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Review Article

# Application of neutron-X-ray dual-modal imaging in oil and gas well cementing under ultra-high temperature conditions

Yabing Wen [a], Xinxiang Yang [b,*]

[a] National & Local Joint Engineering Research Center of Harbor Oil & Gas Storage and Transportation Technology/Zhejiang Key Laboratory of Petrochemical Environmental Pollution Control, Zhejiang Ocean University, Zhoushan, 316022, China
[b] School of Engineering and Materials Science, Queen Mary University of London, London, E1 4NS, UK

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Understanding the failure mechanisms affecting cement sheath integrity under ultra-high temperature (UHT) conditions is essential for ensuring wellbore integrity and supporting the safe and sustainable extraction of deep oil and gas resources. However, difficulties in characterizing moisture migration have limited understanding of the physicochemical mechanisms and cementing processes that drive failure of cementing materials in such environments. To address these challenges and enhance understanding of cement sheath failure mechanisms, this study systematically evaluates the adaptability and advantages of Neutron–X-ray Dual-modal Imaging (NXDI) technology. NXDI's extensive applications in materials science, mineralogy, civil engineering, and energy research provide representative evidence of its potential. Building on this foundation, the study proposes, for the first time, a conceptual framework, technical roadmap, and future prospects for applying NXDI to cement sheath research under UHT conditions. Our findings indicate that intensified moisture migration critically affects the microstructure and physicochemical stability of cement sheaths. NXDI offers unique potential to overcome the limitations of conventional imaging methods by simultaneously characterizing moisture dynamics and microstructural evolution. Nevertheless, its application still faces challenges, including neutron imaging quality, dual-modal image fusion, sample representativeness, and practical implementation. To address these, we outline key research priorities and feasible steps. With continued advances in imaging technologies and experimental methods, NXDI is expected to play an increasingly important role in enhancing the efficiency, safety, and sustainability of deep oil and gas extraction.



## 1. Introduction

In recent years, oil and gas well cementing has received growing attention. Research has increasingly focused on advanced materials, cross-disciplinary engineering solutions, and new analytical tools to improve wellbore integrity, in line with the move toward cleaner and more sustainable petroleum operations (Zheng et al., 2021). The development and utilization of oil and gas resources in settings such as deep-sea and ultra-deep formations have become a central focus (Abdrabou et al., 2025; Estrada and Bhamidimarri, 2016; Fu and He, 2024; Zheng et al., 2021). As a critical aspect of energy security and upstream production efficiency, problems in well cementing can lead to methane leakage, reduced efficiency, and compromised engineering safety, demanding urgent solutions. Notably, over 40% of the world's remaining oil and gas resources are located in formations deeper than 5000 m, where development inevitably faces extreme conditions such as UHT (>200 °C) and ultra-high pressures (>100 MPa) (Zhang et al., 2024; Zheng et al., 2021); moreover, the effects of in-situ stress fields and rock porosity cannot be neglected (Dalirnasab et al., 2024). These increasingly complex well conditions and harsh geological environments greatly increase the difficulty of cementing in UHT wells, leading to frequent technical issues such as wellbore sealing failure (Zhang et al., 2024). In actual field operations, wellbore integrity failure is commonly observed. In China, the United States, and Norway, wellbore sealing failure rates exceed 20% (Jimenez et al., 2016; Zheng et al.,

* Corresponding author. Mile End Road, London, E1 4NS, UK.
*E-mail address:* xinxiang.yang@qmul.ac.uk (X. Yang).
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2021), whereas in deepwater wells, the failure rate can surpass 70% (Pang et al., 2020).

Therefore, ensuring reliable cementing and delaying or inhibiting sealing failure are of critical importance. Under UHT conditions, one of the primary causes of wellbore integrity failure is the rapid strength degradation of set cement, which directly affects sealing capacity. In recent years, increasing attention has been paid to oil and gas well cementing, with a growing emphasis on advanced materials, cross-disciplinary engineering solutions, and novel analytical tools to enhance wellbore integrity in upstream petroleum engineering. These include using nanomaterials to enhance the corrosion resistance of cement (Tiong et al., 2019), as well as improving its multi-scale mechanical properties and fracture resistance (Marji et al., 2023), reduce casing-cement interface damage (Olayiwola et al., 2023), control fluid loss in well cement (Andersen et al., 2019), and enhance durability (Mahmoud and Elkatatny, 2024), mechanical properties (Lima et al., 2022; Montassir et al., 2025), and stability under high-temperature and high-pressure (HTHP) conditions (Khan et al., 2024). Other material innovations comprise adding compressible carbon to improve zonal isolation and bonding strength (Wu et al., 2024a), employing alkali-activated gels to retard cement carbonation (Zhu et al., 2025), utilizing smart expandable fibers to prevent micro-annulus formation (Santos et al., 2020), and incorporating graphene oxide to enhance tensile strength (Khalfin et al., 2024). In the field of novel cement materials, a variety of new formulations have been proposed, including low-cost fly ash-based epoxy resin cement (Salib and Fakher, 2024), a newly developed cement with temperature resistance up to 240 °C (Xia et al., 2024), oil-wettable cement (Huang et al., 2023), specially engineered polymer composite cement (Santra et al., 2025), ceramic waste powder (CWP)-based cement (Al-Fakih et al., 2023), and volcanic ash (VT) blended with alkaline solution cement (Abdelaal et al., 2024). Additional innovations include low-carbon, high-sealability cement (Findlay et al., 2025), foam cement (Mahmoud et al., 2024), high-performance lightweight cement (Matovu et al., 2024), bio-based self-healing cement (Li et al., 2025b), and modified calcium carbonate whisker-reinforced oil well cement (Liu et al., 2025). Additionally, Denduluri et al. (2023), Carpenter (2024), Ogienagbon et al. (2022), and Omran et al. (2023) have investigated the applications and potential of various geopolymers in oil and gas well cementing. Ogienagbon and Khalifeh (2022), Meng et al. (2022), Yakoot et al. (2025), Zhao et al. (2022), and Phi et al. (2019) have explored how different conditions influence cement performance. Other studies have focused on engineering techniques to enhance well cementing, including casing rotation (Shafigullin et al., 2019), quantitative digital image analysis (Alberdi-Pagola and Fischer, 2024), Higher Order Displacement Discontinuity (Haeri et al., 2015), and machine learning-based prediction models (Wang et al., 2024). To build on these advancements, high-resolution visualization of well cement in oil and gas wells can better support the evaluation of cement performance and failure behavior. This requires the support of imaging technologies with certain potential, such as neutron and X-ray imaging.

Currently, neutron and X-ray imaging technologies have found broad applications across multiple disciplines and have demonstrated some potential. Kardjilov et al. (2018, 2011) provided comprehensive overviews of the most recent and impactful applications of neutron imaging in materials research. Meanwhile, neutron imaging has also been successfully applied in specific fields such as electrochemical energy storage and conversion, engineering materials, multiphase flow (Hussey and Jacobson, 2015), durability studies of cement-based materials (Zhang et al., 2018), as well as critical analyses of recent advances and remaining limitations in battery research (Ziesche et al., 2022). Other fields, such as life sciences (Burca et al., 2018) and geomechanics (Tengattini et al., 2021), have also benefited from neutron imaging applications. In particular, Cai et al. (2022) reviewed recent progress in visualizing and quantifying root water uptake, hydraulic redistribution between roots and surrounding soil, and root hydraulic properties. In the domain of X-ray imaging, applications have encompassed energy materials (Cao et al., 2020), materials and manufacturing science (Nguyen et al., 2025), the medical industry (Pfeiffer et al., 2020), preclinical research (Staufer and Grüner, 2023), and coal characterization (Mathews et al., 2017). Notably, Scatigno and Festa (2022) provided an overview of pioneering studies that applying machine and deep learning models to process both X-ray and neutron imaging data, with applications spanning biomedicine, microbiology, and materials science.

Collectively, the above studies demonstrate that both neutron and X-ray imaging have found extensive applications across various fields. Integrating their complementary strengths through neutron–X-ray dual-modal imaging (NXDI) offers a transformative pathway for investigating cement sheath sealing integrity under UHT conditions, with direct implications for enhancing energy system resilience, reducing environmental risks, and advancing the UN Sustainable Development Goals. To date, no studies have been reported on the application of dual-mode imaging to cement sheaths in well cementing, leaving this area of research unexplored. This study therefore takes a novel perspective by reviewing the two imaging modalities and evaluating their combined potential for future application in upstream petroleum well cementing research.

As a forward-looking review, this paper builds upon the applications of NXDI in other fields to propose its potential application in cement sheath sealing integrity studies. It aims to summarize the current research status, existing bottlenecks, and technical challenges associated with the sealing integrity failure of cement sheaths in UHT oil and gas wells, and through theoretical analysis and in-depth exploration of application scenarios, highlights the potential and feasibility of NXDI in investigating sealing integrity. Based on these insights, a logical research roadmap and future outlook are proposed. Section 2 reviews the state of research on cement sheath sealing failure under UHT conditions, and shows the advancement and suitability of NXDI in this context. Section 3 outlines recent advances in NXDI research, with a focus on dual-mode image fusion and its demonstrated potential. Section 4 reviews the applications of dual-mode imaging in the fields of materials science, geological mineralogy, civil engineering, and energy. This demonstrates the justification of transferring this technology to the study of UHT cement sheath sealing integrity and provides a basis for interdisciplinary technology integration. Section 5 demonstrates the feasibility of this research and proposes technical roadmap suggestions. Section 6 discusses the difficulties, challenges, and countermeasures in this research. It also puts forward prospects and recommendations for future related studies. This study is committed to constructing an application framework for NXDI in the research of cement sheath sealing integrity in UHT oil and gas wells, which possesses both cutting-edge scientific significance and practical value for enhancing wellbore safety, efficiency, and sustainability in upstream petroleum operations.

