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Impact of shared facilities in advancing solid-state NMR research: 2025 edition☆

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A B S T R A C T

Shared research facilities (SRFs) offer researchers cost-effective access to advanced analytical instrumentation that individual laboratories may find challenging to acquire or maintain. By centralizing resources, SRFs support a diverse user community including students, early-career scientists, senior principal investigators, and industrial collaborators, while providing expert technical support and ensuring efficient use of infrastructure and funding. These facilities not only drive research productivity and foster interdisciplinary collaboration, but also serve as centers for training the next generation of scientists. In this article, SRFs that offer solid-state nuclear magnetic resonance (NMR) capabilities are discussed, highlighting representative examples, their accessibility, governance models, technical operations, application areas, and data-sharing practices. Usage data reveal that solid-state NMR-based SRFs strongly align with high-priority research goals, contributing to impactful projects across chemistry, life sciences, and materials science, as reflected in publication outcomes. The article also emphasizes that the collaborative networks among SRFs enhance knowledge exchange and resource coordination. Such coordinated inter-facility partnerships are expected to address emerging challenges, ultimately supporting sustainable infrastructure that meets the evolving needs of the solid-state NMR community.

1. Introduction

Solid-state NMR spectroscopy has become an indispensable characterization technique for elucidating the atomic- and molecular-level structures of a wide array of solid materials, particularly for systems that push the limits of conventional analytical techniques and/or where other methods provide ambiguous structural information. Emerging in the mid-20th century, NMR spectroscopy evolved into sophisticated approaches to probe nuclear spins in bulk matter, laying the foundation for today's advanced characterization spanning solids, liquids, and soft matter (e.g., polymers, gels, colloids, foams, biological materials). In the case of solid-state NMR, overcoming early challenges [1], such as addressing inherent sensitivity and resolution limitations, has driven transformative developments in the field. Notably, in the 1970s, techniques like Magic-Angle Spinning (MAS) and Cross-Polarization (CP) significantly improved spectral resolution and sensitivity [2,3]. The 1980–1990s saw continued progress, including the advent of high-power radiofrequency (RF) amplifiers, commercialization of CP/MAS probes, access to magnetic fields of >10 T, and 2D correlation experiments [4–10]. All of this paved the way for high-resolution solid-state NMR studies of polycrystalline materials, polymers, pharmaceuticals, glasses, and biological solids, including membrane proteins and amyloids. New pulse sequences involving dipolar decoupling and recoupling for internuclear distance measurements, and those for separation of the effects of isotropic and anisotropic interactions arising for half-integer quadrupolar nuclei [11,12], have opened further opportunities for the study of inorganic, hybrid, and complex biological materials. These advances have positioned solid-state NMR spectroscopy to fill information gaps left by X-ray diffraction (XRD), neutron diffraction/scattering, and/or electron microscopy (EM) techniques, especially for systems lacking long-range order or requiring detailed structural information on local atomic environments.

In the 21st century, solid-state NMR spectroscopy continues to advance to meet complex scientific demands for higher sensitivity, resolution, faster data collection, and higher throughput analyses [8]. Structural characterization of volume-limited samples is increasingly performed in their native or functional states–examples include biomacromolecules in complex cellular environments, protein–drug complexes to natural biopolymers including biomass and plant cell walls, catalytic supports, functional polymers, gels and electrolytes, coatings, energy materials, and semiconductor thin films used in optoelectronics, photonics, and energy conversion/storage devices [13–18]. Large-scale SRFs for solid-state NMR have played, and will continue to play, transformative roles across scientific disciplines and are important for advancing research in all aspects of chemistry, materials multidisciplinary, and life sciences. Progress in solid-state NMR-based structural analysis increasingly depends on access to state-of-the-art instrumentation and methods, including high magnetic fields (≥800 MHz) [19], robust pulse sequences and optimization of experimental parameters for high-quality data acquisition [7,20], innovations in probe technology such as fast MAS systems (ν_{rot} = 30–160 kHz) [21–23]. Additional capabilities such as MAS cryoprobes for room-temperature signal enhancement [24–26], and dynamic nuclear polarization (DNP) measurements at relatively low-temperatures [27–29], and those enabling a broad range of variable-temperature measurements [30,31], as well as those suitable for *in situ* experiments, and *in operando* studies [18, 32–35], have also become equally important. Solid-state NMR can act in a complementary manner with other structure determination techniques, which has led to the development of fields such as NMR crystallography (i.e., the combined use of solid-state NMR, XRD methods, and molecular modeling to predict, solve, and refine crystal structures) [36,37]. Alongside, computational prediction of NMR parameters, geometry optimization, and machine learning (ML)/artificial intelligence (AI)-driven structure determination are growing in popularity, which will be essential for NMR data interpretation and discovery acceleration [38–45].

The growing complexity and costs of these technologies, plus the expertise required for their optimal use, make national and regional shared solid-state NMR facilities strategically essential. Key idea of shared resources is to provide centralized access, expert support, and state-of-the-art infrastructure for high-end experimentation. In doing so, they create new opportunities in solid-state NMR for both experts and non-experts alike, fostering broader interdisciplinary collaboration.

This article showcases the growing influence of SRFs in pushing solid-state NMR capabilities and applications forward. It also illustrates how coordinated, multi-institutional networks and shared infrastructure enable transformative research that may be often challenging to pursue within the confines of individual research groups and laboratories.

2. Examples of shared NMR infrastructure and facilities

Several SRFs across the United States, Canada, the United Kingdom, Europe, South America, the Middle East, Africa, Australia, and Asia provide access to solid-state NMR infrastructure, offering complementary resources and domain-specific expertise. These centers house diverse instrumentation: solid-state and DNP-NMR spectrometers across a range of field strengths, custom probes, extreme-condition and *in situ/in operando* setups, and apparatus for DNP enhancements. Many of these NMR-based SRFs are integrated into broader research networks and paired with facilities for sample preparation, high-throughput data acquisition, and analysis. Some SRFs integrate complementary analytical methods such as magnetic resonance imaging (MRI), electron paramagnetic resonance (EPR), Fourier-transform ion cyclotron resonance (FT-ICR) mass spectrometry, synchrotron facilities, cryogenic electron microscopy (cryo-EM), computational modelling, data analysis software, enabling holistic and multimodal investigations (see Table 1). Although dozens of SRFs serve the global NMR community, the selected examples below illustrate diverse operational models, shared practices,

Table 1
Examples of SRFs include: National (N), International (IN), Collaborative (C), Industrial (ID), Coordinated Access (CA), Network for Advanced NMR (NAN), National Research facility (NRF) and Hybrid (HYB) modes. The HYB model extends access beyond NMR to other magnetic field-based techniques such as EPR, MRI, and FT-ICR mass spectrometry, while also integrating complementary capabilities including sample preparation, synchrotron characterization, microscopy, data analysis software, and modeling. PANACEA (Pan-European solid-state NMR Infrastructure for Chemistry-Enabling Access) is meta-infrastructure (MI) that coordinates access, expertise, and development efforts across national platforms. This federated model enables users to draw on complementary instrumentation and leading solid-state NMR expertise distributed across multiple centers, while harmonizing operational and training practices. Detailed hardware specifications are available on the individual facility websites or the discussion below. CCP-NC: Collaborative Computational Project for NMR Crystallography.

Shared research facility	Modes of access	Complementary techniques
PANACEA, meta-infrastructure, USA, EU	MI, CA	
National High Magnetic Field Laboratory (NHMFL or MagLab), Florida, USA	N, IN, ID, C, HYB, PANACEA	EPR, FT-ICR, MRI
National Magnetic Resonance Facility at Madison (NMRFAM), Wisconsin, WI, USA	N, IN, ID, C, HYB	Modeling, Data analysis software
Campus Chemical Instrument Center NMR Facility and National Gateway Ultrahigh Field NMR Center, Columbus, OH, USA	N, IN, ID, C, HYB, NAN	EPR, FT-ICR, Proteomics, Cryo-electron microscopy
Infranalytics, French meta-infrastructure	N, IN, CA, HYB, PANACEA	EPR, FT-ICR
The UK high-field solid-state NMR national research facility	N, IN, ID, C, CA, HYB, PANACEA	NMR crystallography (CCP-NC)
Government of Canada Ultrahigh-Field NMR Collaboration Platform, Canada	N, IN, ID, C, CA	
Swedish national NMR facility (SwedNMR)	N, IN, ID, C, CA, PANACEA	
Centro Risonanze Magnetiche (CERM), Firenze, Italy	N, IN, ID, C, CA, HYB, PANACEA	Synchrotron, Cryo-electron microcopy
Spanish National NMR Facilities, Barcelona, Madrid, and Bilbao, INSTRUCT	N, IN, ID, C, HYB	Synchrotron, Cryo-electron microcopy
Portuguese NMR Centre, University of Aveiro, Aveiro, Portugal	N, IN, ID, C, CA, PANACEA	
Shared NMR facility, PAS-Lodz, Poland	N, IN, C, ID	Computational modelling , X-ray diffraction/ scattering
Core analytical facilities at NYU-AD, UAE and KAUST, SA	N, C, ID, CA	Microscopy, Electron diffraction
Multiple SRFs in China	N, IN, C, CA, HYB	EPR, FT-ICR, MRI
National Center for Magnetic Resonance in Wuhan	N, C, IN	MRI
Multiple SRFs in Russia	N, C, ID, HYB	EPR, FT-ICR, MRI, X-ray diffraction/scattering
Multiple NRFs in India	N, C, ID, CA	
Shared NMR facility, NTU, Singapore	N, IN, CA	
RIKEN Yokohama NMR Research Infrastructure, Kangawa, Japan	N, C, ID, CA	
Multiple SRFs Australia, New Zealand	C, ID, CA	
SRFs in Brazil	C, ID, CA	
Multiple SRFs in South Africa	C, ID, CA	
SRFs in Córdoba, Argentina	C, ID, CA	

opportunities and challenges, guiding principles, and common interests. The highlighted centers (Fig. 1: ordered geographically from left to right) are driving interdisciplinary research and innovation in NMR methodology and instrumentation.

