength–reflectance measurements, the database organises samples, metadata, and spectra into interconnected components that support both persistence and efficient consultation through the platform interface.

Across the different domains represented in the library, the database follows a recurring logical pattern based on four main elements: a sample table, a geography table, a domain-specific properties table, and a spectral table storing wavelength–reflectance pairs. This shared structure allows heterogeneous domains—such as rocks, minerals, cultural heritage materials, and surveys—to be accommodated within a common relational scheme while preserving the descriptive specificity of each domain.

A key aspect of this organisation is the use of derived views on top of the core relational structure. These views expose records in forms already adapted to platform-level consultation, including filtering, tabular exploration, georeferenced display, and spectral plotting. As a result, the backend can retrieve outputs already aligned with the needs of the user interface, reducing transformation logic at the application layer and ensuring consistency across consultation modes.

This logical structure also supports the main output families required by the platform: filter values for query refinement, ordered spectral series for visualisation and preprocessing, and georeferenced payloads for map-based exploration. In addition, specialised handling is available for survey-type datasets, where grouped or repeated measurements require batch retrieval of multiple spectra. More broadly, the same organisation facilitates downstream export into lightweight external formats, reinforcing the role of the database not only as a persistence layer, but also as a mediator between internal data organisation and external reuse.

Overall, the database structure of the INGV Spectral Library provides a shared relational backbone through which samples, metadata, and spectra are managed in a consistent and operationally efficient way. By combining common organisational logic with domain-specific descriptive flexibility, the system supports both internal coherence and effective interaction with the graphical interface.

4. Technology and implementation

4.1 Frontend architecture

The frontend of the INGV Spectral Library provides the main user-facing environment through which the platform’s data organisation, search functions, and analytical tools become accessible in a coherent and progressive way. Implemented in React, it was designed to orchestrate navigation across the principal

consultation environments of the platform while preserving context as users move from thematic exploration to record-level spectral analysis.

At the structural level, the frontend follows a global-to-local logic that mirrors the intended user journey. Navigation begins with thematic domain selection, continues through map- or table-based exploration, and converges on the Graph Dashboard, where individual spectra can be visualised, compared, and processed. This progression allows users to move from broad discovery to analytical detail without losing the metadata and contextual information associated with the sample under examination.

A key architectural principle of the frontend is context propagation. Once a domain, filter set, or record has been selected, this context is maintained across the different interface environments so that labels, metadata fields, and retrieval logic remain aligned. This reduces fragmentation and preserves coherence across the workflow when moving between map-, table-, and plot-based views.

From the data-access perspective, the frontend relies on a centralised request model that interacts with the backend through structured GET requests and receives JSON responses already normalised for interface use. This keeps the components focused on rendering and interaction rather than on local transformation logic. Together with comparison selectors, metadata panels, and export functions, this design strengthens the role of the frontend as a practical research environment rather than as a simple graphical shell.

4.2 Backend services and API layer

The backend of the INGV Spectral Library provides the application layer that connects the graphical interface to the underlying data organisation of the platform. Implemented in Node/Express, it exposes data and services to the frontend in a predictable, read-oriented, and stateless way, allowing the interface to retrieve the information required for maps, tables, detail panels, and spectral plots without directly interacting with the database structure.

At the operational level, the backend organises its services into a limited number of functional families. One family is devoted to filters and lookups, providing values such as class, subclass, sample name, location, survey name, or spectroscopy type. A second family handles spectral data, returning the reflectance profile of a selected sample together with any additional spectra requested for comparison. A third family provides georeferenced outputs for the map interface, supplying localities, coordinates, grouped records, and related identifiers that support spatial exploration.

A key design principle is semantic normalisation before data access. Incoming requests may contain domain-specific or user-oriented values that need to be aligned with the internal conventions of the database; for this reason, the backend applies lightweight transformations and parameter checks before querying the data layer. The resulting request–response model remains intentionally simple: the frontend issues structured GET requests and receives JSON outputs already organised for direct use by the interface.

The backend also contributes to the robustness of the platform through clear error handling, stateless service logic, and secure configuration practices. Database and service settings are externalised, access to the data layer relies on parameterised queries, and structured logging supports monitoring and reconstruction of request–response cycles in the event of operational issues. In this way, the backend functions as a controlled mediation layer between the user interface and the relational spectral archive.

4.3 Database and geospatial components

The database and geospatial components of the INGV Spectral Library work together to connect spectral records with their geographic context and to expose them through a unified consultation framework (Innerebner et al. 2017). In this architecture, the database does not function only as a persistence layer for wavelength–reflectance measurements, but also as the structured environment through which samples, metadata, and spatial information are linked and made available to the interface.

At the technological level, the system relies on a relational PostgreSQL organisation in which sample records, geographic descriptors, domain-specific properties, and spectral series are preserved within a common logical structure. This organisation provides the basis for georeferenced consultation, since locality and coordinate information are stored as part of the same record framework used for filtering, plotting, and metadata retrieval. As a result, the geospatial dimension is not an external layer added after data storage, but an intrinsic component of the platform's data model.

This relational structure supports the map interface, which allows users to explore spectral records through their spatial distribution. Interoperability between the spectral database and a GIS environment is therefore crucial to fully exploit the spectral library and its consolidated dataset (Cardoso-Fernandes et al. 2023). Within the platform, this interoperability is expressed through georeferenced payloads rendered on an OpenStreetMap basemap, allowing users to move from territorial overview to sample-level inspection while preserving the connection between location, metadata, and spectral content (Innerebner et al. 2017).

A key advantage of this design is that map-based consultation remains fully integrated with the same record logic used elsewhere in the platform. Grouped records, contextual metadata, and direct access to analytical views are all derived from the same structured database outputs, so geographic access does not operate separately from semantic or spectral consultation. In this way, the database and geospatial components provide the technological junction between structured persistence and spatially aware consultation (Lecca et al. 2009; Souza Jr. et al. 2009).

4.4 Interoperability, export, and extensibility

A relevant design principle of the INGV Spectral Library is that the platform was not conceived as a closed consultation environment, but as a system capable of supporting data reuse, exchange, and progressive extension. This principle is reflected both in the choice of lightweight formats for ingest and

export, and in the separation between frontend, backend, and database components, which makes the platform adaptable to future analytical and infrastructural developments.