## 2. Overview of sealing failure research on UHT cement sheaths

The sealing integrity of cement sheaths is influenced by a wide range of factors, with complex failure mechanisms and various

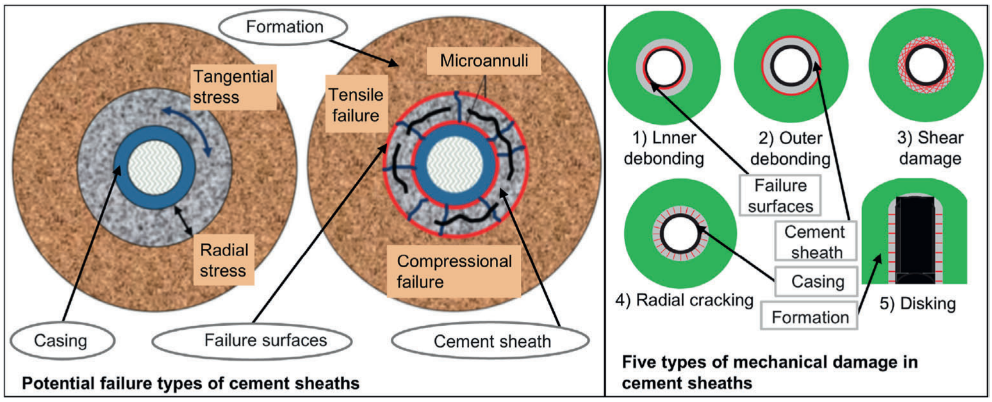


**Fig. 1.** Schematic illustration of common mechanical damages and potential failure modes of cement sheaths (Modified from Shadravan et al. (2014)).

types of failure. As shown in Fig. 1, Shadravan et al. (2014) based on the findings of Bois et al. (2012), summarized the potential failure modes that may occur in cement sheaths.

Firstly, the intrinsic properties of cement such as porosity, permeability, Young's modulus, and Poisson's ratio (Lima et al., 2022; Sauki and Sonny, 2015; Su et al., 2023; Zhang et al., 2022), along with factors like improper cement slurry formulation, incompatible material selection, and uneven placement caused by non-standard cementing practices (Lian et al., 2020), can all compromise sealing performance. Secondly, inadequate interfacial bonding (Yang et al., 2021c) or the presence of micro-annuli (Yang et al., 2024) can also result in leakage. Moreover, harsh environmental conditions, including hydraulic fracturing (Abdollahipour et al., 2015), HTHP, chemical corrosion (Pang et al., 2020; Wang et al., 2024; Yang et al., 2024), can accelerate the deterioration of cement materials and hasten sealing failure. In addition, formation stress, wellbore contamination, and operational loads may exacerbate damage to the set cement (Zhang et al., 2017). In particular, with increasing formation depth, the in-situ stress field and rock porosity cannot be neglected (Dalirnasab et al., 2024). High horizontal stress anisotropy may induce localized stress concentrations and microcrack initiation, whereas high porosity weakens the mechanical strength of cement and formation rocks, facilitating interfacial debonding and fluid channel formation, even though porosity generally decreases with depth (Abdollahipour et al., 2015; Corina and Moghadam, 2025). These coupled thermo–hydro–mechanical effects highlight that cement sheath failure in deep and ultra-deep wells is governed not only by temperature-induced degradation but also by the combined of stress distribution and pore structure (Abdollahipour and Marji, 2020; Haeri et al., 2015; Katz and Thompson, 1986; Rehman et al., 2024). Table 1 summarizes recent research on cement sheaths, primarily focuses on assessing sheath integrity using various investigative approaches. Notably, sealing failure under UHT conditions accounts for a significant proportion of cases, representing one of the key technical challenges in the sustained extraction of deep oil and gas resources. Clarifying the mechanisms by which UHT environments affect the sealing performance of cement sheaths therefore holds substantial research value.

### 2.1. Effects of UHT on the physicochemical properties of set cement

UHT leads to the degradation of set cement strength and the decline of its sealing performance, which are key factors compromising the sealing integrity of the cement sheath (Deng et al., 2025; Lu et al., 2016; Shadravan et al., 2014). With increasing well depth, environmental conditions become more extreme, requiring set cement to satisfy multiple performance demands under conditions of ultra-high temperature and pressure, including thermal stability (Pang et al., 2020), long-term durability (Khan et al., 2024), and adaptability to dynamic stresses. Temperature is one of the primary factors influencing both the strength and sealing performance of set cement (Abraham et al., 2024; Wang et al., 2020). A temperature threshold exists, as shown in Fig. 2 (Ding et al., 2022): when exposure time is constant, cement strength initially decreases slowly with rising temperature, followed by a rapid deterioration beyond a critical point.

While conventional Portland oil well cement exhibits stable hydration products, a dense microstructure, and good mechanical properties under ambient conditions, its strength begins to decline at 110 °C and may be entirely lost by 230 °C. To address this high-temperature strength degradation, siliceous admixtures such as silica flour are commonly introduced to adjust the calcium-to-silicon (Ca/Si) ratio of the cement, thereby improving its thermal resistance (Ding et al., 2022; Jiang et al., 2024; Ra et al., 2023; Zou et al., 2024), and the combined use of polymers and nanomaterials has also been shown to be effective (Marji et al., 2023). However, the hydration products of silica-enhanced cement undergo transformations above 200 °C, leading to continuously increasing permeability with curing time (Liu et al., 2022; Tracz and Zdeb, 2019; Wedatalla et al., 2019). At 300 °C, the cement undergoes

**Table 1**
Some representative studies on cement sheath sealing failure in recent years.

| Year | Authors | Research focus |
|---|---|---|
| 2021 | Chen et al. (2021) | Cement sheath integrity studied with Fiber Bragg Grating (FBG) technology |
| 2023 | Gu et al. (2023) | Investigation of radial cracking in cement sheaths |
| 2023 | Ahmad et al. (2023) | Enhancing the flexibility of cement sheaths |
| 2023 2024 | Alberdi-Pagola and Fischer (2023, 2024) | Quantifying cracks induced by expansion and shrinkage in cement sheaths |
| 2024 | Zheng et al. (2024) | Investigating cement sheath failure under temperature and pressure variations using machine learning |
| 2025 | Deng et al. (2025) | Failure mechanisms of cement sheaths under UHT thermal cycling |

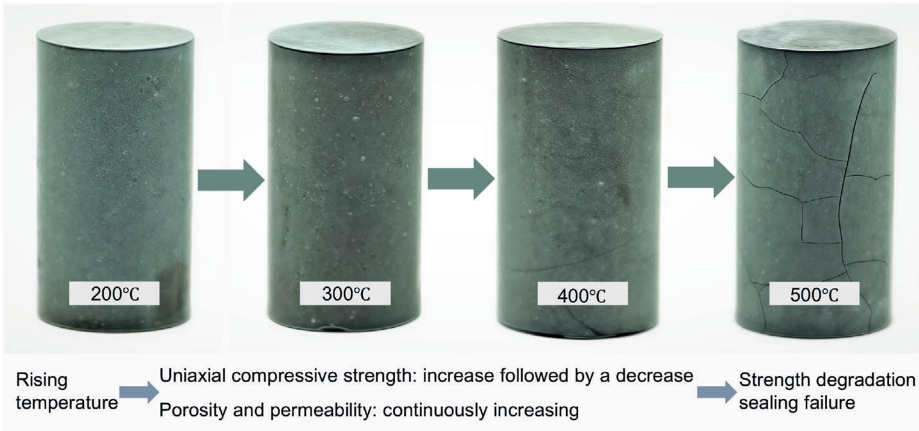


**Fig. 2.** Sealing failure behavior of silica-enhanced cement under elevated temperatures, including changes in uniaxial compressive strength, porosity, and permeability (Modified from Ding et al., 2022).

noticeable strength deterioration and reduced sealing capacity, approaching a critical failure threshold (Tufail et al., 2017; Zhang et al., 2020). When exposed to 400–500 °C, it shows a sharp decline in compressive strength, along with a substantial increase in porosity and permeability (Liu and Chen, 2022; Tufail et al., 2017). Field experience has consistently shown that conventional sand-enhanced cement formulations are inadequate for maintaining long-term sealing integrity of cement sheaths under high-temperature conditions. This is particularly evident in heavy oil thermal recovery wells and geothermal wells, where such systems are no longer suitable. To address this issue, various supplementary admixtures have been introduced to enhance the thermal degradation resistance of set cement. Table 2 summarizes selected admixtures used under UHT conditions in recent years, along with their corresponding curing temperatures and durations. However, Bu et al. (2016) noted that different admixtures exhibit variable, and in some cases even contradictory, effects on the sealing performance of cement sheaths. This may result from complex interactions between the admixtures and cement matrices, leading to an incomplete understanding of the underlying mechanisms. Therefore, further investigation is needed to clarify the specific mechanisms by which these admixtures influence the sealing integrity of cement sheaths.

Moreover, UHT curing conditions exert a notable influence on the sealing performance of cement sheaths. Experimental studies by Xing et al. (2022) and Yang et al. (2020) in investigating the effects of curing temperature and time on the cement-casing interfacial sealing performance showed that, at the same curing duration, the gas channeling pressure of cement sheaths cured at 200 °C is significantly lower than the value observed at 160 °C. This indicates a pronounced decline in sealing capacity under UHT conditions. Such curing conditions may induce complex physical and chemical changes, substantially impacting cement hydration, microstructure, and microphase composition, which can either enhance or impair sealing performance depending on the microstructural evolution. Therefore, it is essential to explore the evolution mechanisms of sealing performance in double-casing cement sheaths under UHT by incorporating various admixtures, adopting higher curing temperatures (>200 °C), and extending curing durations (>30 days).

### 2.2. Cement-casing interface sealing failure

In practical engineering, the double-casing cement sheath structure widely applied and known for its superior performance in wellbores resembles a “sandwich” composed of casing-cement sheath-casing (Meng et al., 2023; Zhou et al., 2023). The integrity of its interfaces is a core element in the barrier systems of both oil and gas wells and carbon sequestration wells (Wu et al., 2024b; Yang et al., 2021c). Once this integrity is compromised, it may lead to sustained annular pressure (Su et al., 2021), leakage of toxic gases (Wu et al., 2024b), or even the abandonment of the wellbore (Wang et al., 2020), posing a severe threat to the safe and efficient operation of oil and gas wells. Therefore, conducting research on the sealing integrity of double-casing cement sheaths is of great significance. It not only helps improve cementing quality and production efficiency but is also crucial for ensuring the long-term safe production of oil and gas wells. Table 3 summarizes some of the recent research progress related to the cement-casing interface.