Since the early 2000s, the growth of many SRFs–particularly national facilities has experienced a shift toward high magnetic fields (18.8–35 T) in conjunction with fast MAS (50–160 kHz) probes and custom-built probes for extreme conditions in order to broaden the scope of solid-state NMR applications. In addition, more than sixty DNP-NMR spectrometers spanning frequencies from 400 MHz/263 GHz to 900 MHz/593 GHz (some of which are accessible via SRFs) are accelerating structural studies of challenging solids. At the time of writing this article, several DNP-enabled NMR facilities are actively supporting the broader solid-state NMR community including 400 MHz/263 GHz systems (Fig. 1: geographically from left to right) in: Santa Barbara CA, Ames IA, Dayton OH, Princeton NJ (U. S. A.); Bruker (U. S. A.); Manchester and Cambridge (U. K.); Utrecht (Netherlands); Lyon, Grenoble, and Marseille (France); Bruker (France); Berlin, Rostock, Frankfurt and Darmstadt (Germany); Gothenburg, (Sweden); École Polytechnique Fédérale de Lausanne/EPFL and Eidgenössische Technische Hochschule Zürich/ETH Zurich (Switzerland); Aveiro (Portugal); Rehovot (Israel); Melbourne (Australia); Jeddah (Saudi Arabia); Wuhan (China); Kyoto and Tsukuba (Japan)–with new systems under installation in Virginia (USA); Bangalore (India); Shanghai (China). Facilities equipped with 600 MHz/395 GHz DNP systems include San Diego, CA, Tallahassee, FL, New York, NY, Dallas, TX, Columbus, OH, and Bruker Billerica, MA (U. S. A); Guelph, ON and Edmonton, AB (Canada); Nottingham (U. K.); Nijmegen (Netherlands); Göttingen, Aachen, and Jülich (Germany); ETH Zurich (Switzerland); Doha (Qatar); Abu Dhabi (U. A. E.); and Beijing (China), with further systems being acquired in Ames IA (U. S. A.), Hangzhou and Hefei (China). High-field DNP facilities include 800 MHz/527 GHz systems in Pacific Northwest National Laboratory/PNNL WS (U. S. A.); Utrecht (Netherlands); Lyon and Paris (France); Munich, Jülich and Berlin (Germany). In addition, EPFL (Switzerland) hosts a 900 MHz/593 GHz DNP system. Hardware specifications at SRFs may change due to upgrades including field strengths, consoles, probe types, DNP capabilities, and maintenance cycles, and the acquisition/replacement of specialized capabilities. Information on key hardware capabilities at each SRF alongside indicative output metrics (user numbers, allocated time, research topics, publication counts and data management plans) are presented in the discussion sections features by individual SRFs (*vide infra*), or directly obtained from the annual reports published in the dedicated websites of the SFRs. High sensitivity and resolution obtained in NMR spectra acquired at high fields and/or with DNP NMR capabilities are expected to facilitate rapid data acquisition and analysis, structural information obtained from which can be further refined through computational modeling, automation, and data-driven approaches such as NMR crystallography, structure prediction, and ML approaches. Therefore, advances in upgrading of the associated hardware from central- (CPU) to graphics processing unit (GPU), exascale interconnects (hybrid CPU-GPU architectures), GPU-dense nodes, and liquid-cooled systems, dramatically boost throughput for molecular modelling, and ML-driven simulations.

2.1. SRFs in Florida, FL, U. S. A. (Robert W. Schurko)

The National High Magnetic Field Laboratory (NHMFL or MagLab, for short) is an NSF-funded U.S. research facility spanning three institutions: the Florida State University (FSU in Tallahassee, FL; headquarters), University of Florida (UF, Gainesville, FL), and Los Alamos National Laboratory (LANL, Los Alamos, NM). The MagLab features a number of world-record magnets and high magnetic fields, and spans research areas such as physics, chemistry, materials science, engineering, biology, biochemistry, and medicine. There are seven user programs: (i) DC field (FSU), which features steady, continuous magnetic fields up to 45 T [46], including resistive and hybrid magnets; (ii) NMR/MRI (FSU), which has high-field solid-state NMR and MRI/S (including in vivo animal imaging) and probe development for solid-state NMR and MRI; (iii) Advanced Magnetic Resonance Imaging and Spectroscopy (AMRIS, UF), which has high-field solution NMR and

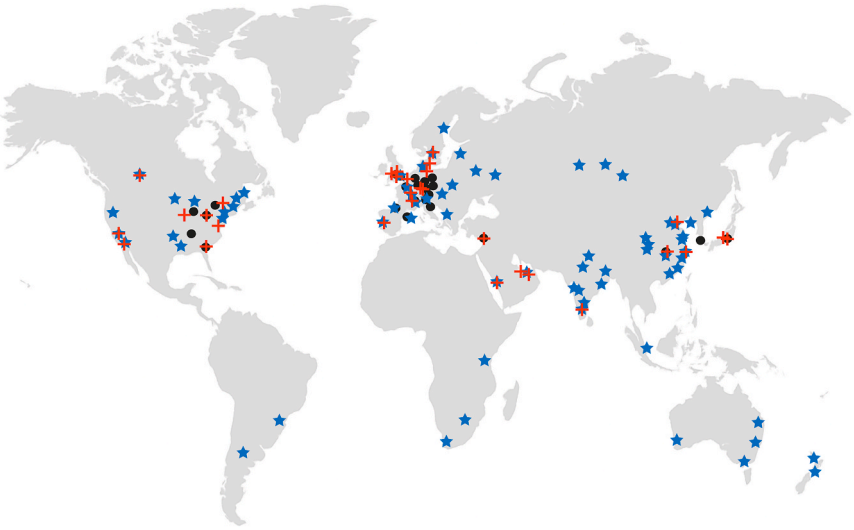

Fig. 1. Approximate locations of selected shared NMR facilities. Black dots indicate facilities with GHz-class spectrometers, and blue stars represent shared NMR facilities (300-900 MHz range). Red color '+' symbols represent DNP NMR facilities. For accurate site details and institutional affiliations, please refer to the discussion in the following sections. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

specialized NMR/MRI for biological and brain studies; (iv) EMR (FSU), which features high-frequency ESR techniques for studying unpaired electrons in materials (and working with the NMR/MRI division on DNP methods); (v) ICR (FT Ion Cyclotron Resonance Mass Spectrometry, FSU), which offers ultra-high mass resolution and accuracy; (vi) High B/T (UF), combining magnetic fields (up to ~15 T) with ultra-low temperatures (~0.4 mK) for quantum fluids/solids research; and (vii) Pulsed Field Facility (LANL), which uses ultra-high magnetic field pulses up to ~100 T for short-duration field experiments. The MagLab served 12,625 users from across the U.S. and around the world from 2018 to 2024, with ca. 50 % of these representing students and postdocs. On average, user counts from universities, government laboratories, and industry are 1390, 280, and 137, respectively, per annum. At the time of writing of this article, all user programs are open access with no user fees, and the only requirement is submission of a brief proposal that is reviewed by scientific peers.

The NMR/MRI and AMRIS user programs collectively serve ca. 550 users and offer >17,000 magnet days per year, with the majority of research focusing on chemistry, materials science, biology, and medicine. There are three flagship instruments, including (i) the 36 T series-connected hybrid (36T-SCH) [47], which is the highest field NMR magnet in the world (operating at 35.2 T/1.5 GHz for ^{1}H NMR); (ii) the 21.1 T/900 MHz ultra-widebore magnet (900 UWB) [48], which is used for in vivo MRI as well as solid-state NMR of quadrupolar nuclides; and (iii) the 395 GHz/14.1 T/600 MHz DNP NMR platform [49], which features a unique quasioptical microwave table that enables simultaneous MAS DNP NMR and Overhauser DNP (ODNP) NMR experiments. There are also 11 other NMR platforms with magnetic fields ranging from 7.1 T to 20.0 T. The NMR Technology Group in the NMR/MRI user program specializes in the construction of solid-state NMR probes with unique capabilities, including unique triple-resonance tuning configurations, low-frequency configurations for unreceptive low-γ nuclides, MAS rates >100 kHz, low-E coils for "lossy" biological samples, and special designs for GHz-class NMR platforms [50].

The large number of magnet days and high volume of users mandates that careful consideration be given to the number of support scientists and technicians, efficient scheduling, and magnet day usage, triaging of experiments, tracking of research output, and safety concerns. The NMR/MRI User Program is overseen by a Director, who reports not only to the Director of the NHFML, but also to External Advisory and User Committees. Collectively, these partnerships govern future scientific directions, acquisition of equipment, and support of high-impact research projects, along with training and recruitment of users and education and mentorship activities for students. Staff scientists (referred to as Research Faculty or Research Associates at the MagLab), work directly with users on experiments, training of students, and dissemination of publications–they also conduct their own independent research projects that serve to improve the rapidity, efficiency, and quality of solid-state NMR experiments, which greatly benefits our users (especially non-experts in NMR). The user support of technical staff is also crucial, who ensure that all instruments are well-maintained, software is up to date, and new hardware and probes are consistently available–this latter aspect ensures that our users have access to the most cutting-edge NMR hardware available.

Many options are provided to current and potential users of the NMR/MRI facilities at the MagLab. For instance, users are offered the opportunity to work on site (this is especially valuable for students and/or initiation of projects) or to run their experiments remotely. Research faculty and technical staff work with directly with users to choose the most suitable magnets, spectrometers, probes, experiments, and pulse sequences, all with the goal of achieving meaningful scientific outcomes. Expert NMR users have the opportunity to work on methodological development and attend workshops at MagLab (e.g., high-field solid-state NMR, DNP, and probe/coil workshops), whereas non-experts are tutored and mentored in the application and interpretation of complex NMR data sets. With education and training in mind, we have recently launched the MagLab Summer School on Solid-State NMR Spectroscopy–our first full-length offering had 18 student participants from a variety of different background and educational levels (undergrad to postdoc) and featured lectures, problem sets, tours, workshops, and hands-on experimentation. In addition, in partnership with the Pan-European solid-state NMR Infrastructure for Chemistry-Enabling Access (PANACEA, which brings together seven national infrastructures from Europe and that at the MagLab), a workshop on DNP for European and American students and postdocs was recently offered at MagLab. Many of these ideas and access/training models are detailed in the following sections.

2.2. SRFs in Madison, WI, U. S. A. (Chad M. Rienstra)

The National Magnetic Resonance Facility at Madison (NMRFAM, Department of Biochemistry at the University of Wisconsin-Madison) is a national SRF supported by the National Institutes of Health (NIGMS) through the P41 Biomedical Technology Research Resource (BTRR) and R24 National and Regional Resource programs, along with user fees. The facility provides open access to students, researchers, and principal investigators, supporting research in biochemistry, structural biology, chemistry, materials science, software for data analysis, NMR methodology, and instrumentation. As a key partner in the Network for Advanced NMR (NAN), NMRFAM contributes to a nationwide effort to enhance NMR infrastructure and collaboration. Through this network, two new 1.1 GHz NMR spectrometers have been made available to the broader NMR community, one at NMRFAM dedicated to solid-state NMR, and the other at the Complex Carbohydrate Research Center (CCRC) configured for solution NMR.

Solid-state NMR capabilities have been substantially augmented at NMRFAM over the last five years through strategic expansion of high-field instrumentation and supporting infrastructure. Recent expansions include additions of several magnets (two 600 MHz, two 750 MHz, 900 MHz, and 1.1 GHz) with solid-state capabilities and a suite of probes with custom features. The 1.1 GHz and 900 MHz instruments are equipped with Bruker NEO consoles and feature an advanced suite of probes including BlackFox 1.6 mm HCN/HPC for biological samples, Phoenix 1.2 mm and 1.6 mm HFXY for fast MAS applications, Phoenix 3.2 mm for low-gamma nuclei, and Bruker 0.7 mm HCN for ultrafast MAS. A custom-developed lock system for the 1.1 GHz spectrometer significantly enhances spectral resolution at ultra-high fields [51]. Probes for the 900 MHz system are compatible with the 1.1 GHz system, including BlackFox low-E field probes in 1.6 mm and 2.5 mm formats optimized for biological NMR applications. Moderate field instrumentation includes a 750 MHz wide spectrometer and three 600 MHz instruments dedicated to solids that provide additional capacity and serve as platforms for method development, staging and sample evaluation.

The facility maintains comprehensive rotor coverage from 0.7 mm to 5.0 mm, including 1.2 mm, 1.6 mm, 2.5 mm, and 3.2 mm sizes, optimized for different experimental requirements. All instruments emphasize compatibility with legacy Varian equipment, currently supported by PhoenixNMR and Resynant, ensuring continuity for established experimental protocols. The instrument suite enables detection of a broad range of nuclei including ^{1}H, ^{13}C, ^{15}N, ^{19}F, ^{31}P, and quadrupolar species, supporting advanced multidimensional NMR experiments across magnetic fields ranging from 600 MHz to 1.1 GHz. Technical innovations include advanced amplifier compensation systems [52], automated optimization software [53] and shimming protocols [54] that deliver improved homogeneity and spectral resolution. Comprehensive sensitivity studies across the magnetic field range have been conducted, providing quantitative performance metrics and optimization guidelines for experimental design [55]. Photoillumination probes enable control of pH within the rotor during solids measurements [56].