At the current operational level, interoperability is expressed through export functions embedded in the interface. The Graph Dashboard allows users to save plots as PNG files and to export numerical spectral outputs in simple tabular formats, including original reflectance values and SRF-resampled profiles. Spectra are represented through lightweight ASCII-based structures, while sensor spectral response functions are managed through structured files in which each band is associated with wavelength–weight pairs. This design allows the platform to support internal computation while also preserving straightforward reuse in external environments.

Interoperability also depends on stable naming and consistent internal conventions. Controlled nomenclature for filenames, domain labels, class names, and user-facing metadata fields ensures that exported data can be traced back to their originating records and reintegrated into subsequent workflows without ambiguity. In this way, the platform combines lightweight exchange formats with a stable reference system that strengthens both reproducibility and reuse.

Because the current environment is based on a modular FE–BE–DB organisation and a consistent data model, it is also structurally prepared for future extensions such as additional spectroscopic techniques, expanded sensor support, guided ingest, automatic spectral matching, and broader interoperability with other internal systems. The platform should therefore be understood not as a closed application, but as an evolving geoinformatic environment for spectral data management and operational reuse.

5. User interface and platform functionalities

5.1 Home and domain-based navigation

The Home page of the INGV Spectral Library serves as the primary entry point to the platform and establishes the initial logic of user interaction. Rather than presenting the archive as a single undifferentiated collection of records, the interface organises access through a set of thematic domains reflecting the multidisciplinary scope of the library. These domains, presented as a grid of visual cards, include categories such as Cultural Heritage, Rock, Minerals, Surveys, Water/Ice/Snow, Man-made, Soil, and Vegetation (Fig. 3).

This domain-based entry logic functions as the first contextual filter of the system. Once a user selects a domain, that choice is propagated across the subsequent interface environments so that labels, icons, filters, and retrieval logic remain consistent throughout navigation. In this way, the Home page functions not simply as a welcome screen, but as the first operational layer of a workflow that progressively narrows the path from thematic orientation to record-level analytical inspection.

5.2 Spectral data exploration

After selecting a thematic domain, users enter the main exploration environment of the platform, conceived as a navigation hub between broad contextual discovery and record-level spectral analysis. This layer is organised around two complementary access modes: a map-based path centred on geographic context, and a table-based path centred on metadata filtering. Although these modes differ in the way users approach the archive, they are functionally equivalent within the platform logic, since both lead to the same analytical environment in which selected spectra can be visualised, compared, and processed.

The first exploration mode is geographic and is implemented through the interactive map (Fig. 4a–b). Samples are represented as spatially referenced records displayed through domain-specific markers and, where necessary, aggregated into clusters to improve readability in dense areas. This allows users to identify localities or spatial patterns of interest and then move progressively toward individual sample records. Where multiple samples are associated with the same locality or survey context, grouped records can be exposed through contextual cards summarising essential metadata and providing direct access to record-level detail.

The second exploration mode is attribute-based and is implemented through tabular consultation supported by reactive, cascading filters (Fig. 5a–b). Users progressively refine the search space by selecting values such as class, subclass, sample name, location, survey name, spectroscopy type, or other domain-dependent descriptors. Once the desired subset is identified, results are displayed in a paginated table whose records can be opened directly in the analytical interface.

These two modes are parallel expressions of the same consultation logic. Whether users start from the map or from the filtered table, the system preserves the active domain and contextual metadata when moving to spectral detail. In this way, the exploration layer acts as the bridge between initial thematic orientation and the Graph Dashboard, allowing users to pass from large multidomain collections to specific, interpretable spectral records in a controlled and efficient way.

5.3 Spectrum visualization and comparison

Spectrum visualisation and comparison are central functionalities of the INGV Spectral Library and are implemented within the Graph Dashboard, which acts as the unified environment for record-level spectral inspection and analysis. Once a sample has been selected through the map or the tabular exploration interface, the platform opens the corresponding spectral record directly in this workspace, preserving the active domain and associated metadata.

At the core of this environment is the visualisation of the primary reflectance spectrum of the selected sample. The interface displays the wavelength–reflectance series on a normalised plotting framework, with the X-axis expressed in micrometres and the Y-axis constrained to the reflectance interval [0–1]. This standardisation is essential for comparison, since it ensures that all displayed spectra share the same visual scale and can therefore be assessed consistently across samples and domains.

A defining feature of the Graph Dashboard is the possibility of adding one or more comparison spectra directly to the same plot (Fig. 6). Additional datasets can be selected from the library, typically by sample name or location, and are overlaid on the primary spectrum while preserving common axes, units, and legend logic. This real-time comparison mechanism allows users to evaluate whether different samples share similar overall shapes, comparable absorption features, or marked divergences potentially related to composition, context, or acquisition conditions.

Interactive controls such as zooming, panning, hover inspection, and selective display of plotted series further support exploratory analysis by allowing users to focus on restricted spectral intervals without losing the broader context of the curve. Because comparison remains fully integrated with the metadata and navigation context of the active record, users do not approach the analytical stage blindly, but work within a coherent subset of the archive. In this way, spectrum visualisation and comparison function as a first analytical layer through which spectral records can be inspected and preliminarily interpreted in a consistent and context-aware way.

5.4 Integrated preprocessing tools

One of the most distinctive functional features of the INGV Spectral Library is the integration of basic spectral preprocessing tools directly within the same environment used for consultation and comparison. Rather than requiring users to export spectra to external software for every intermediate operation, the platform allows a first level of analytical transformation to be performed inside the Graph Dashboard, where preprocessing remains closely connected to record identity, metadata context, and real-time visual inspection.

The first of these tools is the first derivative, which measures local changes in reflectance with respect to wavelength and is used to emphasise slopes, band edges, and subtle variations that may be difficult to identify in the original reflectance curve alone. A second function is continuum removal, which isolates absorption features from the broader baseline trend of the spectrum by computing an upper continuum envelope and normalising the original reflectance curve against it. The third integrated preprocessing function is spectral resampling based on sensor spectral response functions (SRFs) or on user-defined wavelength grids, allowing laboratory or field spectra to be related more directly to the spectral sampling logic of real sensors or custom analytical band sets. The importance of this latter approach is supported by studies showing that sensor-specific variations in the relative spectral response can significantly affect reflectance- and NDVI-based measurements (Trishchenko et al. 2002), and that accurate characterisation of RSR is essential for radiometric consistency in imaging spectroscopy (Cogliati et al. 2021) (Fig. 7a–c).