Under UHT conditions, the mechanical performance of cement sheaths deteriorates significantly, accompanied by a marked

**Table 2**
Summary of research progress on different cement admixtures and curing times under UHT conditions (200 °C and above).

| Curing temperature[a] (°C) | Curing time (days) | High-temperature-resistant admixtures | Reference |
|---|---|---|---|
| 200 | 2, 7, 30, 90, 180 | Silica fume, alumina, nano-$Fe_2O_3$ | Qin et al. (2023) |
| 200 | 2, 14, 30 | Silica powder | Liu et al. (2022) |
| 205 | 14 | Liquid additives | Jadhav and Pisklak (2021) |
| 210 | 28 | DRB-3S | Zou et al. (2024) |
| 220 | 30 | Crystalline $SiO_2$ and reactive alumina compounds | Zhang et al. (2024) |
| 240 | 1–21 | Silica flour | Zhang et al. (2023) |
| 240 | 2, 28 | Retarders, fluid loss additives, stabilizers, and anti-strength retrogression agents | Xia et al. (2024) |
| 300 | 1 | Silica powder, hollow micro spheres, latex, and carbonaceous materials | Bu et al. (2016) |
| 300 | 30 | Fly ash, silica fume | Bakirov et al. (2016) |

[a] This temperature refers to the maximum curing temperature.

**Table 3**
Summary of recent research progress on inhibiting interface failure of cement sheath.

| Year | Authors | Research focus | Conclusions/Findings |
|---|---|---|---|
| 2020a 2020b | Jiang et al. (2020a,b) | Debonding height at the cement-casing interface | Low elastic modulus and high strength of cement can suppress debonding height |
| 2021c | Yang et al. (2021c) | Microscale bonding integrity at the cement-casing interface | Drastic changes in relative humidity have a significant impact |
| 2021a | Yang et al. (2021a) | Cement sheath failure and wellbore pressure/mechanical parameters | Pressure differential across the wellbore and the Young's modulus of set cement are key influencing factors |
| 2021 | Ali et al. (2021) | Use of resin-cement blends to prevent annular pressure buildup | Can effectively prevent annular pressure buildup |
| 2022 | Etoh et al. (2022) | Finite element analysis of cement sheath integrity | A 0.4 water-to-cement ratio yields the strongest mechanical performance |
| 2022 | Hoang et al. (2022) | Impact of UHT cement hydration on casing integrity | Proper cement slurry formulation can significantly reduce failure risk |
| 2023 | Meng et al. (2023) | Stress state at the cement-casing interface under HTHP conditions | Pore pressure in cement increases significantly with rising temperature |
| 2023 | Abid et al. (2023) | Internal structure of micro-annuli at the casing-cement interface under high temperatures | Tensile failure and debonding are more likely to occur at high temperatures |
| 2024 | Congro et al. (2024) | Bonding performance of casing-cement interfaces using cement with 3% expansion additive | Expansive cement exhibits significantly higher displacement load and bonding strength than conventional cement |
| 2025 | Patel et al. (2025) | Quantification of casing wear | Wear factors dependent on contact duration should be considered during quantification |
| 2025a | Li et al. (2025a) | Bond strength at the casing-cement interface | Positively correlated in a linear manner with the interfacial coefficient and the elastic modulus of cement |

increase in porosity and permeability (Dalirnasab et al., 2024; Zou et al., 2022). Micro-annuli can also form at the cement–casing interface (Wu et al., 2023), ultimately leading to gas migration and sealing failure. Although various admixtures such as silica flour have been introduced to improve the high-temperature resistance of cement sheaths (Chen et al., 2022; Liu et al., 2021; Zou et al., 2024), the underlying mechanisms by which these admixtures influence sealing performance and microstructural behavior remain insufficiently understood.

Moreover, environmental relative humidity, which is strongly correlated with temperature, has a pronounced effect on interfacial gap width, displaying an inverse relationship. Large humidity fluctuations exacerbate microscale debonding at the cement surface, although no interconnected pores are typically observed in deeper longitudinal sections. In this context, expansive agents have proven effective in minimizing interfacial gaps and enhancing sealing integrity (Yang et al., 2021c), and the introduction of bridging and toughening composite materials can also inhibit the development of micro-annuli (Marji et al., 2023). Additionally, with the growing interest in carbon sequestration (Zhu et al., 2025), the chemical degradation of cement sheaths by $CO_2$ has emerged as a critical research topic. High-resolution imaging techniques have revealed the potential risks associated with microcracks: although they may have limited impact on short-term leakage, such defects could act as initiation points for chemical attack, posing long-term threats to wellbore integrity (Yang et al., 2021c). Consequently, optimizing cement formulations to mitigate shrinkage (Hoang et al., 2022) and maintaining stable downhole humidity levels, and improving the natural connectivity between the wellbore and the formation have been proposed as viable strategies to preserve interfacial sealing performance (Abdollahipour et al., 2015; Yang et al., 2021c).

It is worth emphasizing that accurate evaluation of interfacial permeability must be accompanied by detailed microstructural characterization, particularly focusing on pore evolution within the interfacial transition zone (ITZ) (Yang et al., 2024). The microstructural heterogeneity of the cement sheath may influence the development and morphology of leakage pathways (Meng et al., 2019), with failure mechanisms varying depending on the interface configuration. In rock–cement–casing assemblies, cement tends to migrate toward the rock interface, resulting in a porosity gradient that decreases from the rock face inward toward the casing. Conversely, in casing-cement-casing systems, both casing interfaces commonly exhibit elevated porosity due to ITZ effects. Additionally, axial pore distribution demonstrates a decreasing trend from top to bottom, primarily driven by gravitational particle sedimentation during hydration (Yang et al., 2024). High-resolution nano-computed tomography (nano-CT) has confirmed that, over prolonged service periods, the rock–cement interface is more prone to degradation due to localized pore accumulation (Yang et al., 2021c). This finding underscores the critical influence of interface architecture on the long-term durability and sealing integrity of the cement sheath. Therefore, employing a casing-cement-casing configuration in future investigations is recommended to minimize the adverse effects associated with microstructural deficiencies and improve the reliability of performance assessments.

### *2.3. Challenges in characterizing moisture migration*

#### *2.3.1. Impact of moisture migration on the sealing integrity of cement sheaths*

Moisture is an important component of the cement sheath, existing in various forms and playing a critical role in its curing process and overall performance. During the hydration process, moisture can generally be classified into three categories: bound water, constrained water, and free water (Fu et al., 2023; Kurihara and Maruyama, 2022). Bound water participates directly in hydration reactions, forming crystalline hydration products that are fundamental to the mechanical strength and durability of well cement. Constrained water is retained within the microstructure of the hydration products, typically adsorbed in gel pores or on pore surfaces. While it does not engage in further hydration, it plays a crucial role in determining the microstructural and physical properties of the hardened cement. Free water, on the other hand, does not participate in hydration reactions; instead, it resides freely within pore spaces, contributing to the workability of the slurry and early-stage setting. This free water is also responsible for moisture transport through evaporation or seepage. Under UHT conditions, various forms of moisture within the cement sheath may undergo a series of transformations, such as evaporation and continued hydration, which can potentially lead to increased porosity and crack propagation, and subsequently result in strength reduction, sealing failure, and decreased durability. Therefore, understanding the internal moisture evolution within the cement matrix is vital for elucidating the fundamental mechanisms governing sealing failure under extreme conditions.

Current research on moisture in cement materials has primarily concentrated on moisture content or relative humidity (Kinda et al., 2022; Wen et al., 2023; Zuo et al., 2023). The microstructure of well cement serves as a key medium for the storage, evaporation, and migration of moisture (Huang, 2020; Wyrzykowski et al., 2017), with its pores acting as the primary channels for moisture transport, which directly influences the spatial distribution of moisture within the system (Dalirnasab et al., 2024). At the same time, moisture also exerts feedback effects on the microstructure itself, for instance by altering the tortuosity of pores (Xue et al., 2021), which subsequently affects cement strength, shrinkage behavior, and service life (Alberdi-Pagola et al., 2023; Long et al., 2023). The formation of micro-annuli at the cement-casing interface is closely linked to the moisture content (Alberdi-Pagola and Fischer, 2023). Yang et al. (2021c) used environmental-SEM to directly capture the dynamic development of micro-annuli at the cement-casing interface in response to fluctuations in ambient relative humidity, as shown in Fig. 3. When the relative humidity decreased, the cement matrix underwent noticeable shrinkage, resulting in a significant enlargement of interfacial micro-gaps, which in turn substantially impaired the sealing integrity of the cement sheath. Therefore, the role of environmental humidity must not be neglected when evaluating sealing performance at the cement–casing interface under UHT conditions.

At present, research on moisture evolution in UHT cement sheaths and its impact on sealing performance remains limited. Most existing studies address moisture in construction materials (Kumar et al., 2014), primarily targeting concrete (Fang et al., 2023; Guo et al., 2024; Pokorný et al., 2021), while research specific to cement sheaths in wellbores remains relatively scarce. Under UHT conditions, moisture behavior, including evaporation and altered hydration kinetics, can influence the structural and functional integrity of the cement sheath. Studying how different forms of moisture evolve with temperature is essential for understanding sealing failure mechanisms and provides a scientific foundation for addressing sealing challenges in ultra-high-temperature well cementing.

### 2.3.2. *Specific challenges in achieving characterization*

Characterizing internal moisture evolution in UHT cement sheaths remains a significant challenge. Although moisture evolution has been extensively studied in the construction sector (Pokorný et al., 2021; Shen et al., 2021), relevant research in the context of oil and gas extraction remains limited (Zheng et al., 2022). Due to constraints in experimental techniques and the influence of external disturbances, existing methods are insufficient for achieving high-resolution, real-time characterization of internal moisture behavior in cement sheaths, and the superimposed effects of thermo–hydraulic coupling and other factors also need to be considered (Abdollahipour and Marji, 2020). As a result, the mechanisms by which moisture evolution contributes to sealing failure under UHT conditions have yet to be fully elucidated, as illustrated in Fig. 4.

Firstly, the forms of moisture within cement sheaths are highly complex, posing significant challenges for accurately analyzing the dynamic transformation of free water, constrained water, and bound water, particularly for real-time monitoring of transient processes, as rapid evaporation and migration are difficult to capture. Secondly, moisture analysis is often subject to interference from multiple coupled factors. Under UHT conditions, moisture migration may interact with concurrent chemical reactions, such as $CO_2$-induced corrosion or exposure to acidic agents (Lu et al., 2016; Pang et al., 2020; Wang et al., 2024), which makes it difficult for laboratory data to accurately reproduce the moisture evolution observed in field conditions. This often leads to discrepancies between experimental outcomes and in-situ behavior.