By integrating state-of-the-art instrumentation, automated data acquisition systems, advanced analysis software, and collaborative expertise, NMRFAM plays an important role in driving methodological innovation and expanding the scientific reach of solid-state NMR spectroscopy. The facility provides comprehensive user support including training programs, collaborative assistance in experimental design, data acquisition optimization, and analysis consultation. All instruments are accessible to the user community through the Network for Advanced NMR (NAN) and the NMRFAM website, supporting both local and external users from academic and industrial sectors.

2.3. SRFs in Columbus, OH, U. S. A. (Christopher P. Jaroniec, Alexandar L. Hansen, W. Trent Franks)

The solid-state NMR facilities at The Ohio State University (OSU, Columbus, OH) are comprised of the Campus Chemical Instrument Center (CCIC) NMR Facility and the National Gateway Ultrahigh Field NMR Center with the first Bruker 1.2 GHz NMR spectrometer in the US, supported by a recent mid-scale research infrastructure award from the National Science Foundation, as its centerpiece. In addition to the ultrahigh field 1.2 GHz instrument, which has solid-state and solution NMR capabilities, the CCIC NMR facility staff operate and maintain an additional eight moderate-to-high field Bruker high-resolution NMR instruments including an 800 MHz solid-state NMR spectrometer obtained through a National Institutes of Health High End Instrumentation award, a 600 MHz/395 GHz DNP solid-state NMR spectrometer, a 800 MHz spectrometer with solids, solution and micro-imaging capabilities, as well as two 600 MHz, 700 MHz, 800 MHz and 850 MHz solution NMR spectrometers, most of which are equipped with cryoprobes. The solid-state NMR spectrometers are described in additional detail below, and collectively this comprehensive suite of state-of-the-art NMR instruments is available for use by academic researchers and industrial partners across the nation in diverse disciplines such as structural biology, materials science, and metabolomics [22,57–65].

The 1.2 GHz Bruker Avance Neo NMR spectrometer is equipped with a set of probes to support a wide range of scientific applications. For solid-state NMR research on materials this system offers a 3.2 mm HX probe for low-gamma nuclei (^{197}Au to ^{13}C; 20–300 MHz) and a 1.9 mm HX probe for high-gamma nuclei (^{13}C to ^{31}P; 300–484 MHz). The facility also offers premier fast- and ultra-fast MAS capabilities for biological samples with 1.3 mm and 0.7 mm HCN probes with MAS rates of up to 67 kHz and 111 kHz, respectively, which are ideal for advanced studies employing proton detection for enhanced sensitivity. The Bruker Avance III HD Ascend 600 MHz wide-bore NMR DNP solid-state NMR spectrometer is equipped with a 395 GHz gyrotron and a low-temperature MAS cabinet. The system offers several DNP and room-temperature probes for studying biological solids, powders, and micro-crystalline samples, including 3.2 mm HCN and HX low-temperature MAS probes for experiments carried out at 100 K as well as a 1.3 mm HCN room temperature probe. The Bruker Avance III HD Aeon 800 MHz wide-bore solid-state NMR spectrometer comes with an extensive collection of advanced probes, including 1.3 mm and 0.7 mm MAS probes capable of spinning speeds up to 67 kHz and 111 kHz, respectively, as well as 3.2 mm HXY and Efree HCN probes. A multi-purpose Bruker Avance Neo Ascend 800 MHz NMR instrument is equipped with a 4.0 mm gradient HR-MAS probe ideal for studies of biological solids such as membrane proteins and tissue samples, and can also accommodate the 0.7 mm, 1.3 mm and 3.2 mm Efree HCN probes.

While the facilities at Ohio State have a strong focus on solid-state NMR, they are also home to a world-class suite of instruments for solution-state NMR and are integrated with a comprehensive mass spectrometry core. For solution-state NMR studies, the 1.2 GHz spectrometer is equipped with a 3 mm TCI (HCN) Cryoprobe, which is ideally suited for resolution-limited studies of large proteins, nucleic acids, and complex mixtures found in metabolomics. To support high-throughput studies, the system is also equipped with a Chilled SampleCase for storing and automatically loading up to 24 samples at controlled temperatures and an Automated Tuning & Matching (ATM) module for streamlined operation. This is complemented by an 850 MHz NMR with a TCI cryoprobe and a 24-sample SampleCase for high-throughput biological studies, as well as a 700 MHz NMR with a TXO cryoprobe and a 510-sample SampleJet. The 700 MHz instrument offers the highest ^{13}C-detection sensitivity of all the solution instruments, providing unique capabilities for studying intrinsically disordered proteins (IDPs), natural products, and polysaccharides. The broader CCIC also includes a Mass Spectrometry and Proteomics (MSP) facility, which houses ten instruments and offers 26 distinct service options. This allows users access to complementary techniques such as Fourier Transform Ion Cyclotron Resonance (FT-ICR) mass spectrometry and targeted compound quantification, creating a hybrid environment for multifaceted materials and biomolecular characterization.

The NMR facilities at OSU support a large and diverse user base consisting of OSU internal users as well as users from external academic institutions, government and non-profit organizations, and industrial partners. Access is provided to both NMR experts and non-experts, with facility staff offering expert training, consultation on experimental design, data collection, and analysis to ensure users can achieve meaningful scientific outcomes. In the fiscal year 2025 alone, the CCIC NMR facility and National Gateway Ultrahigh Field NMR Center served over 200 users representing 25 institutions, and supported external research grants in funding resulting in over 30 publications.

2.4. SRFs in Canada (David L. Bryce, Andreas Brinkmann, Victor Terskikh)

The Government of Canada Ultrahigh-Field NMR Collaboration Platform is operated by the National Research Council Canada with support from Laboratories Canada, and a consortium of other Canadian Government Departments and Universities. Located in Ottawa, the centerpiece of the facility is a Bruker 900 MHz (21.1 T) instrument equipped with a wide array of commercial and custom-built solution-state and solid-state solenoid and magic-angle-spinning (MAS) probes, in particular for low-gamma and quadrupolar nuclei. Since its inception in 2005/06 as the National Ultrahigh-Field NMR Facility for Solids, this facility has received support from the Canada Foundation for Innovation, the Natural Sciences and Engineering Research Council of Canada, the National Research Council Canada, Laboratories Canada, the University of Ottawa, Bruker Biospin, and several other partners. Since its inauguration the facility has hosted visitors and collected experimental data for users in academia, government, and industry from across Canada and worldwide. In 2020, the spectrometer has been significantly upgraded and is now configured to alternate between solution- and solid-state NMR and features a recently acquired liquids cryoprobe for increased sensitivity. Access is provided through partnership agreements and on a per-use cost-recovery basis. As of 2025, well over 330 peer-reviewed publications have relied upon results obtained using the 900 MHz instrument. See, for example, refs [66–76].

In addition to this national platform, several universities in Canada operate local and regional NMR Core Facilities which are open to users and/or sample submission for a fee. Examples include the NMR center at the University of Alberta, the NMR Core Facility at the University of Ottawa, and Dalhousie University's Nuclear Magnetic Resonance Research Resource. In addition, 600 MHz/395 GHz DNP NMR facilities are available at University of Guelph, Guelph, and University of Alberta, Edmonton. There are currently no GHz-class magnets available for solid-state NMR in Canada.

2.5. SRFs in Warwick, U. K. (Steven P. Brown, Dinu Iuga)

The Engineering and Physical Sciences Research Council (EPSRC)- and Biotechnology and Biological Sciences Research Council (BBSRC)-funded UK high-field solid-state NMR national research facility (NRF) hosted at the University of Warwick has been providing access to researchers since 2010, initially at magnetic field of 850 MHz, expanding to include 1 GHz in 2020 and 1.2 GHz in 2025. The facility has been contributing to the UK's fundamental and applied research in academia and industry. The access model, which supports external (within the UK) users, fosters collaboration across disciplines and institutions. By combining cutting-edge technology with other areas of research such as the calculation of NMR parameters using NMR crystallography methods (benefitting from funding by EPSRC since 2010 for the collaborative computational project in NMR crystallography, CCP-NC), the NRF is uniquely positioned to enable cutting-edge research across materials, physical and life science applications, including batteries, catalysts, energy materials, pharmaceuticals, plant cell walls and protein interactions. The access range and impacts of the work carried out at the NRF are illustrated by a few representative examples in the areas biological assemblies [77,78], pharmaceuticals [79,80], hydrogels [81], biomass characterization [82,83], metal organic frameworks [84,85], inorganic and hybrid materials [86–89], and NMR methodology [90,91]. In this way, the NRF not only accelerates scientific discovery but also strengthens the UK's position in advanced characterization via shared NMR facilities. In addition, the Warwick NMR facility enables access to international users through the Pan-European NMR network (PANACEA, see below) facilitated by the EU. In the last 5 years (2020–2024), the UK high field NMR facility served over 400 researchers including PhD students, postdoctoral researchers, principal investigators, and industrial collaborators, yielding to over 100 publications. The NRF operates 24/7, 365 days a year, with all time (excluding a small amount of maintenance days and facility manager time) allocated to the user community.

2.6. SRFs in Europe

Several NMR-based SRFs across Europe offer access through both locally managed centers and the broader Pan-European NMR infrastructure: Germany, Switzerland, the Netherlands, France, Italy, and Spain have developed SRFs accessible to the national users and the EU users, some of which are presented in the below sections. In a separate article published as part of this special issue, Pan-European solid-state NMR Infrastructure for Chemistry-Enabling Access (PANACEA) project more elaboratively features the collaborative effort between these SFRs.

2.7. Multiple SRFs in France (Carine van Heijenoort, Franck Fayon, Sylvain Bertaina, Carlos Alfonso)

In France, the national research infrastructure "Infranalytics", established in 2022 and led by the CNRS Chemistry Department, unites three major user facilities: NMR (solid- and solution-state, and imaging), EPR (spectroscopy and imaging), and high-resolution FT-ICR mass spectrometry, all operating at very high magnetic fields. This decentralized national SRF provides access to cutting-edge magnetic field-based analytical techniques through a network of thirteen sites across France, housing 23 high-field instruments: 9 NMR spectrometers (up to 28.2 T, $^{1}H = 1200$ MHz), 8 EPR spectrometers (up to 9.4 T, 263 GHz), and 6 FT-ICR systems (up to 18.0 T). Operated by internationally recognized research teams with their expertise in various fields, these platforms deliver complementary insights into chemical composition, molecular organization, and dynamics across diverse samples. Specifically, NMR applications span healthcare, biological samples, environmental science, energy, catalysis, advanced materials, and agri-food innovation [22,92–102]. The Infranalytics SRF is open to national and international users, providing approximately 900 days of access per year for NMR, 480 days per year for ESR/EPR, and 420 days per year for FT-ICR measurements, over the range of available instruments. Beyond providing access, the Infranalytics SRF also coordinates national-level investments in advanced instrumentation. Interdisciplinary in nature, it serves the scientific needs of users who cannot independently acquire such sophisticated tools, ensuring access to world-class analytical capabilities. This coordinated framework enhances both the quality and efficiency of access by (i) directing users to the most suitable platform based on expert-reviewed project evaluations, (ii) strengthening complementarity among partner facilities to optimize resources and plan future equipment, (iii) harmonizing user training programmes, and (iv) coordinating investments in ultra-high-field technologies to extend access for French and international research teams, including those using standard magnetic fields.