An important strength of these tools is that they remain fully integrated with the broader comparison environment of the platform. Their outputs remain visually connected to the original curve and can be interpreted immediately within the same context in which the spectra were selected. This continuity prevents preprocessing from becoming a disconnected technical step and instead frames it as an extension of the consultation process. By combining first derivative, continuum removal, and SRF-based

or grid-based resampling within the same context-aware environment, the platform extends consultation and comparison toward a first level of analytical interpretation.

5.5 Querying, filtering, and export functions

The querying, filtering, and export functions of the INGV Spectral Library are designed to make the archive operationally accessible through a set of user-oriented actions that connect record retrieval, spectral inspection, and external reuse.

Querying is primarily supported through reactive filters and tabular exploration. Users can progressively restrict the available records through classificatory and domain-dependent descriptors such as class, subclass, sample name, location, survey name, spectroscopy type, or pigment standard. Filtered results are presented through a paginated table adapted to the selected domain, allowing users to review records before opening them in the Graph Dashboard. In this way, the table functions as a bridge between metadata-oriented retrieval and record-level analysis.

Export functions extend the usability of the platform beyond on-screen consultation. Visual outputs can be saved as PNG figures, and numerical spectral outputs can be exported in lightweight ASCII formats, including reflectance data and resampled products. This allows the results generated within the library to be reused in external workflows without requiring proprietary formats or additional conversion steps. The consistency of filenames, domain labels, and internal naming conventions further supports this reuse by preserving the link between exported outputs and their originating records.

Overall, the querying, filtering, and export functions contribute substantially to the operational value of the INGV Spectral Library. By allowing users to construct coherent subsets of records, inspect them within a metadata-aware framework, and reuse selected outputs outside the platform, these functions help transform the system from a searchable archive into a practical environment for spectral data consultation and downstream analysis.

6. Representative use contexts

The current content of the INGV Spectral Library spans multiple scientific domains, reflecting the multidisciplinary scope of the platform. The examples below are intended not as full standalone case studies, but as representative contexts currently reflected in the archive, highlighting the versatility of the platform in handling different kinds of spectral data, metadata, and consultation workflows.

6.1 Geological and mineralogical context

One of the main areas currently represented in the library concerns geological and mineralogical materials. In this domain, the platform supports the organisation, retrieval, and comparison of spectral records associated with rocks, minerals, and related sample metadata. Domain-based navigation, metadata filters, georeferenced access, and direct spectral comparison make the platform suitable for the consultation and preliminary interpretation of geological and mineralogical signatures.

Representative materials currently reflected in the archive include samples from contexts such as the kaolinite quarry at Sasso di Furbara.

6.2 Environmental context

A second representative context is environmental analysis, where the platform supports the consultation of spectra linked to natural surface materials and field-based observations. In these cases, the integration between spectral signatures, metadata, and geographic context is particularly important, since interpretation often depends on the relationship between sample properties and the surrounding environment. Representative environmental contexts currently reflected in the archive include settings such as the salt pond of Sal'e Porcus (Melis et al. 2024; Musacchio et al. 2024).

6.3 Cultural heritage context

The platform is also designed to support cultural heritage applications, where spectral data are used for the non-invasive characterisation of materials and the preliminary assessment of conservation-related properties. In this domain, metadata fields such as pigment standards, material categories, and other domain-specific descriptors become particularly important. The possibility of combining filtered search, spectral visualisation, comparison, and preprocessing tools within the same interface increases the practical value of the archive for heritage-oriented consultation workflows.

Overall, these representative contexts show that the INGV Spectral Library is not restricted to a single disciplinary niche, but is structured to manage and expose spectral records across different domains through a common environment for consultation, comparison, and preliminary analysis.

7. Current limitations and future developments

7.1 Current limitations

Although the INGV Spectral Library is already operational for consultation and basic analytical preprocessing, a number of structural and functional limitations remain at the current stage of development. These limitations do not undermine the present usefulness of the platform, but they define its current perimeter and indicate where further development will be required.

A first limitation concerns data ingestion. The platform does not yet provide a user-facing upload workflow through the web interface. The insertion and update of spectra and metadata are currently handled through controlled scripts and curator-managed procedures, which helps preserve consistency and data quality but limits spontaneity in content growth and slows the integration of new external datasets. The present system is therefore well suited to curated institutional use, but not yet to broader self-service contribution scenarios.

A second limitation concerns the analytical tools currently integrated into the Graph Dashboard. Functions such as first derivative, continuum removal, and resampling/SRF operate directly on the stored

spectra without automatic denoising or smoothing stages. As a result, highly noisy spectra or irregularly sampled datasets may produce outputs whose interpretation requires particular caution. The current implementation therefore assumes informed use by users who are aware of the quality and provenance of the input data.

The resampling and SRF component also reflects an early but functional stage of implementation. Although the current system supports selected sensors and user-defined wavelength grids, it does not yet provide systematic coverage of all operational sensors, spectral ranges, or instrument-specific response functions relevant for broader remote-sensing applications. In addition, any transition from high-resolution spectral data to resampled profiles inevitably implies a loss of fine spectral detail, which must be considered when interpreting narrow absorption features or complex spectral structures.

From the infrastructural and access perspective, the platform is currently designed for internal, read-oriented use and is not publicly exposed. It does not yet implement advanced external-access features such as public authentication layers, role-based application management, API keys, or fine-grained data versioning. Similarly, the database stores the current state of samples and spectra without a full change-history mechanism. These aspects are acceptable within the present controlled operational setting, but would become more critical in the event of broader institutional deployment or public-facing use.

A further limitation concerns traceability and performance assessment at scale. The platform already supports basic observability through structured logging, explicit connection checks, and a stateless service design, while scalability is aided by dedicated database views, pagination, and marker clustering. However, systematic quantitative benchmarking under larger loads or on significantly expanded datasets is still in progress. For this reason, the present paper describes the platform as operational and structurally scalable, but does not yet claim exhaustive performance validation under high-demand scenarios.

7.2 Planned developments

Although the INGV Spectral Library is already operational for consultation and basic preprocessing, its current architecture and data model provide substantial room for further methodological and infrastructural development. The platform was intentionally designed as a modular system, so that new analytical functions, broader data coverage, and more advanced deployment solutions can be incorporated progressively without altering its general logic of consultation, metadata integration, and georeferenced access.