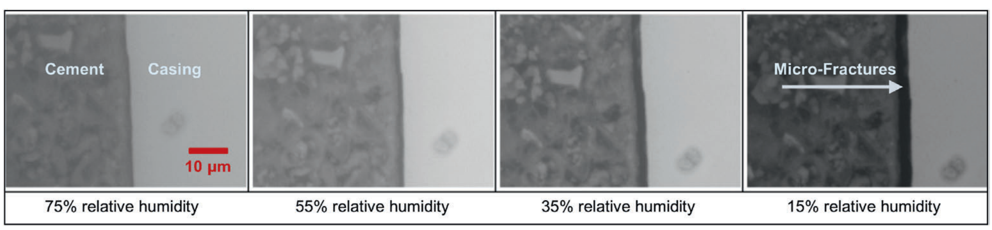


**Fig. 3.** Dynamic evolution of micro-gaps at the cement–casing interface under varying relative humidity captured by environmental-SEM. (Modified from Yang et al. (2021c)).

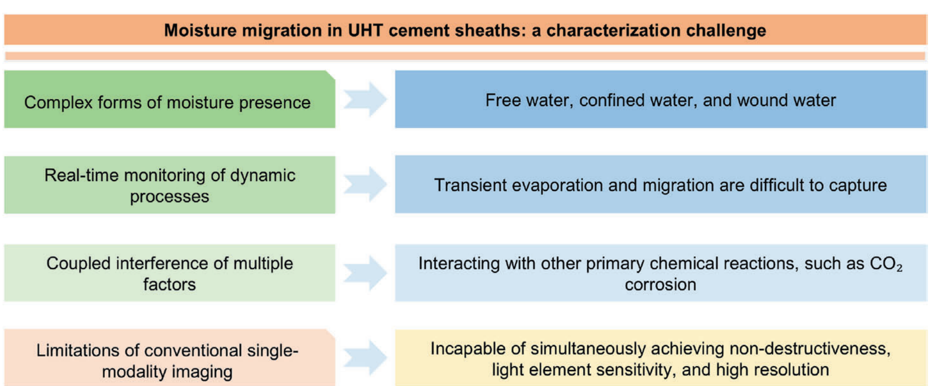


**Fig. 4.** Main challenges in characterizing internal moisture migration in UHT cement sheaths.

In addition, conventional single-mode imaging and detection methods, including X-ray imaging, computed tomography (CT), and SEM have inherent technical limitations that hinder their ability to characterize moisture migration effectively.

In light of these challenges, integrating advanced techniques that are sensitive to light elements, such as neutron imaging and nuclear magnetic resonance (NMR), with complementary imaging modalities offers a promising multi-scale approach. By tailoring the combination to specific application needs, it may be possible to achieve more accurate and comprehensive characterization of moisture transport in UHT cement sheaths. Among current options, the combination of neutron imaging and X-ray imaging appears to be well matched and holds great potential.

#### 2.3.3. Summary of scientific and technical challenges pending breakthrough

As shown in Fig. 5, the application of NXDI to study the sealing performance of cement sheaths faces several prominent scientific and technical challenges that must be addressed: (1) Based on advanced NXDI, how can dual-mode image fusion be used to achieve visualization and microscopic quantification of the double-casing cement sheath? Specifically, how can it enable high-precision and dynamic characterization of moisture inside the cement sheath? How can this help to comprehensively reveal the role of moisture evolution in sealing failure under UHT conditions? This represents a critical problem for future research. (2) Under UHT conditions, how do admixtures and curing conditions influence the moisture distribution, microphase composition, and microstructure of the cement sheath? Furthermore, how do these changes impact the sealing performance? These are key scientific questions that warrant detailed investigation.

Given the current technological limitations in cement sheath sealing research for oil and gas well cementing, the introduction of the emerging NXDI may offer valuable opportunities. A clear understanding of its fundamental principles and distinctive advantages can support its effective application, facilitating more robust experimental design and guiding future research efforts.

## 3. NXDI analysis based on recent advances

### 3.1. Overview of neutron and X-ray imaging from recent applications

#### 3.1.1. Neutron imaging

Neutron imaging is a non-destructive technique that visualizes and reconstructs the internal structure of materials. It is based on detecting changes such as attenuation, scattering, or diffraction that occur when uncharged neutron beams interact with matter during penetration (Kardjilov et al., 2018; Tang et al., 2025). Due to its unique physical properties, neutron imaging offers several notable advantages, especially in the detection of light elements (Buczkó et al., 2024; Fedrigo et al., 2018). It can accurately locate hydrogen and deuterium atoms and provide information about the orientation of water molecules (Liebschner et al., 2023; Murakawa et al., 2022). It has been applied to study the durability of cementitious materials and the process of water transport in concrete (Kim et al., 2021; Li et al., 2024b). It also enables three-dimensional visualization of water content distribution within opaque porous samples (Nemati et al., 2025). At the same time, neutron imaging is limited by several inherent challenges. Its resolution is insufficient for features smaller than 1 μm (Martell et al., 2024). It cannot effectively distinguish between materials with similar neutron attenuation properties (Koestel et al., 2022). In addition, high humidity environments can lead to image blurring and reduced clarity (Kaestner et al., 2015). Table 4 summarizes the current major advantages and limitations of neutron imaging.

#### 3.1.2. X-ray imaging

X-ray imaging technology reconstructs internal images of materials by capturing attenuation variations that occur when X-rays interact with the electron clouds of atoms as they pass through matter (Deschler-Erb et al., 2004; Li et al., 2024b). This non-destructive technique has been widely applied and proven effective in multiple disciplines, including materials science (Buczkó et al., 2024; Törnquist et al., 2021; Treffert et al., 2024), geosciences (Fedrigo et al., 2018; Sinha et al., 2013), and civil engineering (LaManna et al., 2020; Li et al., 2024b). It offers high-resolution visualization of microstructures in materials such as concrete and asphalt mixtures. Additionally, it provides detailed information on key features such as cracks, pores, voids, and permeability (Kim et al., 2021; LaManna et al., 2020; Li et al., 2024b). Despite these advantages, the technology faces inherent limitations due to its physical principles and technical constraints. For example, it struggles to measure low atomic number elements like lithium (Yu et al., 2024), cannot directly quantify organic carbon (Koestel et al., 2022), and fails to differentiate between similar fine aggregates, such as quartz sand and cement paste (Kim et al., 2021; Roubin et al., 2019). Table 5 summarizes its current main strengths and limitations.

By integrating the above content, the main strengths and limitations of neutron and X-ray imaging technologies in the study of UHT cement sheaths are summarized, and illustrated in Fig. 6. It can be clearly observed that the strengths of one method can effectively compensate for the limitations of the other. The fusion

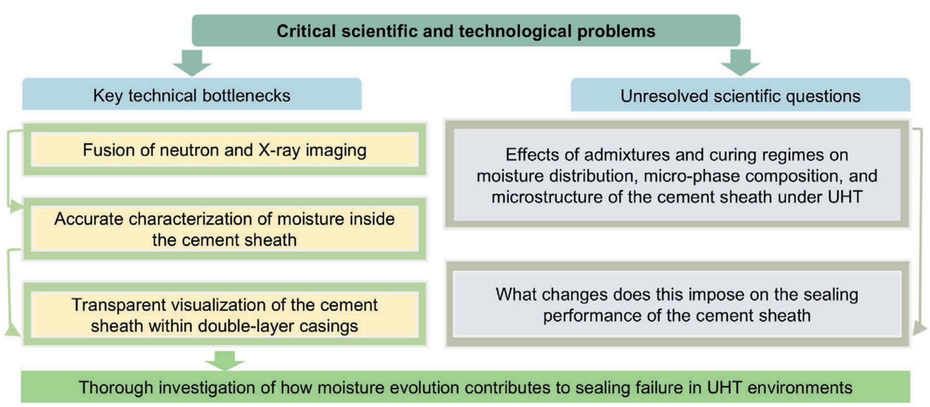


**Fig. 5.** Urgent challenges in NXDI study of UHT cement sheath failure.

**Table 4**
Summary of the advantages and limitations of promoting neutron imaging technology in more fields.

| | Content | Reference |
|---|---|---|
| Advantages | High sensitivity to light elements: Enables precise analysis of hydrogen-containing phases and organic materials. Supports detection of spontaneous water uptake in cracks, fluid localization, and reveals water transport mechanisms and molecular orientation | Buczkó et al. (2024); Fedrigo et al. (2018); Koestel J et al. (2022); LaManna et al. (2017b); Lehmann et al. (2021); Losko and Vogel (2023); Mancini et al. (2019); McGregor et al. (2021) |
| | Non-destructive detection and characterization: Maintains the structural integrity of samples during imaging | Kardjilov et al. (2018) Mazzinghi et al. (2024); Mannes et al. (2015); Lehmann et al. (2009) |
| | No systematic dependence on atomic number; sensitive to isotope and cross-section differences: Capable of distinguishing materials with similar density but different elemental composition | Martell et al. (2024); Yu et al. (2024); Fedrigo et al. (2018); Ziesche et al. (2020); He et al. (2021) |
| | Strong penetration of high-Z materials: Enables visualization of light elements embedded within metal enclosures or dense high-Z matrices | Kardjilov et al. (2011); Distefano et al. (2017); |
| | Adaptability to extreme conditions: Performs stably under extreme environments such as high temperature and pressure. Suitable for hazardous sample identification and phase analysis of nuclear fuel | Tang et al. (2025); Zboray and Trtik (2019); Kockelmann et al. (2006); |
| Limitations | Limited spatial resolution: Typically limited to the tens-of-microns scale. Lacks the resolution needed to capture fine structural details | Martell et al. (2024); Roubin et al. (2019); Mohammadi et al. (2022); Novelli et al. (2022) |
| | Background noise interference: High hydrogen content can cause excessive neutron attenuation; Short sample-to-detector distance may result in image blurring and quantification errors; Large incoherent scattering cross-section of hydrogen further increases noise levels | Buczkó et al. (2024); Losko and Vogel (2023); Raventós et al., (2018); Lombardo et al. (2025) |
| | Complex operation and high cost: Data acquisition often takes hours or longer. High-resolution imaging relies on intense sources such as spallation neutron sources, increasing both complexity and cost | Tang et al. (2025); Martell et al. (2024); Kockelmann et al. (2006) |
| | Limited scalability and deployment: High-quality neutron imaging systems are typically large and immobile, restricting broader application in smaller laboratories | Kardjilov et al. (2018); Tang et al. (2025); |
| | Low material contrast in some cases: Difficult to distinguish between materials with similar thermal neutron cross-sections, such as isotope-enriched samples | Sinha et al. (2013) |
| | Lack of standardized evaluation criteria | Raventós et al. (2018) |
| | Potential negative effects on samples: Gamma radiation from reactor-based sources may damage electronic components. Risk of sample activation limits the use for biological or radiation-sensitive materials | Martell et al. (2024); LaManna et al. (2017a); Deschler-Erb et al. (2004) |

of imaging data from both techniques offers the potential to achieve high-precision structural characterization and accurate moisture analysis.