Infranalytics experimental NMR facility (previously known as l'infrastructure de Recherche Résonance Magnétique Nucléaire à Très Haut Champ, IR-RMN-THC) today brings together a 1.2 GHz (Lille) and a 1 GHz (Lyon) spectrometer both equipped for solution, or solid-state applications with unique ultra-fast MAS capabilities at 1 GHz, two 950 MHz (Gif-sur Yvette, Grenoble), and one 900 MHz (Lille) for

biomolecule and biosolid applications with *in situ* high pressure or sample illumination capabilities at 950 MHz, one 850 MHz (Orléans) for solid-state NMR with unique high-temperature facilities, and two MAS DNP NMR 800 MHz systems (Paris, and Lyon) with polarizers for DNP-dissolution. A new 1 GHz spectrometer with solution and MAS cryo-probes (Bordeaux, 2026) is envisaged to join the range of facilities. Each spectrometer offers 100 days of access per year, with an exception to 1.2 GHz spectrometer, which is open to users 200 days per year. Over the last five years, Infranalytics' ultra-high-field NMR facility has provided users with more than 4890 experiment days, corresponding to the completion of 481 scientific projects (more than 96 projects and 980 experiment days per year on average). Across all research areas, this results in over 100 publications each year from users and affiliated research teams, spanning disciplines such as chemistry, biology, materials science, environmental science, and earth sciences.

2.8. Multiple SRFs in Sweden (Göran Karlsson, Gerhard Gröbner)

SwedNMR is a national and nation-wide research infrastructure that provides access to advanced NMR instrumentation and expert support across all areas of NMR spectroscopy in Sweden. SwedNMR supports a diverse range of applications from the atomic-level characterization of organic and pharmaceutical compounds, proteins, RNA, and DNA to studies of batteries, solar cells, and clinical samples [103–112]. The infrastructure operates through a distributed, node-based model organized into three thematic modules: bioNMR, materials NMR, and translational NMR. SwedNMR is supported by the Swedish Research Council and involves the following participating NMR partners: University of Gothenburg, Chalmers University of Technology, Lund University, Linköping University, Royal Institute of Technology (KTH), Stockholm University, Swedish University of Agricultural Sciences (SLU), Umeå University, and Uppsala University. The infrastructure includes three access nodes located in Gothenburg, Stockholm, and Umeå, providing researchers with on-site and remote access to high-field NMR systems, while five expert nodes offer technical consultation, methodological development, and user training. SwedNMR is open to users from all scientific backgrounds and levels of expertise, from academic groups and industrial partners to early-career researchers and students, thus promoting widespread adoption of NMR across disciplines. The main solid-state NMR centre is located in Umeå, together with the smaller Stockholm and Gothenburg nodes offers access to solid-state including cryo-MAS and DNP-NMR capabilities. Together, these sites offer broad access to advanced solid-state NMR, including cryogenic MAS and DNP-NMR. The flagship instrument is the 850 MHz solid-state NMR spectrometer in Umeå, equipped with a 0.7 mm HXY MAS probe, alongside a 600 MHz system featuring a 3.2 mm Cryo-MAS probe. Additional instrumentation includes an 800 MHz spectrometer with a 1.3 mm MAS probe (expected in 2026) and a 600 MHz HX MAS system in Stockholm, as well as 400 MHz systems with 3.2 mm HXY and HFX DNP capabilities in Gothenburg. Between 2022 and 2024, these facilities collectively supported 205 users across approximately 3600 access days. On average, SwedNMR annually serves 150 external users from Sweden, supporting 30 research projects per year. During 2020–2024, this usage has led to over 209 peer-reviewed publications and dissemination activities across a wide range of disciplines, including biomacromolecular research (40 % usage), catalysis and advanced materials (30–40 % usage), cellulose-based biopolymers, and pharmaceutical and other applications (20–30 % usage).

2.9. SRF in Łódź, Poland (Marek J. Potrzebowski)

The NMR Laboratory at the Centre of Molecular and Macromolecular Studies, Polish Academy of Sciences (CMMS PAS, Łódź) serves as a central hub, among others, for solid-state NMR spectroscopy in Poland. Funded through research grants from the National Science Centre (NCN), internal resources and industrial contracts, the laboratory supports around 30 domestic users annually (2020–2025) and engages in scientific collaborations with several European countries including the Czech Republic, Croatia, France, and Portugal, as well as collaborative effort with research labs in the United States. The SRF at Łódź is equipped with four solid-state NMR spectrometers with fields ranging from 9.4 T to 14.1 T (AVANCE Neo 400, AVANCE III WB 400, AVANCE III 500, and AVANCE III 600), along with a diverse set of probeheads supporting rotor diameters from 4 mm to 1.3 mm, with dual-channel broadband and triple-resonance dedicated probes, enabling analysis of several NMR active nuclei crucial for studying biological samples, pharmaceuticals, organic and organic–inorganic hybrid materials. The NMR Center in Łódź offers tailored support for research projects ranging from routine analysis of powders with basic ^{13}C CP-MAS to high-resolution 2D correlation NMR experiments for spectral analysis in conjunction with advanced NMR crystallography, and solid-state NMR methods development [113–124]. For projects beyond the SRF's capabilities, researchers from Poland are encouraged to apply for access through the PANACEA network. Encouraged by the success of the local capability and international collaboration, Poland is currently working toward forming a national NMR infrastructure, obtained a favorable evaluation, making a step towards investments in the Polish Roadmap for a shared NMR Research Infrastructure.

2.10. SRF in Florence, Italy (Linda Cerofolini, Enrico Ravera, Marco Fragai, Moreno Lelli)

Italy's Magnetic Resonance Center (CERM–Centro Risonanza Magnetica) at the University of Florence provides access to 13 NMR spectrometers (9.4–28.2 T, 400–1200 MHz), spanning solution- and solid-state applications in structural biology, drug–protein interactions, catalysis, pharmaceuticals, and materials. Of these instruments, the 1.2 GHz, 850, 800, and 700 MHz, are equipped with solid-state NMR probes and a 600 MHz instrument is equipped with an HR-MAS probe. Access is offered through three routes: Instruct-ERIC (transnational, EU including supported Italian users), Instruct-ITALIA (national structural biology network, started its activity in early 2020), and PANACEA (2021 onwards, global solid-state NMR for chemistry, pharma, and materials). At the national level, CERM has been providing access to state-of-the-art NMR instrumentation since 1990 and transnational access since 1994, overall, with more than 30 years of experience in hosting users. Since 2010, CERM together with its associated Consortium for the Magnetic Resonance of Metalloproteins (CIRMMP) is also included in the "Italian Roadmap of Research Infrastructures of Pan-European Interest". CERM is also the Italian node of the European Instruct-ERIC, the European research infrastructure consortium for integrated structural biology defined in the European Strategy Forum on Research Infrastructures (ESFRI) Roadmap and active since 2012. CERM is contributing to the Instruct-ITALIA infrastructure with its NMR or the EPR instrumentation, complementing facilities offering platforms and techniques which include 3D structural methods such as X-Ray crystallography and cryo-EM, Circular Dichroism, and other biophysical platforms. In parallel, CERM/CIRMMP is also the core centre of the Instruct-ITALIA network, an infrastructure to promote and foster an integrated approach in structural biology at the national level.

Regarding solid-state NMR, CERM offers probes ranging from 4 mm to 0.7 mm HCN (MAS speed up to 111 kHz) to support a wide range of scientific applications. The 1.2 GHz Bruker Avance Neo NMR spectrometer with 0.7mm probe is particularly suited for advanced studies employing proton detection with enhanced sensitivity and resolution without the need for deuteration, and enabling detailed investigations of dynamics and interactions in the solid state. The Bruker Avance III 850 MHz wide-bore system with 3.2 mm CP MAS DVT $^{15}N/^{13}C/^{1}H$, 1.3 mm CP MAS $^{1}H^{19}F/BB/^{15}N$ and 0.7 mm CP MAS $^{1}H/^{13}C/^{15}N$ probe-heads for biomolecular applications. The Bruker Avance III 800 MHz standard-bore system with 3.2 mm CP MAS DVT E-free $^{15}N/^{13}C/^{1}H$, 1.3 mm 3γ $^{1}H^{19}F/BB$-X/BB-Y and 1.3 mm CP MAS $^{1}H/^{13}C/^{15}N$ probes allow to

perform measurements on inorganic materials and biomaterials with high salt concentrations. The Bruker Avance NEO 700 MHz systems come with two CP MAS BB/BB/1H probe-heads (4- and 3.2 mm) which allow to record also solid-state NMR spectra on ^{27}Al and ^{11}B nuclei.

Specifically, the CERM/CIRMMP infrastructure provides state-of-the-art instrumentation and expertise to perform the most comprehensive array of experiments needed for the structural and dynamic characterization of biological macromolecules and their complexes, with well-known expertise in structural determination of protein, paramagnetic proteins (CERM contributed to the identification of structure of a paramagnetic metalloprotein (MMP12) uniquely through solid-state NMR restraints [125] and protein amyloids) [126,127], antibiotics [128,129], biomaterials [130], material sciences [131,132] and DNP-enhanced NMR [99,133–135] are also active fields of research. The research at CERM is devoted to integrated approaches, and not only in structural biology. CERM facilities are also enabled with other complementary techniques that are also included in the user access possibilities, such as EPR, protein production for in-cell NMR, computational services, and proprietary infrastructure dedicated to industrial research providing access to instrumentation and expertise. A Cryo-EM instrument and an X-ray diffraction platform are available at the facility jointly with the Chemical Department. Together, these facilities supported 205 users over approximately 3600 access days, resulting in more than 209 peer-reviewed publications and dissemination outputs. Specifically, for solid-state NMR, during the last 5 years (2020–2024) 42 users accessed the facility with more than 560 access days distributed in the areas of biomacromolecular and cellular systems, advanced materials, and pharmaceutical sciences. These contributions reflect diverse domains including biomacromolecular systems, advanced functional materials, cellulose-based biopolymers, and pharmaceutical sciences as well solid-state NMR and DNP-NMR methodology, demonstrating broad interdisciplinary impact.

2.11. SRF in Aveiro, Portugal (Luis Mafra)

The Portuguese NMR Centre, established in 2023–2024 at the University of Aveiro, is Portugal's largest NMR facility. It houses six spectrometers, including a 700 MHz Bruker Avance III HD for high-resolution studies of biomaterials and polymers, a 400 MHz Bruker Avance Neo DNP-NMR with cryogenic MAS probe, and four mid-field systems (300, 400, and two 500 MHz), and operates within both the national PTNMR network and the Pan-European PANACEA network. Managed by 10 permanent researchers, two technical staff, and several PhD students, the Centre benefits from funding from CICECO (Centre for Research in Ceramics and Composite Materials)–Aveiro Institute of Materials, which fosters strong interdisciplinary research. Operating through PANACEA's peer-review system (see below - PANACEA project), the Centre serves approximately 32 local users annually, supporting both academia and industry (e.g., Hovione, Bondalti). Services include a wide range of multinuclear 1D/2D MAS NMR methods. The research at this SRF also involving developing novel MAS-DNP methodologies to polarize gases in confined spaces and exploring additive manufacturing (3D printing) to produce custom NMR components [136]. The Centre has been a hub for methodological innovation, with expertise in developing advanced solid-state NMR techniques. Key contributions include enhancing the sensitivity and resolution for challenging quadrupolar nuclei using methods such as multiple-quantum (MQ) and satellite-transition (ST) MAS, and developing high-resolution ^{1}H-based combined rotation and multiple-pulse spectroscopy (CRAMPS) approaches at fast MAS, combined with ^{1}H-inverse detection and ^{1}H–^{1}H double-quantum–single-quantum (DQ-SQ) recoupling. Experimental capabilities are complemented by computational approaches, including first-principles calculations and ab initio molecular dynamics. Research spans materials science and biophysics, supported by National (FCT) and European Research Council (ERC) grants. Applications include atomic-scale studies of CO_2 chemisorption and physisorption in nanoporous materials such as metal-organic frameworks (MOFs), covalent-organic frameworks (COFs), and amine-functionalized silicas (using DNP-enhanced ^{13}C/^{15}N NMR); investigations of battery electrolytes, *in situ* photoelectrochemical NMR, drug delivery systems, and pharmaceuticals, bioadhesives, biomass, studies of energy materials, glasses, heterogeneous catalyst acidity (e.g., ^{31}P probe molecules in zeolites); and luminescent nanothermometry [137–147]. Specifically, the biophysical research addresses protein–lipid interactions in membrane dynamics, integrated with complementary methods, while machine learning with neural network potentials is applied to model gas interactions and reactions under confinement.