A first development axis concerns analytical expansion. One of the most natural next steps is the introduction of automatic spectral matching functions based on similarity measures such as Euclidean distance or cosine similarity. Because the current archive already stores structured spectra together with their metadata context, the platform is well positioned to support comparison modules capable of identifying the most similar signatures to a selected sample or of quantifying spectral proximity against internal or external reference sets. In a longer-term perspective, these same datasets could also support

assisted classification workflows or automated material recognition models trained on sufficiently well-characterised subsets of the library.

A second development axis concerns data ingestion and curation. The current script-based, curator-controlled workflow is appropriate for ensuring consistency and quality, but it could be extended through a guided web-based ingest interface enabling the addition of new samples through a more user-friendly process that includes validation steps, preview of uploaded spectra, and automatic checks on file format and metadata completeness. Even in this scenario, curator review would remain an important control layer.

A further line of development concerns content and sensor coverage. The platform is conceptually prepared to accommodate additional spectroscopic techniques, expanded spectral ranges, and new classes of records, provided that they can be mapped onto the same general organisational model of sample, geographic metadata, domain-specific properties, and spectral measurements. In parallel, extending the library of available sensor spectral response functions would strengthen the resampling module and improve the usefulness of the platform for linking laboratory or field spectra with remote-sensing products and multi-scale analytical workflows.

From an infrastructural perspective, particularly relevant directions include the introduction of data versioning mechanisms for tracking the evolution of records over time, containerisation of the architecture to facilitate deployment and environment replication, and lightweight continuous integration procedures to automate builds, tests, and consistency checks prior to release. In addition, the current architecture leaves open the possibility of a progressively controlled expansion of interoperability toward other internal systems and workflows, including GIS, remote sensing, or computational environments beyond the graphical interface itself.

Overall, the planned developments of the INGV Spectral Library point toward a platform that is already operational, but structurally prepared for broader analytical, infrastructural, and interoperability-oriented growth. The current implementation therefore represents not an endpoint, but a robust foundation for future extensions in spectral analysis, data curation, and institutional spectral data management.

8. Discussion

The main contribution of the INGV Spectral Library lies in its role as a technical-scientific platform that makes spectral data operationally accessible across multiple domains (Hueni et al. 2009). Rather than functioning only as a repository of downloadable spectra, the system combines structured metadata, geospatial context, and preliminary analytical tools within a single web-based environment. This integration is particularly relevant because the practical usefulness of a spectral archive depends not only on the availability of spectra, but also on the conditions under which those spectra can be queried, contextualised, and interpreted.

A central aspect of this contribution is the metadata model. In multidisciplinary spectral environments, metadata are not merely descriptive additions, but part of the interpretative framework of the spectrum itself (Hueni et al. 2009; Rasaiah et al. 2015). Geographic provenance, spectroscopy type, thematic classification, and domain-specific descriptors determine whether comparison is meaningful and whether a spectral signature can be reliably reused. By structuring these elements within a coherent relational model, the platform supports context-aware retrieval and reduces the fragmentation that often characterises heterogeneous spectral archives.

The integration of web-GIS further strengthens this framework by allowing users to approach the archive through spatial logic as well as through metadata-driven search. This is especially relevant in Earth science and survey-oriented contexts, where locality and territorial distribution often contribute directly to the significance of the sample. In this sense, the platform benefits from the combination of geodatabase logic and web-GIS consultation, bringing together geospatial exploration and spectral inspection in a way that remains coherent and operationally efficient (Cardoso-Fernandes et al. 2023; Innerebner et al. 2017).

Another distinctive aspect is the integration of preprocessing tools within the same environment used for consultation and comparison. The availability of first derivative, continuum removal, and SRF-based or grid-based resampling shifts the platform beyond passive access to stored data and toward an environment for preliminary analytical interpretation. At the same time, the current implementation remains appropriately limited: these tools support informed exploratory use, but do not aim to replace more advanced domain-specific processing pipelines. Their value lies precisely in reducing the gap between archive consultation and first-level analysis.

More broadly, the platform occupies an important intermediate space between two extremes: a static archive on one side and a full computational spectroscopy environment on the other. Its contribution lies in making consultation operational through interface design, metadata structure, geospatial integration, and lightweight analytical functionality. From this perspective, the INGV Spectral Library can be seen as a robust initial implementation of a broader infrastructural model for institutional spectral data management (Lecca et al. 2009; Souza Jr. et al. 2009).

Overall, the platform suggests that the value of a spectral library is defined not only by the amount of data it contains, but by the quality of the environment through which those data can be contextualised, queried, compared, and preliminarily interpreted (Schade et al. 2020). The INGV Spectral Library contributes to this perspective by framing spectral data management as a geoinformatic problem as much as a spectroscopic one, and by offering a practical environment for the controlled operational use of spectral records in research and applied contexts.

9. Conclusions

The INGV Spectral Library was developed as a unified platform for the management, exploration, and basic analytical preprocessing of spectral data across multiple domains, including geology, mineralogy,

environmental studies, and cultural heritage. Its main contribution lies in the integration of structured metadata, georeferenced consultation, spectrum visualisation, comparison functions, and preprocessing tools within a single web-based environment. In this way, the platform addresses the gap between heterogeneous spectral archives and the operational tools required to consult and use them effectively in research and applied contexts.

From a technical perspective, the platform is based on a modular Frontend–Backend–Database architecture that separates presentation, application logic, and persistence while supporting a coherent user workflow from domain selection to detailed spectral analysis. The relational organisation of samples, geographic descriptors, domain-specific properties, and spectral measurements—together with dedicated views for consultation—provides a robust basis for querying, geospatial exploration, and graphical inspection of records. The integration of first derivative, continuum removal, and SRF-based or grid-based resampling further extends the role of the platform beyond archive consultation toward preliminary analytical interpretation.

At the current stage, the INGV Spectral Library should be understood as an operational but still evolving infrastructure. Its present implementation already demonstrates the value of combining metadata-rich organisation, web-GIS access, and lightweight preprocessing tools in a controlled environment for curated spectral data. At the same time, the current limitations in ingest openness, advanced sensor coverage, versioning, and large-scale validation indicate that the platform remains under active development.