### 3.2. Advances and potential of image fusion in NXDI

#### 3.2.1. Image fusion principles

NXDI combines the complementary strengths of both techniques. By fusing imaging data, it enables the extraction of more diverse, comprehensive information and richer image details (Kaestner et al., 2017; Li et al., 2024b; Tang et al., 2025). The underlying principle lies in the distinct yet compatible interaction mechanisms of neutrons and X-rays with matter, particularly their differing attenuation characteristics. Neutron attenuation is largely independent of atomic number (Martell et al., 2024), while X-ray attenuation increases with atomic number (Lehmann et al., 2021). This fundamental difference leads to pronounced contrast differentiation in images. X-ray imaging highlights material

**Table 5**
Summary of the advantages and limitations of promoting X-ray imaging technology in more fields.

| | Content | Reference |
|---|---|---|
| Advantages | High resolution and non-destructive characterization: Enables *in situ* 3D analysis while preserving morphological details, offering high-resolution imaging of internal structures | Martell et al. (2024); Mazzinghi et al. (2024); Mannes et al. (2015) Koestel et al. (2022); McGregor et al. (2021) Ziesche et al. (2020); (Tandrup et al. (2023); |
| | Sensitivity to high-density and high atomic number materials: Well-suited for detecting metals, bone-like minerals, and microstructural features in low-density matrices; reveals more detail through density contrast | Buczkó et al. (2024); Fedrigo et al. (2018) LaManna et al. (2017b); Mannes et al. (2015); Ziesche et al. (2020); Mohammadi et al. (2022) Törnquist et al. (2021); Treffert et al. (2024) |
| | Adaptability to extreme conditions: Maintains high-precision analysis under extreme environments such as HTHP | Koestel et al. (2022); Saadat et al. (2024) |
| | Mature development: Offers lower operational costs, broader and more flexible application scenarios; supported by long-term use and accumulated credibility | McGregor et al. (2021); Mazzinghi et al. (2024); Mannes et al. (2015) LaManna et al. (2017a) |
| Limitations | Low sensitivity to light elements: Performs poorly in tracking light elements or imaging hydrogen-containing phases, such as water distribution or light elements sealed in metal | Buczkó et al. (2024); Törnquist et al. (2021) Yusuf (2024) |
| | Limited penetration of high atomic number materials: Penetration depth is constrained in dense materials; imaging of thick metal parts often suffers from artifacts | Buczkó et al. (2024); Lehmann et al. (2021); Mannes et al. (2015) Törnquist et al. (2021) |
| | Inability to distinguish isotopes or similar attenuation materials | Sinha et al. (2013); Törnquist et al. (2021) |
| | Potential risks: May cause ionization or localized heating, potentially damaging radiation-sensitive materials | Martell et al. (2024); Treffert et al. (2024) |

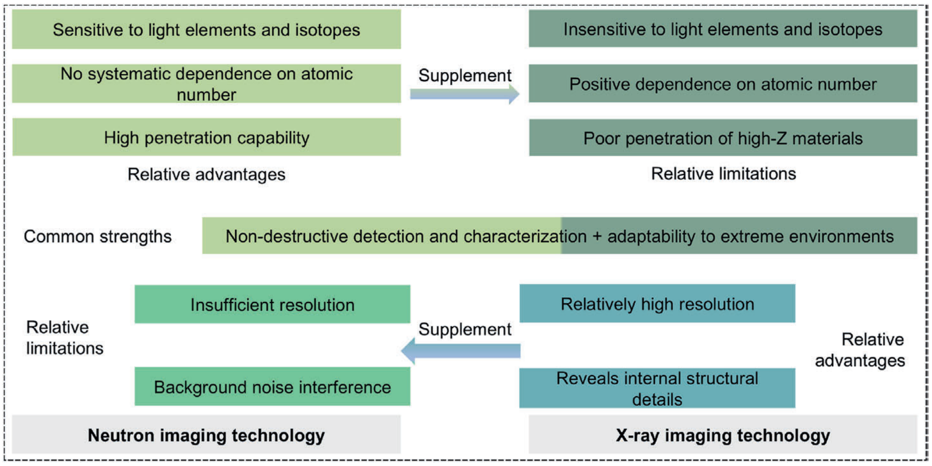


**Fig. 6.** Summary of the relative advantages, limitations, and complementarity of neutron and X-ray imaging in the study of UHT cement sheath sealing performance, based on characteristics reflected in current applications.

density distributions and microstructures (Koestel et al., 2022; McGregor et al., 2021; Tandrup et al., 2023), whereas neutron imaging is highly effective in revealing light elements (Buczkó et al., 2024; Fedrigo et al., 2018; LaManna et al., 2017b). Though combining both modalities, dual-mode imaging not only reduces certain imaging artifacts but also overcomes the limitations of single-modality techniques (Deschler-Erb et al., 2004). It enhances the visibility of previously hidden features and offers new perspectives for achieving high-resolution, multi-dimensional characterization of internal structures.

A representative example is the study by Tengattini et al. (2021) which built upon the work of Stamati et al. (2018). Using a cold neutron tomography system and a 150 kV laboratory X-ray CT scanner, they performed combined tomographic characterization of concrete, as shown in Fig. 7. While X-ray imaging effectively distinguished features such as pores and matrix, it failed to differentiate aggregates from mortar due to their similar densities. Neutron imaging, by contrast, clearly resolved these components, providing a valuable supplement to the information captured by X-rays.

### 3.2.2. Demonstrated advantages

Conventional characterization techniques exhibit notable limitations due to their single-modality nature. For example, SEM requires samples to be dry and electrically conductive, and it operates under high vacuum conditions. These constraints significantly limit its applicability for the direct observation of biological specimens or liquid-containing materials (Zhao et al., 2024). In addition, SEM primarily provides surface morphology data and has limited capability for resolving internal structures (Wu et al., 2021). CT faces its own set of challenges, including metal artifacts (Zhu et al., 2024), limited discrimination between materials of similar density, poor contrast in soft tissue imaging (Owens et al., 2023), and high time costs associated with high-resolution scanning (Lachance and Horton, 2024). Although NMR imaging offers clear advantages for studying casing–cement sheath systems such as allowing non-destructive characterization of moisture distribution and pore structures within solid cement samples (O'neill et al., 2023; Song et al., 2025; Yang et al., 2023), its use remains constrained, include sample size restrictions, sensitivity to magnetic interference (O'neill et al., 2023), insufficient temporal resolution (Kleckner and Foster, 2011), complex data interpretation (Cardoza et al., 2004), and high equipment costs.

In contrast, as a widely applied complementary probe pair (Li et al., 2024b; Mannes et al., 2015), NXDI offers several advantages (as summarized in Table 6). This approach overcomes the inherent limitations of single-modality techniques by enhancing spatial resolution, accuracy, and the overall comprehensiveness of material visualization. Moreover, it has been successfully adapted to a wide range of research fields, including materials science, geology, civil engineering and energy systems (Lehmann et al., 2021). Key application advantages are illustrated in Fig. 8.

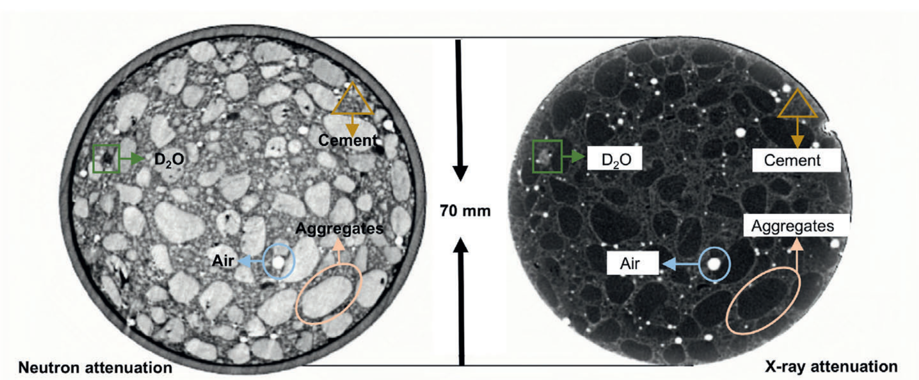


**Fig. 7.** Example of complementary neutron and X-ray tomography (Modified from Tengattini et al. (2021)).

**Table 6**
Characteristics and advantages of NXDI compared to traditional and single imaging techniques.

| Content | Demonstrated in | Reference |
|---|---|---|
| Complementary and Enhanced Imaging Information | Significantly enhances image contrast, captures richer details, improves reconstruction quality, and reduces artifacts and background noise; enables broader moisture-related information acquisition | Tang et al. (2025)<br>Buczkó et al. (2024)<br>Fedrigo et al. (2018)<br>Yusuf (2024)<br>Kaestner et al. (2017) |
| More In-Depth and Comprehensive Image Processing | Effectively aligns, segments, adjusts, and reconstructs neutron and X-ray image data | Li et al. (2024b)<br>Kim et al. (2021)<br>Lehmann et al. (2021)<br>He et al. (2021)<br>Roubin et al. (2019)<br>LaManna et al. (2020) |
| Combines Non-Destructiveness with Strong Penetration Capability | Enables in-depth exploration of internal features while preserving sample integrity, providing detailed structural and compositional information | Buczkó et al. (2024)<br>Martell et al. (2024)<br>Mazzinghi et al. (2024)<br>LaManna et al. (2017a) |
| Broad and Flexible Application Scenarios | Wide applicability across subjects: from micro-scale materials to rocks, energy systems to civil structure; Adaptable to diverse experimental settings: from standard labs to extreme HTHP environments | Lehmann et al. (2021)<br>McGregor et al. (2021)<br>Zboray and Trtik (2019)<br>Novelli et al. (2022)<br>Henry et al. (2022)<br>Tengattini et al. (2020)<br>Danly et al. (2016) |