2.12. Coordinated access between SRFs in EU and in U. S. A. (Anne Lesage, Guido Pintacuda)

The PANACEA project is a European distributed infrastructure designed to facilitate access to advanced solid-state NMR instrumentation for the broader chemistry community. Funded by the EU Horizon 2020 INFRAIA-02-2020 (*Integrating Activities for Starting Communities*), PANACEA has been operating since 2021, and brings together eight NMR-based SFRs operating as national infrastructures across Europe as well as a strategic partnership with the US-based National High-Magnetic Field Laboratory [148]. It includes the High-Field NMR Center in Lyon (CRMN, France), the Extreme Condition and Materials: High Temperature and Irradiation Laboratory in Orléans (CEHMTI, France), the High-Field Solid-State NMR National Research Facility (NRF) in Warwick (UK), the Danish Center for Ultrahigh-Field NMR Spectroscopy in Aarhus (Denmark), the Magnetic Resonance Center in Florence (CERM/CIRMMP, Italy), the Solid-State NMR Facility for Advanced Materials Science in Radboud (the Netherlands), the Aveiro Institute of Materials, in Aveiro (CICECO, Portugal), and the Swedish NMR Centre in Gothenburg (Sweden).

Unlike the above-mentioned centralized facilities, PANACEA acts as a meta-infrastructure, coordinating access, expertise, and development efforts across national platforms. This federated model allows users to benefit from complementary instrumentation and forefront expertise in solid-state NMR spread across multiple centers, while aligning operational and training practices. The consortium currently offers access to 30 NMR spectrometers (with proton frequencies ranging from 100 to 1500 MHz), fully equipped for the most advanced solid-state NMR applications, including 6 DNP systems, enabling a wide range of applications from pharmaceuticals and biomolecular systems to fine chemicals, cosmetics, food, materials, fuel, polymers, and clean energy tries [148]. As of mid-2025, more than 200 projects have been supported through over 1100 trans-national access days, with an average project length of 5–6 days. The user activities represent between 10 and 17% of the available time at each participating infrastructure, preserving capacities for national users and local in-house research programs. To support this transnational access, PANACEA has implemented common user interfaces, streamlined proposal review processes, and provided training resources to assist non-expert users in adopting solid-state NMR techniques. Beyond access, PANACEA promotes methodological and technological innovation through joint research activities involving four key partners: Bruker Biospin, Mestrelab, Weizmann Institute of Science, and École Polytechnique Fédérale de Lausanne (EPFL). These collaborations have enhanced instrument performances, software usability, and analytical workflows, impacting areas as probe technology, remote access tools, metadata standards, and NMR crystallography. In turn, these joint research activities improve the quality of the trans-national access to the infrastructures for the users. By leveraging and connecting national capabilities, PANACEA exemplifies a next-generation model of infrastructure coordination, serving as a backbone for European solid-state NMR while fostering global partnerships and enhancing the reach, efficiency, and impact of shared scientific resources.

2.13. SRFs in Barcelona, Madrid, and Bilbao, Spain (Miquel Pons)

Spain's high-field NMR centers are organized as a distributed national research infrastructure under the Infraestructura Científico-Técnica Singular (ICTS) program, with three service nodes located in Barcelona, Madrid, and Bilbao. These centers provide competitive access to researchers through evaluation by an independent external committee. The facilities feature NMR spectrometers in the 18.8 T–23.5 T (800 MHz–1 GHz) range. The GHz instruments in Barcelona and Bilbao employ high-temperature superconducting magnets, eliminating the need for liquid helium cooling below 2 K. Each service node offers distinct expertise to the users: the Barcelona center focuses on intrinsically disordered proteins and pharmaceutical biologics; the Madrid node is advancing biosolids NMR with a MAS cryoprobe and is soon to install a fast MAS probe on its 800 MHz instrument; and the Bilbao node has strengths in glycobiology and metabolomics [26,149–156]. All three centers are actively involved in integrative structural biology efforts, in close collaboration with complementary large-scale facilities such as the ALBA synchrotron located within 30 km proximity to the Barcelona node, and cryo-EM hubs co-located near each NMR site. The three high field NMR centers are now part of INSTRUCT ERIC (pan-European research infrastructure in structural biology) following a major expansion of the Spanish center to enhance international access and foster collaborative research across multidisciplinary platforms.

2.14. SRF in São Paulo, Brazil (José Fabián Schneider)

In Brazil, the NMR-Lab of São Carlos Institute of Physics, University of São Paulo hosts a multiuser solid-state NMR facility, which was established in 2021 with funding from the São Paulo State Foundation for Research Support (FAPESP). A Bruker Avance Neo 400 MHz wide-bore spectrometer is among the heavily used instruments for external users. The facility is overseen by administrative and users committees. This spectrometer is equipped with multiple probes (1.3 mm HX, 2.5 mm HXY, 3.2 mm XY low gamma, 4 mm H/FXY, 5 mm HX, and 7 mm HX) and capable of spinning speeds up to 60 kHz. Additional resources include a Bruker 600 MHz, a Varian 300 MHz, and an Agilent 250 MHz system. Instruments operate year-round on a 24/7 basis, with ~ 5% time dedicated to maintenance. Several modes of access and services are provided: reduced fees for researchers supported by federal or state grants, free of charge on a collaborative basis with NMR-Lab staff, or by paid packages for industry. Technical and academic staff assist users, many of them non-NMR specialists, in selecting experiments and ensuring high-quality data. In the past four years, over 50 users accessed the facility. Research areas include materials science (40%), physical chemistry (30%), structural chemistry (10%), and environmental chemistry (20%). Research projects and samples include ceramics, glasses, biomaterials, nanoparticles, concretes, polymers, small molecules, and hybrid materials [157–162].

2.15. SRF in Córdoba, Argentina (Gustavo Monti, Rodolfo Acosta, Horacio Pastawski)

In Argentina, the National Laboratory for Research and Services in Solid-State Nuclear Magnetic Resonance (LANAIS-RMS) was established at the National University of Córdoba in 1990 as part of Argentina's network of open national facilities for research and services. The laboratory is centered on a Bruker AVANCE NEO 300 WB spectrometer equipped with various probes, including 4 mm CP/MAS, wide-line proton and X-nuclei, as well as diffusion and micro-imaging options. Research activities encompass quantum phenomena, pharmaceuticals, polymers, porous media for petrophysics, battery electrodes, and pulse sequence development [163–171]. Complementary resources include low-field solid-state NMR at 20 MHz (Bruker Minispec mq20) and 60 MHz (custom-built with a Magritek KEA console), single-sided NMR (Magritek profile MOUSE PM25/PM5), and a Magritek Spinsolve80 Ultra Multi X for solution-state NMR. LANAIS-RMS provides extensive services in materials characterization, with emphasis on catalysis and food polymers. More than 120 researchers from Argentina, Brazil, the U. S. A., and Europe have collaborated at the facility, which also serves 13 private companies (including pharmaceutical and oil industries) and 41 academic laboratories. Access is offered through collaborative projects or paid services, supported by the National University of Córdoba and national research grants. Services include training, experiment design, data acquisition, analysis, and simulations.

2.16. Multiple SRFs in Russia (Yury G. Kolyagin)

Multiple sites in Russia host NMR-based SRFs including Lomonosov Moscow State University, St. Petersburg State University, Kazan Federal University, Novosibirsk State University, and the Russian Academy of Sciences institutes. These SRFs provide open access to solid-state NMR facilities to researchers through collaborative arrangements. These facilities are equipped with multinuclear solid-state probes, MAS capabilities, and advanced pulse sequence libraries, enabling studies of both crystalline and amorphous solids. Applications of solid-state NMR in Russia are diverse, ranging from fundamental investigations of mineral structures, catalysts, and porous materials to studies of polymers, pharmaceuticals, and biomolecular assemblies. Particular emphasis has been placed on porous materials, as well as heterogeneous catalysts and clays of geological interest. Shared access models allow researchers from smaller institutions to benefit from advanced NMR infrastructure. Recent studies include NMR studies of metal–organic polyhedral frameworks [172–174], NMR crystallography of salts and zeolite materials [175–177], and methodological advances in solid-state NMR of quadrupolar nuclei such as ^{51}V, ^{93}Nb, and ^{95}Mo [177,178]. Notably, research groups are developing *in-situ* and *operando* solid-state NMR approaches, often combined with MAS under batch or flow conditions, to investigate heterogeneous catalysts [179–182] and/or hydrothermal synthesis [182]. Beyond enabling access to SRFs, these facilities act as training hubs, offering workshops and technical support that broaden expertise in solid-state NMR across the community. Annually, an estimated 30–50 users access these facilities, contributing to the publication of over 200 papers between 2015 and 2024. By fostering collaboration and efficient use of resources, Russia's shared NMR facilities play a vital role in multidisciplinary innovation at the national level, and knowledge exchange.

2.17. SRFs in Abu Dhabi, U. A. E., and Jeddah, S. A. (Brijith Thomas)

In the Gulf, Middle-East and North Africa regions (broader MENA), the NMR infrastructure is booming and facilitating access to users from different research areas. Regionally, a high-field solid-state NMR facility in Saudi Arabia supports access to 14 instruments with magnetic fields up to 21 T (^{1}H = 900 MHz), including variable-temperature capabilities and a 400 MHz DNP-NMR system. At the King Abdullah University of Science and Technology (KAUST), researchers access instrumentation at core facilities via a Request for Service (RFS) platform and receive independent training, facilitating research in wider chemistry areas such as porous materials and membranes, for example [183,184]. The facility supports approximately 150 users, of whom about 10% are external, including industrial partners such as SABIC and ARAMCO. The KAUST maintains active collaborations with universities across Saudi Arabia and frequently hosts external researchers and industrial partners for training activities and instrument access. In addition, the shared core NMR platform at New York University Abu Dhabi (NYU-AD) houses four moderate field NMR spectrometers (11.7 T–14.1 T or 500–600 MHz) with solution and solid-state 600 MHz and a 600 MHz DNP NMR instrument, supporting about 10 internal users and external collaborations with academic institutions and industry partners. Operated by the Core Technology Platform (CTP) at NYU-AD, the primary research focus includes solid-state NMR studies of supramolecular assemblies, organic

crystals, MOFs and COFs, catalysts, membranes, polymers related materials, dynamic and self-healing crystals, NMR crystallography, and methodology development [185–194]. The overall facility usage rate is ~ 60%, with the 600 MHz wide-bore solid-state NMR being the most heavily utilized.