Overall, the platform represents a relevant contribution as a geoinformatic environment for spectral data management and consultation. Its modular design, controlled data workflow, and openness to future extensions provide a solid foundation for further developments in spectral matching, machine-learning-assisted analysis, guided ingest, and broader interoperability with other research workflows.

Declarations

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

Conceptualization: Marco Solinas, Massimo Musacchio, Malvina Silvestri, Maria Fabrizia Buongiorno, Sergio Falcone, Angelo La Regina; Methodology: Marco Solinas, Massimo Musacchio, Malvina Silvestri;

Software: Marco Solinas; Data curation: Marco Solinas, Massimo Musacchio, Malvina Silvestri; Writing – original draft preparation: Marco Solinas; Writing – review and editing: Massimo Musacchio, Malvina Silvestri, Maria Fabrizia Buongiorno, Sergio Falcone, Angelo La Regina; Supervision: Massimo Musacchio, Maria Fabrizia Buongiorno, Angelo La Regina. All authors read and approved the final manuscript.

Data availability

The datasets associated with the INGV Spectral Library are currently curated within an institutional environment and are not fully publicly available at this stage. Information on data access and possible conditions for reuse can be provided by the corresponding author upon reasonable request, subject to institutional and curatorial constraints.

Code availability

Code related to the development of the INGV Spectral Library is available in a GitHub repository maintained by the authors: https://github.com/Solly87INGV/Client_Server_Spectral_Library. The repository documents the software components associated with the platform described in this study.

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Figures

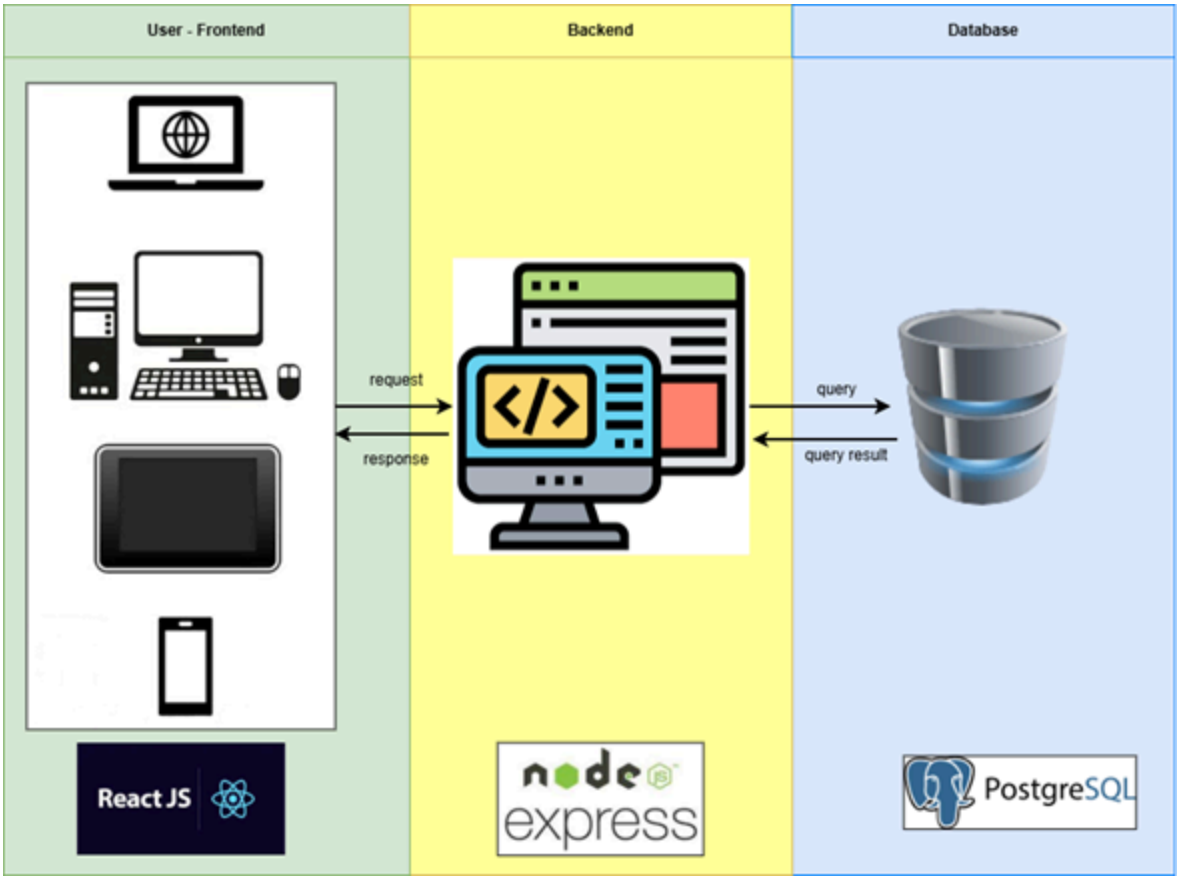


Figure 1

High-level architecture of the INGV Spectral Library, showing the separation between the React frontend, the Node/Express backend, and the PostgreSQL database, together with the request/response flow between frontend and backend and the query/result flow between backend and database