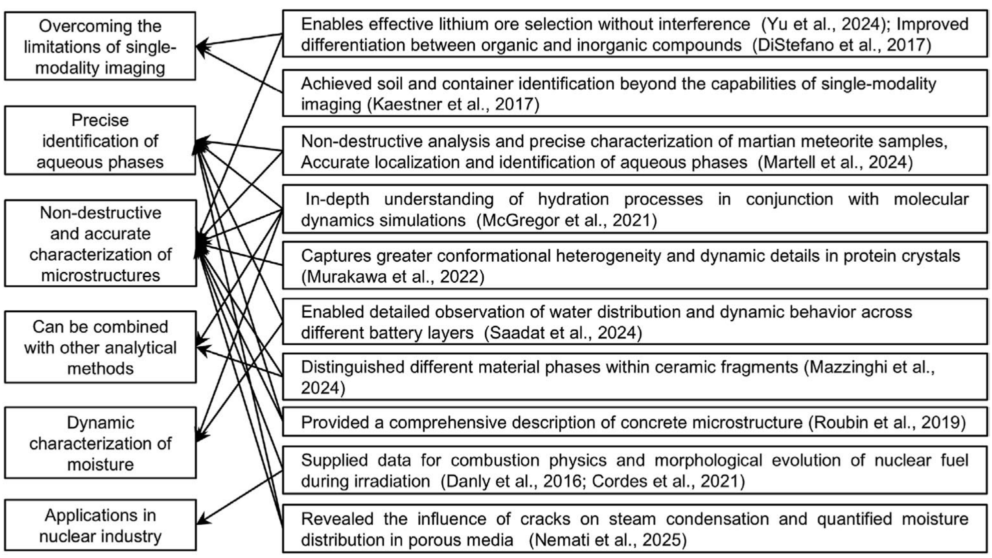


**Fig. 8.** The potential of NXDI in studying UHT cement sheaths as demonstrated in some practical applications.

### 3.2.3. Realization of image fusion

The choice of image fusion type depends on the specific research conditions and content. However, the common goal is to enhance imaging information and reveal more detailed features. Based on current knowledge, image fusion approaches can generally be classified into three categories (shown in Table 7). (1) Image fusion using jointly developed imaging systems. This approach focuses on the imaging equipment itself. By improving the compatibility and coordination between neutron and X-ray sources, it generates images that meet the experimental requirements while reducing the complexity of post-processing and fusion. (2) Image fusion based on algorithm models and processing procedures. Given variations in sample types, scanning environments, and research objectives, fusion methods may differ. Commonly used techniques include grayscale threshold enhancement, noise reduction through filtering (Li et al., 2024b), tomographic reconstruction, volume registration, and image filtering optimization (LaManna et al., 2020). (3) Image fusion through joint refinement of scanning data followed by simplified reconstruction. This method integrates neutron and X-ray information during the data processing phase and then completes the image formation in a simplified manner.

An illustrative example is the multimodal reconstruction and visualization of concrete microstructure achieved by Kim et al. (2021), as shown in Fig. 9. After sample preparation, the concrete was scanned separately by X-ray and neutron imaging. The resulting images underwent grayscale processing, threshold segmentation, noise reduction, and artifact correction. Following this, the images were registered and fused. The final three-dimensional reconstruction was performed at the pixel level: pore regions were represented using X-ray pixel data; aggregate regions combined neutron and X-ray pixel information while excluding pores; and the remaining pixels corresponded to the cement paste. This process successfully realized a comprehensive 3D reconstruction and visualization of the concrete microstructure.

From the discussion in this section, it is clear that NXDI overcomes the individual limitations of neutron and X-ray imaging while

**Table 7**
Summary of some typical types of NXDI in the world and their characteristics.

| Types | Content | |
|---|---|---|
| Dual-mode imaging based on integrated imaging systems | Substance-driven compact dual-modal imaging platform | 1) Achieved high-resolution dual-modal imaging in the low-energy range (Yu et al., 2024)<br>2) Enabled precise analysis of internal structures within the sample (Treffert et al., 2024) |
| | NeXT-Grenoble from the collaboration between the Universite Grenoble Alpes (UGA) and the Institut Laue Langevin (ILL) | 1) Achieved higher resolution and image quality in dual-modal imaging, with improved material identification accuracy (LaManna et al., 2017a)<br>2) Performed real-time flat-field and dark-field correction of scanned data, followed by 3D reconstruction of the fused images (Tengattini et al., 2020) |
| | NEUTRA of the Paul Scherrer Institute (PSI) | 1) Visualized complete neutron and X-ray tomographic datasets (Mannes et al., 2015)<br>2) Realized both visualization and quantitative analysis of the sample (Kaestner et al., 2015) |
| | combined neutron x-ray imaging system at the National Ignition Facility (NIF) | Achieved high-accuracy data registration through source position localization, geometric correction, and global optimization, followed by denoising to obtain high-quality sample characterization images (Danly et al., 2016) |
| Dual-mode imaging assisted by algorithmic models and procedural operations | Based on operational steps:<br>1) Merged grayscale values into pseudo-color images for visual representation through segmentation, registration, phase separation, and data alignment (Fedrigo et al., 2018)<br>2) Applied multimodal registration algorithms to align images and generate joint histograms, then performed bivariate Gaussian fitting for phase segmentation and quantitative volume fraction analysis (Törnquist et al., 2021)<br>3) Improved alignment accuracy by correcting overlap and suppressing noise in neutron data, calibrating grayscale in X-ray data, and registering images using the elastix software (Koestel et al., 2022)<br>4) Achieved comprehensive understanding and visualization of sample structures through combined and joint analysis with advanced fusion techniques (Lehmann et al., 2021)<br>5) Realized high-precision visualization by identifying optimal linear transformation operators through iterative optimization (Roubin et al., 2019)<br>Applied algorithms and models:<br>1) Weighted averaging, logical filtering, color space transformation, multi-resolution pyramid fusion, wavelet-based fusion, and Kalman filter-based fusion (Mao and Zhao, 2002)<br>2) Image fusion algorithm in the Nonsubsampled Contourlet Transform (NSCT) domain based on a simplified Pulse-Coupled Neural Network (PCNN) (He et al., 2021)<br>3) Biphasic multimodal image fusion model based on Mamba (Li et al., 2024a)<br>4) Multi-Pose Fusion algorithm, pixel-weighted fusion algorithm, sinusoidal map weighting algorithm, and sample-adaptive measurement algorithm (Yang, 2024) | |
| Dual-mode imaging after combined refinement of bimodal data | 1) Independently refined the datasets to achieve complementary information, enhancing data accuracy and reliability, and facilitating subsequent image fusion (Liebschner et al., 2023)<br>2) Performed joint refinement of X-ray and neutron data using the Phenix software suite, with model building conducted in Coot (Tandrup et al., 2023)<br>3) Applied full-matrix least-squares refinement to X-ray data and anisotropic displacement parameter refinement to neutron data; the combined refinement significantly improved the precision of structural parameters (Novelli et al., 2022) | |

combining their respective advantages. In terms of fusion imaging, different types of fusion strategies can be adopted based on specific research needs or experimental conditions. As this technique continues to gain attention and evolve, its expanding application across a wide range of fields further demonstrates its potential for investigating the sealing performance of UHT cement sheaths.

## 4. Applications and insights from NXDI in other fields

NXDI has been applied in a wide range of research areas (Kaestner et al., 2017), including material characterization (LaManna et al., 2020; Sinha et al., 2013; Woracek et al., 2018), geological and mineralogical studies (Lehmann et al., 2021; Martell et al., 2024), moisture analysis in civil and building materials (LaManna et al., 2017a; Li et al., 2024b; Lima et al., 2025), and energy-related investigations (Danly et al., 2016; Yusuf, 2024; Ziesche et al., 2020). These diverse applications provide valuable methodological insights for extending the use of this technology to the study of UHT cement sheaths.

### 4.1. Applications in materials science and geomineralogy

NXDI has shown distinct analytical strengths in both materials science (LaManna et al., 2020; Sinha et al., 2013; Woracek et al., 2018)and geological mineralogy (Fedrigo et al., 2018; Lehmann et al., 2021; Martell et al., 2024). In materials research, it provides a multidimensional, non-destructive method for characterizing complex multiphase systems (Buczkó et al., 2024; Marquardt et al., 2020; Martell et al., 2024; Tang et al., 2025). By integrating data from both modalities, NXDI enables correlation between composition, morphology, and functional properties. This supports improved material design and processing. In geological and mineralogical studies, this technology offers an advanced tool for examining the internal structure of rocks, minerals, and meteorites (Fedrigo et al., 2018; Lehmann et al., 2021; Martell et al., 2024). It can also detect evidence of fluid activity in geological history (Kaestner et al., 2017), providing important clues for studies on planetary geological evolution (Martell et al., 2024) and the reconstruction of ancient cultural artifacts (Deschler-Erb et al., 2004; Mannes et al., 2015; Mazzinghi et al., 2024). Selected applications are listed in Table 8.

The above applications demonstrate the potential of dual-mode imaging in identifying complex phases, resolving microstructures, and non-destructively characterizing critical materials. These findings suggest the feasibility of achieving high-precision visualization of internal structures in cement sheaths while maintaining their integrity, thereby aligning more closely with real engineering conditions.

### 4.2. Applications in building materials and civil engineering

In a range of exploratory studies within this field, NXDI has provided multi-dimensional and high-precision analysis for

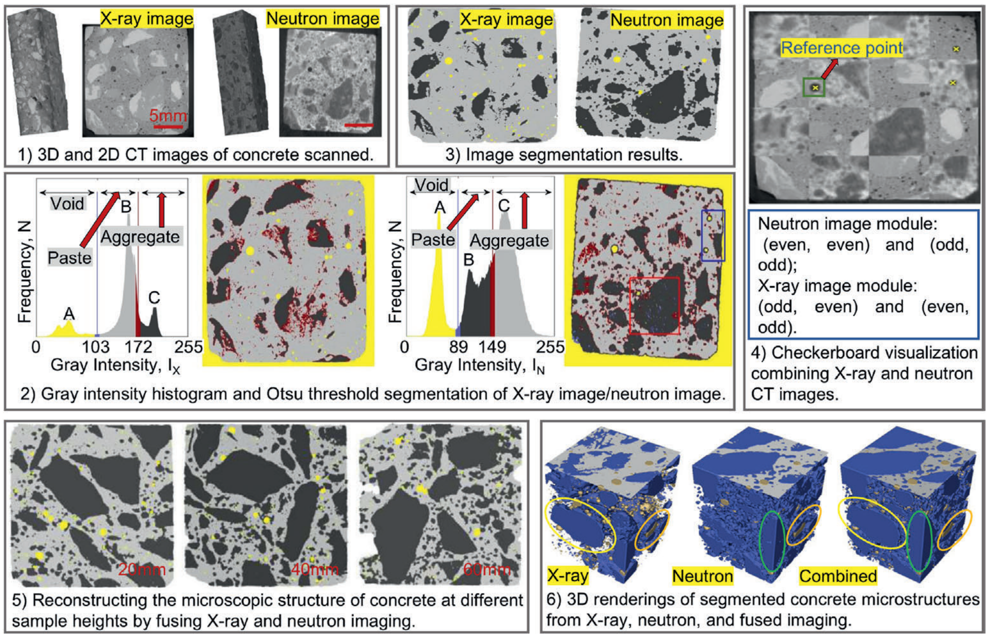


**Fig. 9.** Reconstruction and visualization of concrete microstructure using NXDI (Modified from Kim et al. (2021)).

investigating moisture migration mechanisms and material-environment interactions. As summarized in Table 9, NXDI has been widely applied to the study of concrete, asphalt mixtures, and moisture behavior.