2.18. Multiple user facilities in South Africa

The NMR facilities at Stellenbosch University (Central Analytical Facilities, CAF), the University of the Witwatersrand, and Nelson Mandela University, are among the characterization hubs with solid-state NMR capabilities in South Africa. These labs support studies on clays, minerals, cements, catalysts, polymers, and biomaterials, addressing structural problems in energy, mining, and environmental sustainability [195–197]. Applications also include probing local structure in aluminosilicates, tracking cement hydration, studying catalytic active sites, and investigating drug–excipient interactions in pharmaceuticals.

2.19. Multiple SRFs in India (Vipin Agarwal)

India's progress in solid-state NMR research has been driven by growing technical expertise and improved access to both commercial solution and solid-state NMR instrumentation. Several SRFs are already in place at national research institutes and centers: Indian Institute of Science (IISc, Bangalore) and technologies (IITs), Indian Institute of Science and Research (IISER's), Tata Institute of Fundamental Research (Hyderabad), Centre of Biomedical Research (CBMR, Lucknow), Indian Institute of Chemical Technology (IICT, Hyderabad), and the National Magnetic Resonance Facility (NMRF, CSIR-NCL Pune). These SRFs have been proving access to support a broad range of experiments including static and MAS, multidimensional correlation spectroscopy including studies of spin-half and quadrupolar nuclei [23,198], and actively involved in designing novel solid-state NMR methods from first-principles [198–203]. The facilities are geographically distributed to enhance accessibility across the country. The IISc and the TIFR SRFs were established as early as the 1980s and these facilities today host eight spectrometers ranging from 400 to 800 MHz, with solution- and solid-state capabilities, while NCL and IICT SRFs host 9 and 10 spectrometers, respectively, aligned with the mission of supporting NMR access to researchers both in academia and industry nationwide. In addition, the Industrial Research and Consultancy Centre at IIT Powai hosts a 750 MHz solid-sate NMR spectrometer, accessible to both academic and industrial users. Most of the other centers operate solid-state NMR instruments in the 300–700 MHz range and are equipped with 1.3 mm MAS probes capable of spinning up to 65 kHz. Two facilities also house fast MAS probes operating at speeds up to 111 kHz, enabling high-resolution proton detection in solids. Many of these SRFs actively collaborate and support non-NMR researchers working in the area of pharmaceuticals, energy storage, catalysis, polymers, COFs, MOFs, biomolecules, and materials characterization [204–207]. Researchers affiliated with these SRFs maintain close collaboration through the National Magnetic Resonance Society (NMRS-India), established in 1995, which brings together more than 1,000 lifetime members from India and around the world including scientists from NMR, EPR, NQR, quantum computing, and related fields.

The SRFs in India also offer access to researchers, often at minimal cost, in order to promote wider scientific participation and community building, making an impact across disciplines. To promote awareness of basic principles, recent advancements, and applications in NMR, the SRFs frequently organize national-level training and workshops for users. TIFR biannually organizes the advanced workshop to train and attract new talent in the field, and NMRS organizes annual national symposia hosted at different centers across the country and also supports a variety of local events focused on specific areas within these disciplines, and to date featured over 30 annual symposia. Strengthening collaboration among academia, industry, and instrument manufacturers, along with upgrading SRFs, are projected to be an important aspect optimizing resource sharing and promoting interdisciplinary innovation. Recently, academia-industry allies have significantly enhanced structural insight and quality assurance in applied sectors such as pharma, oil, renewable energy, and materials companies. To continue advancing the field, strategic investments are envisaged to expand access to dynamic nuclear polarization (DNP), ultrafast MAS, and high-field magnets.

2.20. Multiple SRFs in China (Guangjin Hou, Feng Deng)

Multiple user facilities for solid-state NMR have been established across China, supporting cutting-edge research in chemistry, material science, and structural biology. Major shared NMR facilities include the Beijing NMR Center, the Center for Physicochemical Analysis and Measurement (Beijing), the State Key Laboratory of Magnetic Resonance Spectroscopy and Imaging (Wuhan), the Shanghai Key Laboratory of Magnetic Resonance (Shanghai), the NMR center in Dalian Institute of Chemical Physics (DICP, Dalian), and the Lanzhou NMR center (Lanzhou), University of Science and Technology of China (USTC, Hefei), among others. These NMR centers host multiple standard solid-state NMR spectrometers operating in 300–600 MHz, with some facilities offering magnetic field up to 18.8 T (800 MHz), such as those in Beijing, Wuhan, and Dalian. These platforms are fully equipped for conventional solid-state NMR analysis as well as advanced experiments such as fast MAS, MAS-CAT, Laser heating VT experiments. Notably, three DNP MAS NMR instruments have been installed in Wuhan (400 MHz), Beijing (600 MHz) and Shanghai (400 MHz), with several additional systems currently on order by other NMR centers. Research groups within these centers, particularly in Dalian, Wuhan and Shanghai, are actively engaged in the development of advanced solid-state NMR methodologies [208–211]. Custom-built NMR equipment is also in operation, including hyperpolarized ^{129}Xe NMR (Wuhan, Dalian), parahydrogen-induced polarization NMR (Wuhan, Shanghai), high-temperature/high-pressure *in situ* MAS NMR (Dalian), *in situ* electrochemistry NMR probes (Dalian, Shanghai), among others. All of these solid-state NMR SRFs are accessible to domestic and international users from both academic and industrial sectors, either free of charge or at moderate fees according to the policies of each center.

Most SRFs maintain active collaborations with multidisciplinary researchers in the field of chemistry, materials science and the life sciences, and have supported numerous publications in areas such as catalysis, energy storage materials, functional materials, polymers, and biomolecules [212–216]. While China has now built a robust solid-state NMR infrastructure comprising over 100 spectrometers dedicated to solid-state NMR studies (most of which are within SRF platforms), the community continues to work toward a more efficient, equitable and user-friendly SRF network. Ongoing efforts aim to enhance resource and expertise sharing, and to promote cross-disciplinary research and innovation both nationally and globally.

In addition to the shared NMR platforms (primarily based on commercial spectrometers), China is also advancing the research and development of high-field NMR spectrometers. A prominent example is the high-field NMR facility located in Beijing, which is dedicated to developing an advanced hybrid superconducting magnet that integrates both low- and high-temperature superconducting technologies to achieve magnetic fields ranging from 25 to 32 T (some currently under construction), enabling NMR experiments at ^{1}H frequencies exceeding 1 GHz. Complementing this effort, the High Magnetic Field Laboratory (CHMFL) in Hefei operates steady-state magnets, including resistive, superconducting, and hybrid systems, with current capabilities reaching up to 45.22 T. The CHMFL hosts solid-state NMR systems operating between 18.8 and 23.2 T, and supports high-end applications in chemistry, materials, and medical imaging through the integration of hybrid magnets for NMR/MRI and surface-sensitive microscopy techniques for molecular-level investigations [35,211,213,217–229].

2.21. SRF in Singapore (Kai Xue)

The use of solid-state NMR spectroscopy is rapidly growing in Singapore's shared facilities and centers. For example, the high field NMR Centre at Nanyang Technological University (NTU), is emerging as a national hub for advanced NMR capabilities. The center hosts moderate to high-field ranging from 14.1 T to 18.8 T (600 MHz and 800 MHz) solid-state NMR spectrometers. For the solid-state NMR measurements, the facility is equipped with a comprehensive set of MAS probes (7 mm, 4 mm, 3.2 mm, 1.9 mm, and 0.7 mm) with varying MAS capabilities, a high-resolution (HR)-MAS probe, a cryogenic probe for solution-state NMR detection, and a microimaging system. During 2022–2024, the center supported a wide range of research projects across disciplines such as materials science, civil engineering, chemistry, physics, and structural biology. Since 2019, the center has contributed to over 50 publications in biological studies [230,231], catalysis [232], and materials [233–235]. In addition to serving NTU researchers, the center provides access to users from other national institutions, including the National University Singapore (NUS), the Agency for Science, Technology and Research (A*STAR), and maintains active collaborations with international partners from the UK, Germany, Belgium, Saudi Arabia, Malaysia, Thailand, and China [236–241]. In response to growing demand, the center is exploring future expansion, with a focus on advanced high-field NMR applications including 2D correlation experiments with indirect detection via proton and the study of low-γ nuclei and insensitive quadrupolar nuclei.

2.22. Multiple facilities in Australia and New Zealand

Examples of solid-state NMR facilities in Australia include University of New South Wales (UNSW), Monash University (MU), Deakin University, University of Queensland, and the Australian National University (ANU). These hubs offer multinuclear NMR instrumentation with MAS, variable-temperature control, and a suite of advanced pulse sequences, enabling users to characterize local structures and their impact in driving bulk properties in molecular solids, polymers, inorganic materials, and biological systems [242,243]. Facilities at UNSW and ANU involve in characterization of catalysts, battery and semiconductor materials, glasses, polymers, and porous frameworks [244,245].

In New Zealand, the distributed NMR platforms at the University of Auckland, Victoria University of Wellington, the University of Otago, and the University of Canterbury feature solid-state NMR instrumentation and expert staff who provide training. Applications span energy materials (batteries, catalysts, perovskites), organic electronics and polymers, geological and cementitious solids, pharmaceuticals, and agro/food systems (notably dairy and plant-based matrices) [246]. often in partnership with Research Institutes such as GNS Science, Scion, and AgResearch.

2.23. SRF in Yokohama, Japan (Takanori Kigawa)

In Japan, the RIKEN Yokohama NMR Research Infrastructure (YNMR) offers access to thirteen high-performance NMR systems for researchers within and outside RIKEN, including those from industry, supporting diverse scientific fields such as chemistry, life sciences, materials science, environmental science, drug discovery, and healthcare [247–253]. As one of Japan's leading research infrastructures, YNMR houses three 900 MHz NMR systems, including a solid-state NMR system equipped with multiple probe heads with access to examine spin-half and quadrupolar nuclei including ^{17}O, ^{27}Al, ^{45}Sc, ^{93}Nb, and ^{139}La, to name a few. In addition, YNMR serves as the lead institution of the "NMR Platform," a national network comprising eight NMR research infrastructures and four partner companies, supported by Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT). In the past five years (2020–2024), YNMR infrastructure has enabled access to 128 projects with 7253 access days, contributing to 108 publications. Among them, 24 projects and publications involve solid-state NMR research across a wide range of areas. In addition, efforts have also been expended to construct high field magnets for NMR applications [254].

3. Funding, organization, governance, and management

The national or regional SRFs are typically governed through multi-tiered structures of management, which strategically align with national research priorities. Facility directors and scientific advisory committees provide strategic and technical leadership, while oversight boards including representatives from academia, industry, and funding bodies, ensure alignment with broader scientific, economic, and societal goals. Engagement with industry can further strengthen the impact of SRFs by supporting commercially relevant research and development. Financial support for research, equipment, and infrastructure is usually provided by national or regional governments, which reflects the value of SRFs as public investments in scientific capacity, training, and competitiveness. In many cases, this funding covers the acquisition and installation of large-scale instrumentation, as well as ongoing needs such as maintenance, consumables, upgrades, user training, outreach, administrative costs, and sustainability initiatives.

Operationally, SRFs rely on strong coordination between administrative and scientific teams. Management oversees compliance, budgeting, safety, data governance, and strategic planning, while scientific staff maintain instrumentation, schedule magnet time, develop methods, and support user access, training, and data analysis. Instrument time (magnet days) is often organized thematically or methodologically to provide consistent access across disciplines and user groups.