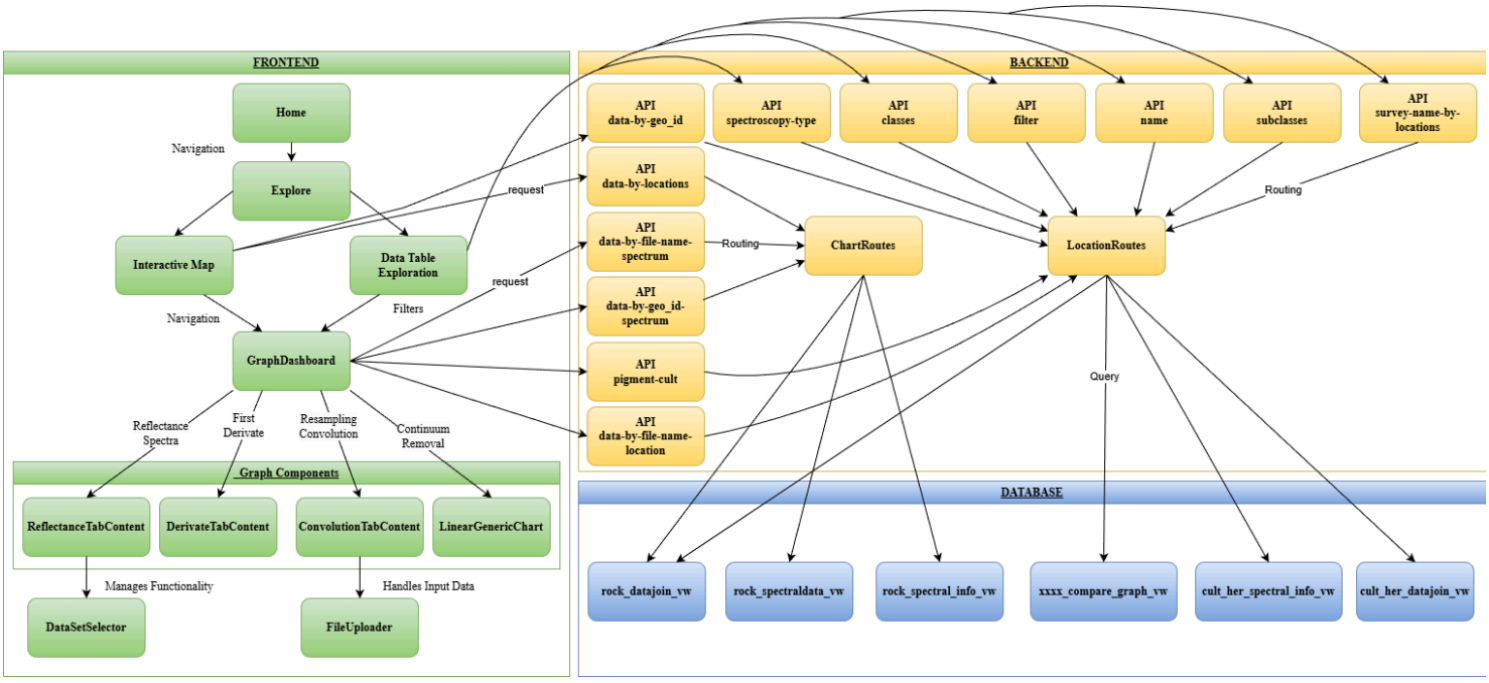


Figure 2

Simplified three-tier structure of the INGV Spectral Library, showing the user-facing frontend layer, the backend service layer, and the database layer underpinning the platform's operational workflow

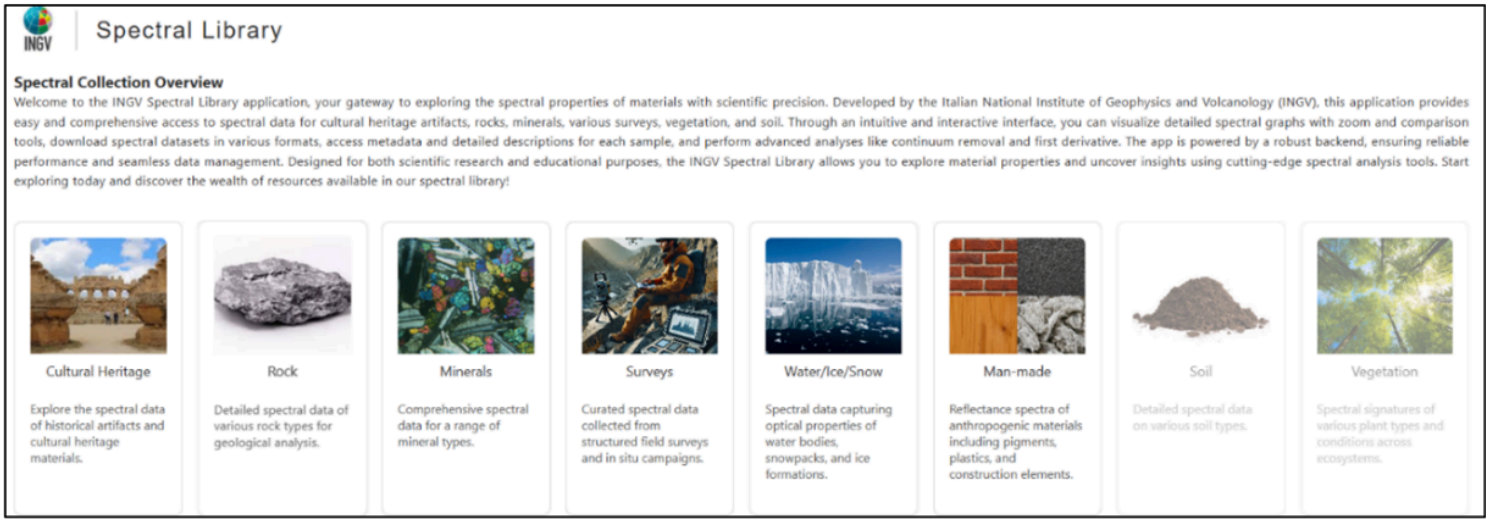


Figure 3

Home page of the INGV Spectral Library, showing the domain-based card interface used to initialise the consultation context and guide users toward the main exploration environments of the platform