It is clear that NXDI plays an important role in many areas closely related to cement, whether in characterizing internal structures, exploring deeper material features, or conducting detailed moisture analyses. Therefore, this technology may be capable of performing similar tasks in the study of cement sheath sealing performance.

### *4.3. Applications in energy*

Benefiting from the stability of neutron imaging and X-ray imaging in high-temperature and high-pressure environments (Zboray and Trtik, 2019), as well as their capability to eliminate contamination caused by these adverse conditions, such as signal distortion and noise artifacts, NXDI not only drives innovative cross-scale characterization of energy systems from microscopic mechanisms to macroscopic performance but also provides advanced tool options and support for more in-depth research in the nuclear industry. Selected applications and case studies are summarized in Table 10.

Sections 1–3 highlight the potential of NXDI in supporting exploratory research across multiple disciplines. As a relatively new analytical tool, NXDI offers promising capabilities in visualizing internal structures and characterizing both the static and dynamic behavior of moisture (Doktorova et al., 2022; LaManna et al., 2017b; Lima et al., 2025; Maier et al., 2020; McGregor et al., 2021; Saadat et al., 2024; Ziesche et al., 2020), particularly in materials associated with cement properties, such as concrete (LaManna et al., 2017a; Lehmann et al., 2021; Roubin et al., 2019) and asphalt mixtures (Tengattini et al., 2020). These applications are closely related to the current challenges in studying sealing performance failure of UHT cement sheaths in oil and gas wells, particularly the difficulty in characterizing microstructures and tracing internal moisture evolution. These insights suggest that extending this technique to cement sheath research is both logical and worthy of further investigation.

### *4.4. Insights from technology transfer and application*

One key aspect in studying the sealing failure mechanisms of cement sheaths under UHT conditions is accurately characterizing internal moisture evolution, along with detailed structural information such as pores and cracks. Based on the preceding discussion, several key technical insights can be drawn regarding the application of NXDI in this area (Fig. 10). First, the technology has demonstrated high-resolution visualization capabilities across diverse materials, including glass, industrial products, and biological specimens. This suggests its potential to offer more detailed and higher-quality structural information on cement sheaths. Second, NXDI applications in cultural heritage, energy systems, and nuclear materials demonstrate its ability to deliver non-destructive 3D characterization in extreme environments. These features are particularly relevant to the complex and harsh conditions of oil and gas wells. Third, its application to materials with characteristics similar to those of cement sheaths, such as soil, minerals, rocks, concrete, and asphalt, further supports its suitability for studying cement sheath structures. Finally, NXDI's ability to capture and analyze internal moisture in various materials highlights its strength in investigating moisture-related behaviors within cement sheaths.

These insights suggest that NXDI holds the potential to support research on the sealing failure mechanisms of UHT cement sheaths. It may even provide access to structural details that are not readily captured by other techniques, thereby facilitating progress in this area. This represents both a continuation and an extension of existing imaging methodologies, and may further stimulate innovative research in related fields. The feasibility of this research will be analyzed, and a well-reasoned technical roadmap will be developed to provide practical guidance for its implementation.

**Table 8**
Selected representative applications of NXDI in materials science and geomineralogy.

| Types | Research objects | Findings | Reference |
|---|---|---|---|
| Complex material bodies | Multi-material objects | Achieved high-resolution characterization of features across different materials | Treffert et al. (2024) |
| Glass | 1) Libyan desert glass (LGD);<br>2) magnesium aluminosilicate glass | 1) Non-destructively localized internal spherical materials;<br>2) revealed the role of magnesium in aluminosilicate glass | Martell et al. (2024)<br>Mohammadi et al. (2022) |
| Microcrystals | 1) $CoFe_2O_4$ nanoparticle crystals;<br>2) Lentinus edodes polymorphic crystal LsAA9_A;<br>3) Copper amine oxidase crystals | 1) Precisely determined the degree of inversion in spinel;<br>2) Identified Cu(II) coordination residues and their protonation states;<br>3) Determined the true chemical structure of the enzymatic catalytic site | Tandrup et al. (2023)<br>Henry et al. (2022)<br>Murakawa et al. (2022) |
| Microscopic compounds | 1) Copper sulfate pentahydrate samples;<br>2) Sodium perborate powder;<br>3) Niobate and bismuth sodium titanate solid solution | 1) Significantly improved the precision of structural parameters;<br>2) Provided more comprehensive information;<br>3) Demonstrated that structural phase transitions are composition-dependent | Novelli et al. (2022)<br>Sinha et al. (2013)<br>Jayakrishnan et al. (2023) |
| Electronic waste | Complex electronic waste | Achieved efficient segmentation | Buczkó et al. (2024) |
| industrial products | 1) Key and turbine blade samples;<br>2) Mechanical pencil; | 1) Obtained comprehensive information;<br>2) Gained a unique perspective; | Yu et al. (2021)<br>Sinha et al. (2013) |
| Bio-soil composite samples | 1) Rooted soil samples;<br>2) Soil samples containing lupin plants;<br>3) Soils containing organic carbon | 1) Enabled precise characterization;<br>2) Achieved more efficient segmentation and clearer results;<br>3) Identified quartz grains and differentiated plastic from plant seeds | Kaestner et al. (2017)<br>Kaestner et al. (2015)<br>Koestel et al. (2022) |
| Metal-implanted biological samples | Proximal rat tibia implanted with titanium | Provided more comprehensive and accurate data, along with new insights into moisture content | Törnquist et al. (2021) |
| Biological samples | Natural and cultured pearls | Clearly visualized internal structures of pearls | Distefano et al. (2017) |
| Various minerals | 1) Lithium ore beneficiation products;<br>2) Mineral samples | 1) Achieved an average error of approximately 0.2%;<br>2) Characterized complex internal structures | Yu et al. (2024)<br>Lehmann et al. (2021) |
| Various rocks and meteorites | 1) Carbonate claystone, aluminum impact melt, and Martian meteorites;<br>2) Rock from Chilean impact craters;<br>3) Porous media rocks; 4) Shale | 1) Reconstructed 3D internal structure of soil and rock, revealed impact history, identified olivine grains and hydrated minerals;<br>2) Identified various mineral and metallic phases; 3) Investigated under multiple hydraulic conditions;<br>4) Obtained more complete imaging | Martell et al. (2024)<br>Fedrigo et al. (2018)<br>Tengattini et al. (2020)<br>LaManna et al. (2017b) |
| Archaeological artifacts | 1) Swiss ancient sword and Roman crucible fragments;<br>2) Multi-material pottery fragments;<br>3) Roman dagger | 1) Fully revealed manufacturing techniques and preservation status;<br>2) Distinguished different material phases;<br>3) Comprehensively analyzed internal structures and compositions | Mannes et al. (2015)<br>Lehmann et al. (2021)<br>Mazzinghi et al. (2024) |

**Table 9**
Selected representative applications of NXDI in building materials and civil engineering.

| Types | Research focus | Findings | Reference |
|---|---|---|---|
| Concrete | 1) Delayed ettringite formation (DEF) process;<br>2) Degradation patterns;<br>3) Comparison between steel fiber–reinforced and plain samples;<br>4) Internal information reconstruction;<br>5) Microstructural investigation;<br>6) Drying process | 1) Achieved more accurate detection and identification of internal defects and degradation patterns;<br>2) Precisely correlated the damage formation process;<br>3) Provided in-depth understanding of moisture transport mechanisms and their influence on material performance;<br>4) Achieved effective reconstruction results;<br>5) The descriptions became more completer and more accurate;<br>6) Demonstrated significant potential | LaManna et al. (2020, 2017a)<br>Lehmann et al. (2021)<br>Kim et al. (2021)<br>Roubin et al. (2019)<br>Tengattini et al. (2020) |
| Asphalt mixtures | Structure and composition | Significantly improved the identification accuracy of internal structures in asphalt mixtures | Li et al. (2024b) |
| Dynamic studies of moisture | Hydration reactions;<br>2) Hydro-mechanical evolution of grey sandstone;<br>3) Liquid–gas diffusion layer (LGDL);<br>4) Fluid phase structure of sphingomyelin (SM);<br>5) Soil water retention and evaporation; 6) Hydraulic conditions in localized single cells | 1) Completed stepwise investigations;<br>2) Facilitated understanding of fluid dynamics within rocks;<br>3) Enabled spatial characterization of moisture distribution;<br>4) Determined structural parameters of various sphingomyelin phases;<br>5) Revealed moisture distribution and drying processes;<br>6) Visualized intracellular water distribution | McGregor et al. (2021)<br>Lima et al. (2025, 2024)<br>Maier et al. (2020)<br>Doktorova et al. (2022)<br>LaManna et al. (2017b)<br>Saadat et al. (2024) |

**Table 10**
Selected representative applications of NXDI in energy.

| Types | Research Focus | Findings | Reference |
|---|---|---|---|
| Energy Batteries | Chemical-mechanical instability at solid-solid interfaces of all-foil solid-state batteries (AF-SSBs) | Achieved *in situ* 3D characterization of interface degradation | Yusuf (2024) |
| | Visualization and characterization of lithium batteries | Enabled four-dimensional imaging of lithium batteries | Ziesche et al. (2022) |
| | Discharge process of commercial Li/$MnO_2$ primary cells | Achieved the first spatially resolved correlation between local mechanical failure and global electrochemical behavior | Ziesche et al. (2020) |
| | Enhancement of alkaline and lithium batteries for improved capacity and lifespan | Enabled three-dimensional visualization of battery structures | LaManna et al. (2020, 2017b) |
| Nuclear Physics | Core physical phenomena such as fuel mixing and asymmetry | Provided more accurate data support for combustion physics research | Danly et al. (2016) |
| | 3D characterization of nuclear fuel | Offered 3D insights into the morphological evolution of nuclear fuel cores | Cordes et al. (2021) |