Access to SRFs is typically regulated through open calls and peer-reviewed proposal systems. Researchers submit proposals detailing their scientific objectives, resource needs and specifications, and required spectrometer time. Proposals are evaluated on merit, feasibility, and alignment with SRF capabilities, while also considering user diversity (e.g., students *vs.* early-career scientists *vs.* senior PIs; industrial collaborations *vs*. fundamental research in strategic areas).

To sustain excellence in research dissemination and deliverables, SRFs prioritize robust feedback and careful monitoring of scientific output (*i.e.*, publications, conference presentations, Ph.D. theses, *etc*.). In this regard, the SRFs provide much more than access to instrumentation and data collection. Training programs, such as workshops, tutorials, hands-on experimentation, and direct participation in outreach activities are of great value as they promote knowledge sharing, build operational proficiency, and support effective dissemination of research outcomes and facility capabilities. During such training programs, technical and scientific staff offer expert guidance tailored to user end-goals, help design experiments, and support data analysis using custom-built pipelines and software platforms. Staff play a central role in guiding experiment design, troubleshooting methodologies, and supporting data processing, which is especially important for researchers from institutions with limited in-house expertise. Remote-operation systems further expand access and collaborative capacity, a need highlighted and accelerated during the COVID-19 pandemic. Initiatives such as the HORIZON-EU REMOTE-NMR (R-NMR, a project by a consortium of 26 European NMR centers) aim to establish standardized remote access platforms across European partners.

In addition to supporting individual research groups and projects, SRFs are playing an increasingly important role in advancing open-science practices. Many facilities are implementing standardized data formats, rich metadata, and digital archiving frameworks aligned with FAIR (Findability, Accessibility, Interoperability and Reuse) principles. Since 2021, the MagLab encouraged users to adapt to the principles of FAIR data management, which strive to make high-field NMR data more accessible, interpretable, and reusable. Researchers are also encouraged to use the Open Science Framework (OSF), with support from partners including NSF, FSU and UF. In addition, the Network for Advanced NMR

(NAN, funded by the NSF) has taken a step forward with the launch of the NAN Data Archive and NAN Data Transport System (NDTS). These platforms ensure that NMR data are automatically saved, securely archived, organized, and linked to sample information, making them readily accessible and easier to track.

4. Impact of SRFs on multidisciplinary research

The broader impact of large-scale solid-state NMR SRFs stems from key advancements: (i) enhancements in sensitivity and resolution for investigating mass- or volume-limited samples, including experiments involving insensitive, unreceptive nuclides [22,26,55,255–265] and (ii) the integration of solid-state NMR with other complementary analytical techniques and computational modeling [42,266–275]. These advances, along with new real-time, *in situ* and *in operando* experiments, enable the investigation of molecular-level structure, dynamics, and reaction kinetics and their relation to physicochemical properties and emergent functions of materials–this extends from small organic molecules to complex hybrid materials to the largest polymeric and/or biological macromolecules [18,32,34,276,277]. In addition, solid-state NMR studies are increasingly investigating systems in their functional states such as biomacromolecules at the cellular levels, thin films and membranes of importance in energy storage and harvesting devices including batteries and solar cells, and the natural biomass and biominerals such as wood and bone [14,15,17,22,278–284].

A survey of the literature from 2015 to 2024 demonstrates a steady increase in the use of solid-state NMR across multiple domains (Fig. 2), including materials science, chemistry, pharmaceutical science, energy storage, biomolecular sciences, and catalysis. Certain research fields require substantially more NMR measurement time, staff expertise, and iterative experiments to generate publishable data or resolve complex structures, making direct comparisons between publication output and instrument-time allocation challenging. Productivity per instrument hour varies significantly across disciplines. Although it is difficult to precisely quantify the contributions of SRFs to the outcomes shown in Fig. 2, they play a central role in enabling broad access to advanced instrumentation, technical knowledge, and specialized methodologies that are often difficult for individual groups to realize and implement. For example, collaborative efforts across European SRFs have supported major scientific achievements within the PANACEA network, demonstrating the benefits of coordinated SRF support in driving community-wide advances during its first three years of activity [148], and discussion featured above highlight similar contributions from individual SRFs. In this way, SRFs complement the topic-specific research programs led by individual principal investigators.

A search using Clarivate® Web of Science with keywords “solid state NMR” and “solid-state NMR” displayed approximately 29k and 26k publications, respectively. These 29k publications span a broad range of chemistry topics (including physical, analytical, applied, organic, and inorganic chemistry) accounting for ~45 % of the total. Other areas include materials science (~11 %), biological/biomedical/pharmaceutical sciences (~7 %), multidisciplinary physics (~10 %), nanoscience (~5 %), and polymers (~4 %). While solid-state NMR is also employed in engineering, environmental science, and condensed-matter physics, its activity is limited in these domains. Overall, this distribution highlights the multidisciplinary breadth of solid-state NMR and its increasingly important role across diverse areas of contemporary research.

Fig. 3 shows publication trends over the past decade reflecting the use of solid-state NMR spectroscopy in different research areas. In chemistry and materials science, solid-state NMR has become indispensable for elucidating local structure and intermolecular interactions, with results consistently reported in 600–800 publications annually. The rise in materials characterization is particularly noteworthy, increasing from ~400 publications in 2015 to over 600 in 2024. Other fields including nanoscience/technology, catalysis and pharmaceuticals have seen growth, while outcomes of biomacromolecules and polymers have remained steady.

In material solids, properties such as crystallinity, defect structures,

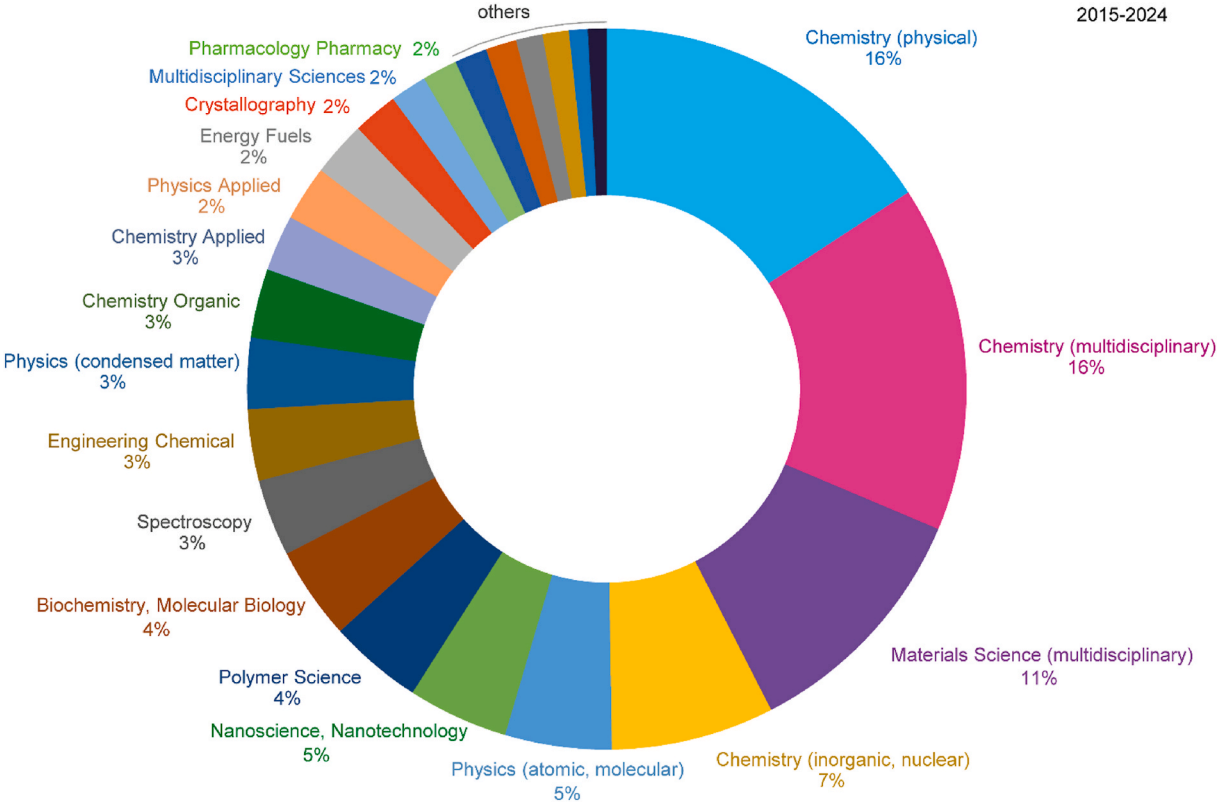

Fig. 2. Distribution of solid-state NMR spectroscopy usage by research area (2015–2024), based on ~29k records from Clarivate® Web of Science.

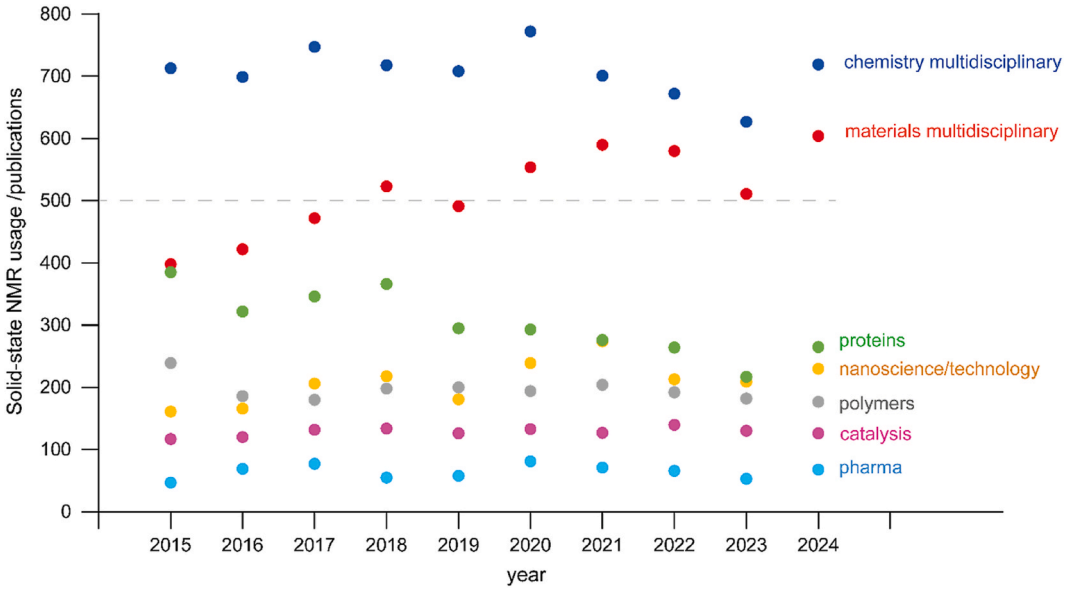

Fig. 3. Trends in publication outcome across selected research areas (2015–2024).

grain boundaries, and phase heterogeneity are among the determinants of their performance. High-field solid-state NMR and DNP-enhanced NMR, in combination with complementary analytical techniques, make the connections between structures, properties, and function that are necessary for understanding complex systems, including semiconductor films, nano- and quantum materials, functional polymers, and organic-inorganic hybrid materials [15,285–293]. Solid-state NMR can also be used to monitor phase transitions and the effects of electronic, optical, and mechanical inputs and stressors, which are important for applications in electronics, photonics, and spintronics. *In situ* solid-state NMR studies under extreme conditions (temperature, pressure, illumination, *etc*.) can provide real-time insights into the effects of atomic and molecular rearrangements on phase transitions, chemical transformations, and/or degradation. Integration with other techniques and computational modeling (e.g., Monte-Carlo methods, molecular dynamics, first-principles calculations, ShiftML, AI/ML crystal growth calculations) serves to accelerate materials discovery in the aforementioned areas [42,266–274]. In nanotechnology, solid-state NMR has advanced understanding of hybrid nanomaterials, nanoparticle surfaces, and host–guest architectures, especially for energy storage and delivery [294–297]. Studies of glasses and disordered systems has advanced with multinuclear, and multidimensional experiments acquired with conventional or DNP NMR spectrometers, enabling unprecedented resolution of atomic-scale structure and dynamics [298–303]. These applications extend to the energy storage systems [304–306]. Combined with computational modeling, these approaches reveal local environments, medium-range order, and dynamics, providing insights into structure–property relationships in such amorphous materials. In addition, research on emerging molecular semiconductor such as metal halide perovskites [17,131,286,288,307–313], and organic semiconductors [262,314–321] benefit from solid-state NMR spectroscopy measurements and analysis for gaining insights into synthesis-structure-property relationships.