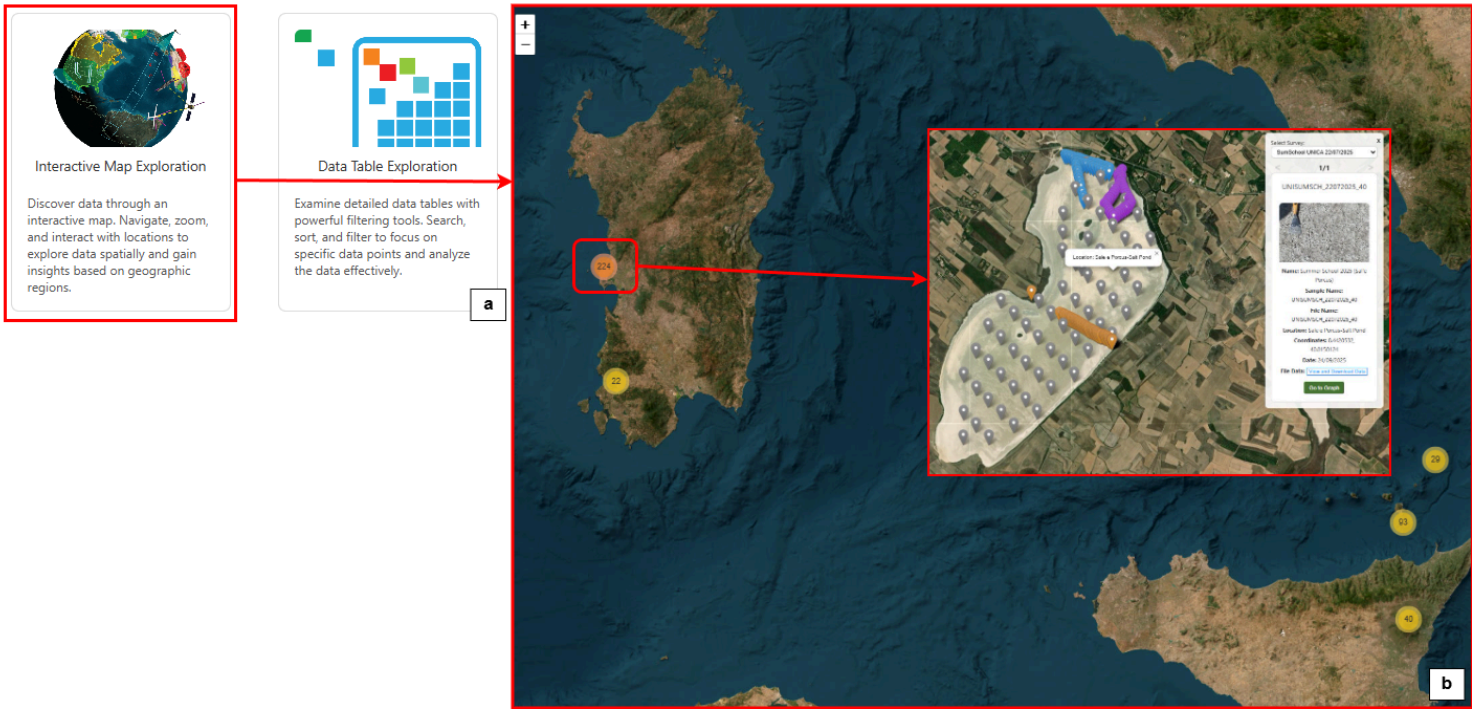


Figure 4

Map-based spectral data exploration in the INGV Spectral Library: (a) entry point to the Interactive Map from the exploration interface; (b) Interactive Map view showing georeferenced samples through markers and clusters for spatially guided exploration

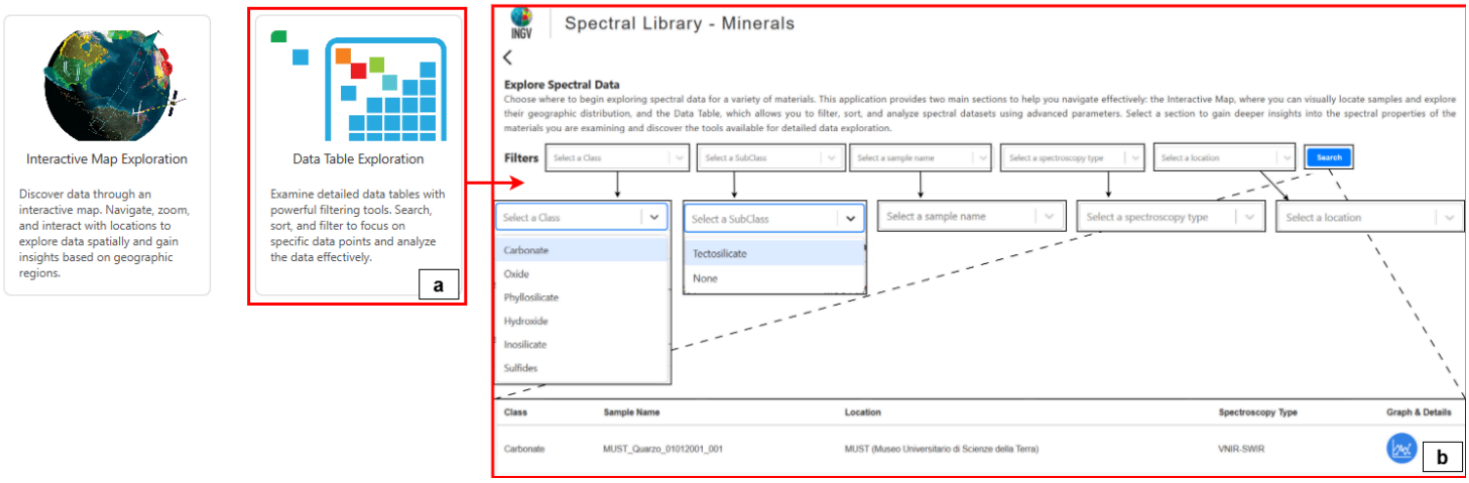


Figure 5

Table-based spectral data exploration in the INGV Spectral Library: (a) entry point to the Data Table Exploration interface; (b) Data Table Exploration view showing metadata-driven filtering and tabular access to spectral records