Protein and biomolecular applications have expanded from microcrystalline and fibrillar systems to complex assemblies such as membrane proteins, amyloids, biomaterials and large supramolecular complexes, providing atomic-level insights into structure and dynamics in native-like environments [258,284,322–326]. The SRFs equipped with solid-state NMR instrumentation have significantly contributed to structural biology, particularly in the study of amyloid fibrils and aggregates associated with neurodegenerative diseases such as Alzheimer's and Parkinson's. Solid-state NMR has uniquely enabled atomic-resolution insights into complex and dynamic membrane proteins, information often inaccessible by means of other analytical techniques. Additionally, research on naturally occurring biopolymers, such as plant cellulose, nucleosides, and biomass-derived polymers, equally benefits from solid-state NMR or DNP NMR measurements and analysis [327–330].

In polymers, solid-state NMR spectroscopy enables quantitative assessment of crystallinity, chain packing, segmental mobility, and phase separation, directly linking microstructure to mechanical, thermal, and electronic properties [331–335]. In this way, soft matter and polymers, with their dynamic and multiscale structures, benefit from the ability of solid-state NMR to resolve conformational difference/changes, inter- and intramolecular interactions, and heterogeneous domains [293,336–342]. For thin films and coatings, it can probe buried interfaces, dopants, additives, detect subtle chemical modifications, and reveal molecular orientation, all of which are important for applications in electronics, packaging, and protective layers [262,318,321]. Its ability to study interfaces without selective labeling is particularly valuable for multi-component and heterogeneous systems. Another booming research area is thin film polymeric organic semiconductors for wider optoelectronics and energy paradigms [282,314,320,343,344]. Analysis of interfaces between multi-layer thin-films particularly benefit from solid-state NMR and DNP NMR [280], though challenges remain. The inherently low sensitivity of NMR can be limiting for the nanometer-to-micrometer thicknesses typical of thin films and coatings, where only microgram sample quantities are available. Achieving high resolution in complex, disordered, or multiphase materials often requires advanced isotopic labeling or fast sample spinning, which may be costly or impractical for routine use. Interfaces present additional difficulties due to signal overlap from bulk phases and low interfacial volume fractions.

Combined solid-state and DNP NMR investigations of heterogenous catalysts in conjunction with modelling techniques have enabled atomic-level insights into these materials, guiding the design of efficient and robust catalysts for chemical conversions [345–350]. Complementary surface-sensitive techniques, such as X-ray photoelectron spectroscopy (XPS) and scanning tunneling microscopy (STM), work well with solid-state NMR to reveal transient states and interfacial interactions critical to catalytic function. In addition, porous materials such as MOFs and COFs have greatly benefited from the conventional solid-state and DNP NMR analysis, and modelling techniques, lending insight into not only the complex molecular frameworks, but also into

host-guest interactions and mobile components within MOFs that may have value in future applications in sensors or data storage devices [351–355].

In pharmaceutical research, solid-state NMR is entering a golden age, enabling the differentiation of polymorphs, identification of unique solvates, hydrates, and salts, and increasing our understanding of complex drug formulations [129,356–368]. Active pharmaceutical ingredients (APIs) and nutraceuticals can be investigated in both their "bulk" forms as well as in dosage formulations [252,357,367,369–371], especially using multinuclear solid-state NMR methods. Structure elucidation of both can be accomplished using 2D NMR analysis and/or NMR crystallographic approaches [372,373]. The DNP NMR has recently been shown to be useful for understanding the crystallization processes of APIs, as well as for the detection of APIs in low concentrations. An exciting frontier is the use of solid-state NMR to investigate protein-drug interactions and perform pharmacokinetics analyses–these may be game changers for both manufacturers and consumers of a variety of drug and nutraceutical products.

Industrially, solid-state NMR spectroscopy plays an increasingly vital role in the characterization of pharmaceutical polymorphs, drug formulations, catalysts, composite materials, and energy storage materials. Its non-destructive nature, sensitivity to the local structure of each atomic environment, and chemical specificity, make solid-state NMR an indispensable tool for quality control, failure analysis, regulatory compliance, and driving innovation across a plethora of commercial sectors. Noteworthy techniques include HR-MAS based diffusion NMR spectroscopy [374,375], dynamic magnetic resonance imaging (MRI) in chemical process and reaction engineering [34,276,277], enabling the *in situ* reaction monitoring and chemical separation. Importantly, several SRFs have enabled this research in the context of industrial research and developments by closely coordinating with pharma, chemical, energy, and advanced materials companies [80,280,376–379].

The spectrometer vendors such as Bruker and JEOL, related hardware vendors like Doty Scientific, Phoenix NMR, BlueSky NMR, ePROBE, and NMR SERVICE, have all played significant roles in shaping the trajectory of solid-state NMR research by driving both hardware and software innovations. These advances include static and MAS probes, higher magnetic fields, and low-temperature technologies have dramatically improved spectral resolution and sensitivity, and *in situ* and *in operando* capabilities that enable time-resolved NMR data acquisition, permitting to carry out experiments that were previously inaccessible [21,25,51,54,380–387]. Beyond instrumentation, these vendors have fostered strong partnerships with the SRFs through collaborative projects, beta tests, workshops, sponsorships and training programs at conferences, thereby accelerating the adoption of cutting-edge methods. The SRFs also help producing spin-offs such as BlackFox (U.S. probe construction), Quadrufy (Canada, NQR), and Bridge12 (DNP). Their sustained contributions have not only advanced methodology, but also expanded the reach of solid-state NMR into emerging areas of chemistry, life sciences and materials paradigm.

In a broader context, multidisciplinary research areas involving chemistry, biochemistry, and advanced materials play a role in addressing Sustainable Development Goals (UNSDG) [388,389], where solid-state NMR is expected to find opportunities and challenges (Fig. 4). Among the list of 17 goals as of the time of writing this article, the aforementioned research publications and outcomes are linked to good health and well-being (~60 %), affordable and clean energy (~11 %), and climate action (~6 %). Research on biology, biomedical and pharmaceuticals particularly contribute towards these goals, while understanding structure-property relationships helps better design molecular/materials solids for clean energy and climate action. Additionally, industry innovation and infrastructure (UNSDG-09) are also expected to benefit from research on materials solids.

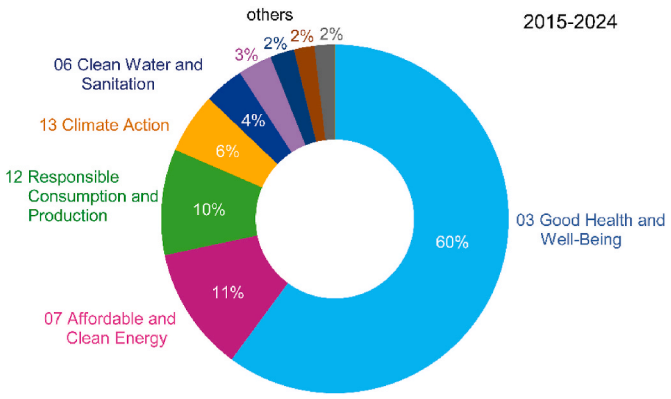

Fig. 4. Usage of solid-state NMR by research area (2015–2024) linked to the Sustainable Development Goals. Approximately 29k hits are partitioned based on Clarivate® Web of Science analysis.

5. Summary and looking forward

Looking ahead, current and future SRFs are expected to evolve as innovation centers that not only provide access to advanced instrumentation but enhance progress in magnetic resonance spectroscopy and imaging, enabling high-throughput characterization across disciplines. Sustainability will be central to this evolution—particularly for SRFs operating GHz-class magnets, cryogenic probes, and high-field DNP platforms—requiring continued efforts to minimize helium consumption, improve cryogenic efficiency, and modernize infrastructure in line with environmental and financial responsibility. Probe design will remain an important aspect in solid-state and DNP NMR applications by directly influencing sensitivity, resolution, and experimental capabilities at high magnetic fields and extreme conditions (*i.e.*, MAS frequencies >100 kHz, cryogenic temperatures, and high microwave-power DNP setups). The rotor size, bearing design, and RF coil configuration must be precisely optimized to ensure mechanical stability, high RF efficiency, and high-sensitivity detection on multiple channels, as well as accommodating microwave irradiation from high-power gyrotrons in the case of DNP MAS NMR probes. Moreover, customized probes and sample tubes (rotors) expand the types of experiments that can be performed, including multi-resonance detection (*e.g.*, HCN, HFXY), *in situ* monitoring, or sample environments that mimic harsh conditions (e.g., temperature, gas flow, new generation of cryogenic MAS probes, or electrochemical control). As materials, biological systems, and microstructured films become more complex—and sample quantities decrease—such tailored probe solutions 'will be crucial. Meeting these challenges will also require closer integration with complementary characterization techniques and computational modeling to link NMR observables with functional performance across materials, pharmaceutical, biological, catalytic, and energy-related fields.

Digital transformation including, real-time collaboration, and AI/ML-assisted experiment design, data collection, reducing access barriers and analysis is expected to gain popularity in NMR research [390–392]. While many of these capabilities are still emerging and implemented to varying degrees, they hold great promise for the future of the field. Emerging applications in autonomous NMR control, predictive experiment planning, automated analysis pipelines, and NMR-guided structure determination draw inspiration from parallel advances in materials informatics and biomedical imaging. Interlinked SRFs with shared expertise and complementary resources will play an increasingly important role in enabling these capabilities.

At the same time, SRFs may face mounting pressures from rising hardware costs, rapid technological turnover, and uneven user demand can strain resources and accelerate instrument usage. High-field NMR systems and DNP platforms demand frequent upgrades and place significant burdens on cryogen supply chains, energy use, and maintenance

budgets. Addressing these issues requires sustained investment in helium recovery, efficient cooling technology, predictive maintenance, and, importantly, specialized scientific and technical staff. Without dedicated personnel, even state-of-the-art SRFs risk reduced uptime, limited training capacity, and under-realized scientific impact. Achieving a balance between sustainability, operational reliability, and financial constraints will be essential to ensure the long-term viability of SRFs with current (and future) funding models.

In summary, solid-state NMR will remain indispensable for molecular-level characterization across scientific disciplines. To stay competitive and maximize impact, SRFs must continue to evolve strategically, strengthen collaborations, and embrace sustainable, technologically forward models of operation. If successful, they will provide significant benefits to fields spanning materials science, sustainable energy, health, catalysis, and quantum technologies, while contributing to a more collaborative, open, and resilient global research ecosystem.

Notes

The manuscript was written through contributions from all authors. The views and opinions expressed in this article are those of the authors and do not necessarily reflect those of the publisher.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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