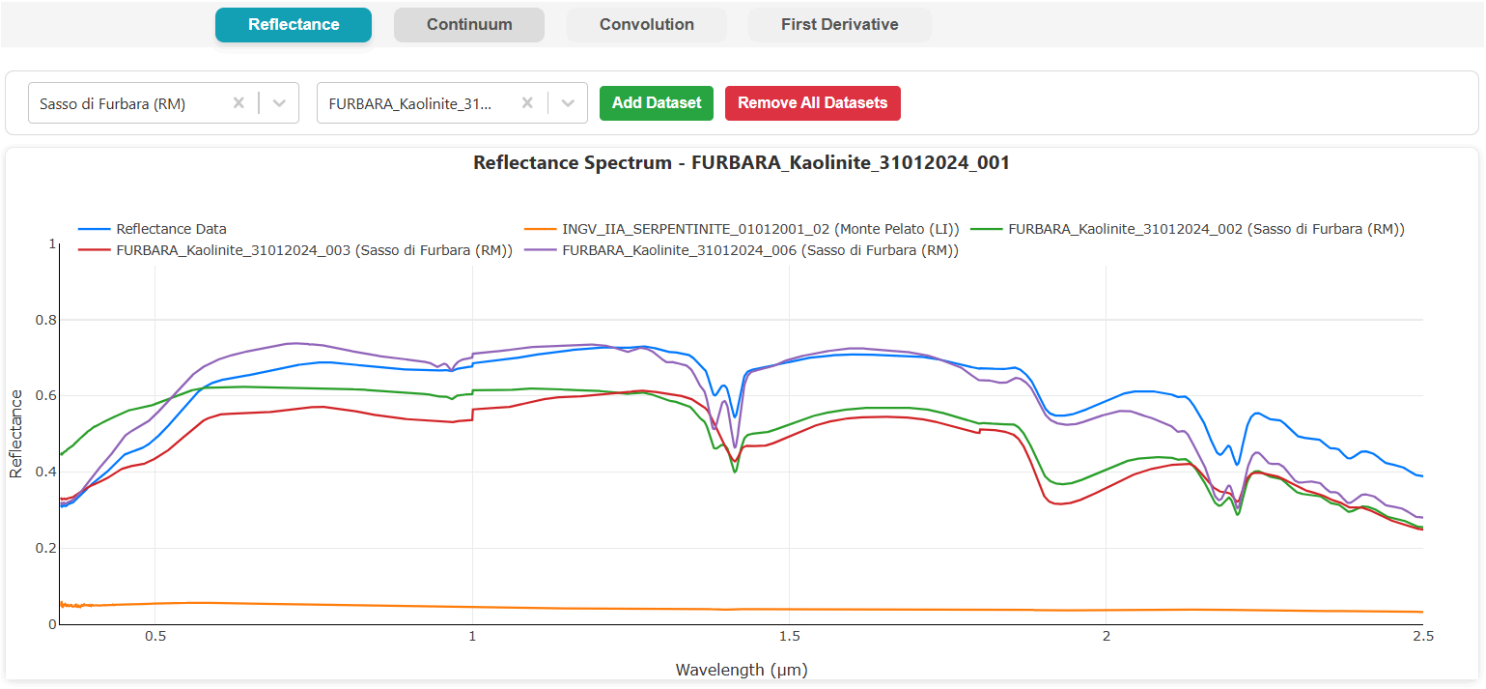


Figure 6

Reflectance visualisation and multi-spectrum comparison in the Graph Dashboard of the INGV Spectral Library. The interface allows users to display the primary spectrum and add additional datasets from the archive for direct comparison within a common plotting framework

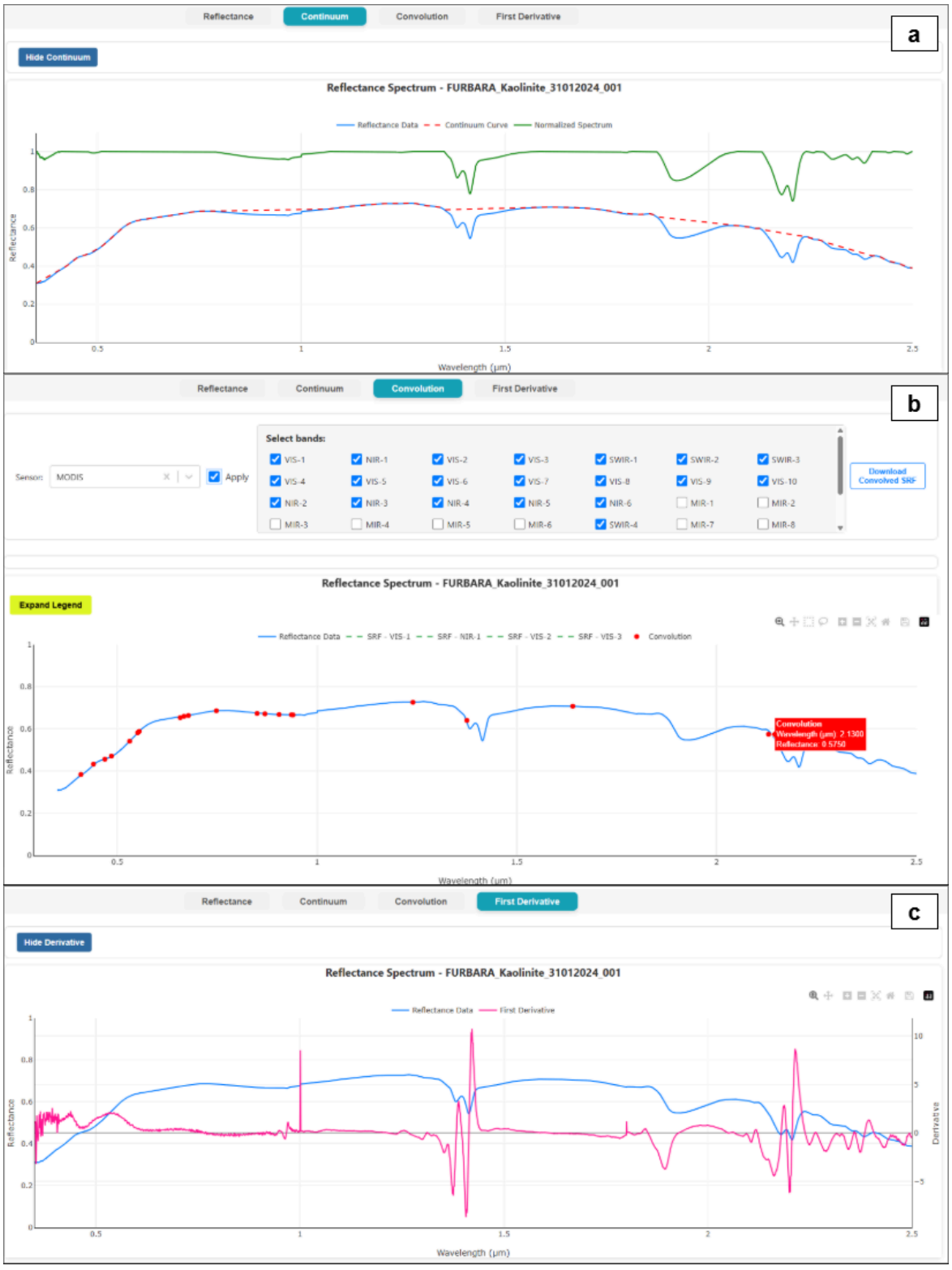


Figure 7

7Integrated preprocessing tools available in the Graph Dashboard of the INGV Spectral Library: (a) continuum removal; (b) SRF-based spectral resampling; (c) first-derivative analysis