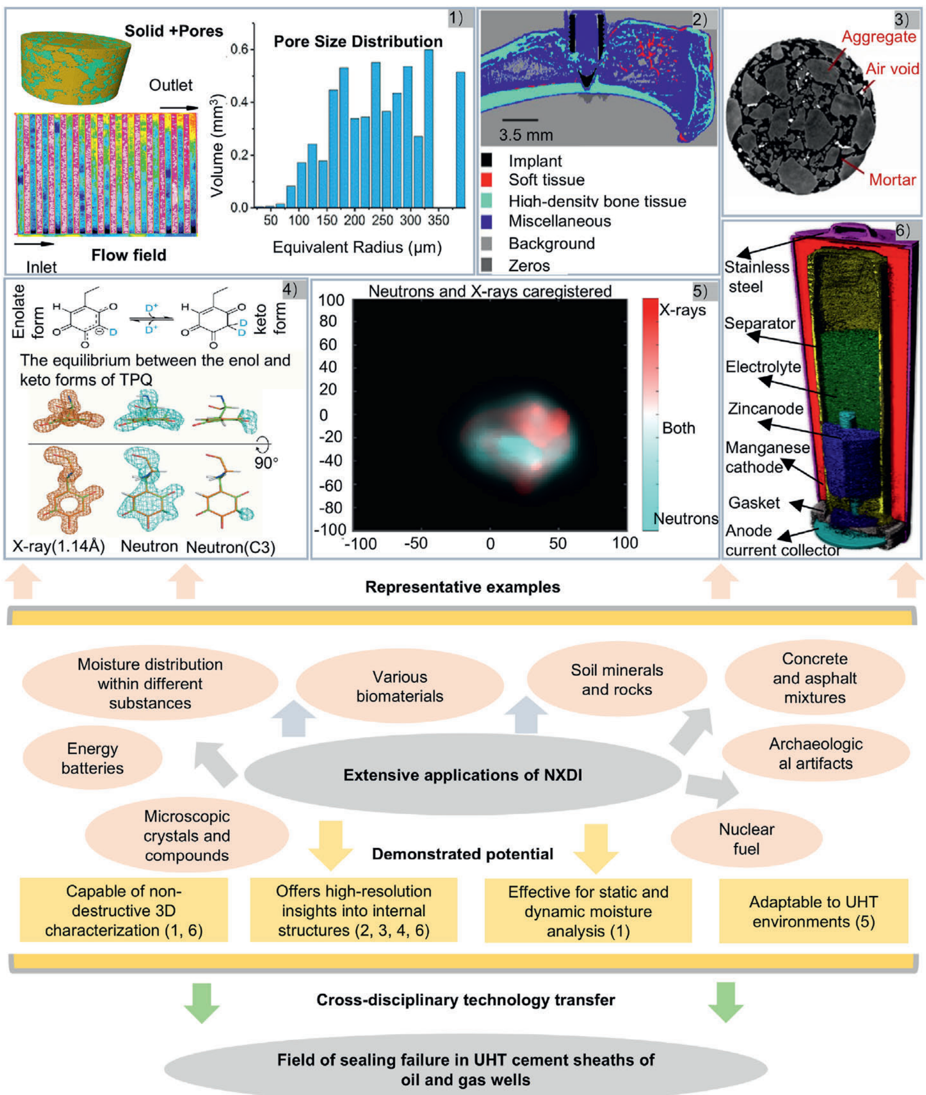


**Fig. 10.** Based on existing application experience, the migration of NXDI to the study of UHT cement sheaths is illustrated by several examples: 1) X-ray imaging provides microstructural information of the LGDL, including solid phase, porosity, and pore size distribution, while neutron imaging characterizes moisture distribution within the LGDL (Maier et al., 2020); 2) Dual-mode segmented rendering of rat proximal tibia implanted with titanium base (Törnquist et al., 2021); 3) Accurate differentiation of aggregate, voids, and mortar in asphalt mixtures (Li et al., 2024b); 4) Refined structural information of trihydroxy-phenylalanine quinone (TPQ) (Murakawa et al., 2022); 5) Three-dimensional simulation and characterization of asymmetry in nuclear fuel combustion (Danly et al., 2016); and 6) Dual-mode visualization of alkaline batteries with 3D rendering (LaManna et al., 2020).

## 5. Feasibility and technical roadmap of NXDI in UHT cement sheath research

### 5.1. Technical feasibility analysis

#### 5.1.1. Methodology is technically capable of meeting the research requirements

Difficulties in effectively characterizing moisture migration within cement sheaths highlight the potential value of neutron imaging, which has not yet been introduced into this field. As a non-destructive characterization technique (Kardjilov et al., 2018; Lehmann et al., 2009; Mannes et al., 2015; Mazzinghi et al., 2024), neutron imaging is highly sensitive to moisture (Mannes et al., 2015; Ziesche et al., 2020), shares several advantages with traditional imaging techniques, and ensures data stability under extreme conditions such as UHT (Zboray and Trtik, 2019). These features collectively demonstrate its considerable potential in relevant research. At present, challenges such as limited resolution (Roubin et al., 2019) and background noise (Liebschner et al., 2023; Losko and Vogel, 2023; Martell et al., 2024; Sinha et al., 2014) remain key obstacles to using neutron imaging for tracking moisture evolution in cement sheaths. However, X-ray imaging is particularly effective in addressing these issues (Koestel et al., 2022; McGregor et al., 2021; Tandrup et al., 2023). By taking advantage of the complementarity between the two modalities (Lehmann et al., 2021; Martell et al., 2024), a synergistic outcome may be achieved, allowing access to valuable information previously difficult to obtain, which can then be further analyzed using other tools, such as numerical simulation methods like the thermo–hydraulic coupled discontinuous displacement method (THM-DDM) to interpret the evolution of microcracks (Abdollahipour and Marji, 2020). Therefore, from both a technical and theoretical perspective, this approach is feasible for investigating sealing failure mechanisms in UHT cement sheaths.

#### 5.1.2. Support from imaging software and algorithm models

With ongoing development and upgrades in image processing software, an increasing number of complex image operations have become feasible. Image fusion, a key part of NXDI (Li et al., 2024b), represents a major challenge, innovation, and breakthrough in this study. This process involves denoising and smoothing (LaManna et al., 2020), alignment and registration (Kaestner et al., 2015, 2017), and fusion reconstruction (Törnquist et al., 2021; Treffert et al., 2024) of neutron and X-ray imaging data. It also requires complementary enhancement of image information from both modalities (Mohammadi et al., 2022; Törnquist et al., 2021; Treffert et al., 2024) to reveal more useful details under current technical conditions. In addition to dedicated platforms, a range of open-source tools are available, including ImageJ (LaManna et al., 2017b), Avizo (Maier et al., 2020), SIMPLEWARE, and ANSYS CFX. Some support fusion processing of neutron and X-ray images, while others can independently extract key information impacting sealing performance, including pores, fractures, micro-annuli, and moisture content in cement sheaths. Comparing results across different software or using multiple software together is recommended to achieve optimal processing and improve chances of meeting research goals.

Regarding algorithm models, targeted choices can be made depending on specific needs. These models assist in improving image quality, filtering irrelevant information, and reducing interference. A variety of algorithms and models exist to meet diverse requirements, such as the Mamba-based dual-phase model for multimodal image fusion (Li et al., 2024a); Multi-Pose Fusion algorithms, pixel-weighted Multi-Pose Fusion algorithms, sinogram-weighted algorithms, and sample-adaptive measurement algorithms (Yang, 2024); the NSCT fusion algorithm (He et al., 2021); the Gaussian model (Roubin et al., 2019); and Otsu and Sobel edge detection algorithms (He et al., 2021; Kim et al., 2021). Proper application of these algorithms and models can resolve many imaging issues, promote effective image fusion, and support comprehensive research progress.

#### 5.1.3. Adequate research facilities and well-established sample preparation experience

Although this research area remains unexplored, sufficient experimental resources are available. Aside from neutron imaging, which typically relies on large-scale scientific infrastructure to ensure high imaging quality, most other required instruments, such as X-ray micro-CT (Yang et al., 2021c), SEM (Yang et al., 2021c), XRD (Liebschner et al., 2023; McGregor et al., 2021), and equipment for preparing G-grade cement and admixtures (Pang et al., 2022), are accessible in many laboratories. High-quality neutron imaging spectrometers are available at major spallation and reactor-based neutron sources worldwide, including ISIS (UK), SNS (USA), ESS (Sweden), and J-PARC (Japan). In China, neutron imaging is supported by facilities such as the China Spallation Neutron Source in Dongguan and research reactors like CARR (Beijing) and CMRR (Mianyang). In addition, several research institutes have developed integrated dual-mode imaging systems capable of acquiring both modalities efficiently, including platforms such as NeXT-Grenoble, NEUTRA, and NIF, as outlined in Section 3.

For this research, the preparation of downscaled cement casing samples will be required, and existing studies offer valuable experience in this area. A series of investigations focused on cement integrity at the micron scale (Yang et al., 2019; Yang, 2020; Yang et al., 2021b; 2021c, 2024) have validated the feasibility and effectiveness of preparing and characterizing scaled-down cement-casing samples. These efforts provide valuable references and technical support for advancing this study.

### 5.2. Suggested roadmap for technical implementation

As discussed in Sections 2–4, neutron and X-ray imaging exhibit strong complementarity. The integration of these two modalities enables the acquisition of additional structural and compositional information, demonstrating their potential in the investigation of cement sheath sealing failure mechanisms. Since the influence of admixtures and curing conditions remains unclear, a series of comparative experiments is proposed. These experiments will investigate how different admixture types and curing regimes affect internal moisture behavior in UHT cement sheaths used in oil and gas wells, thereby offering insights into sealing failure mechanisms.

Based on methodologies from related studies, a technical implementation roadmap is outlined in Fig. 11. A multi-project research strategy will be adopted. Downsized sample design, fabrication, and curing will be conducted first (Yang et al., 2021c), with sealing performance optimization as a priority. NXDI will then be employed to simultaneously explore the mechanisms associated with admixtures and curing condition effects, accompanied by permeability measurements. This will be followed by transparent characterization of the cement sheath, involving denoising, registration, fusion, and reconstruction of neutron and X-ray datasets, which represents one of the major technical challenges in future work. Subsequent analysis will incorporate SEM, EDS, and XRD techniques (Liebschner et al., 2023; McGregor et al., 2021; Yang et al., 2021c) to obtain both planar and three-dimensional microstructural parameters. Finite element seepage simulations will also be performed (Kim et al., 2021). The resulting dataset will provide critical information, including moisture

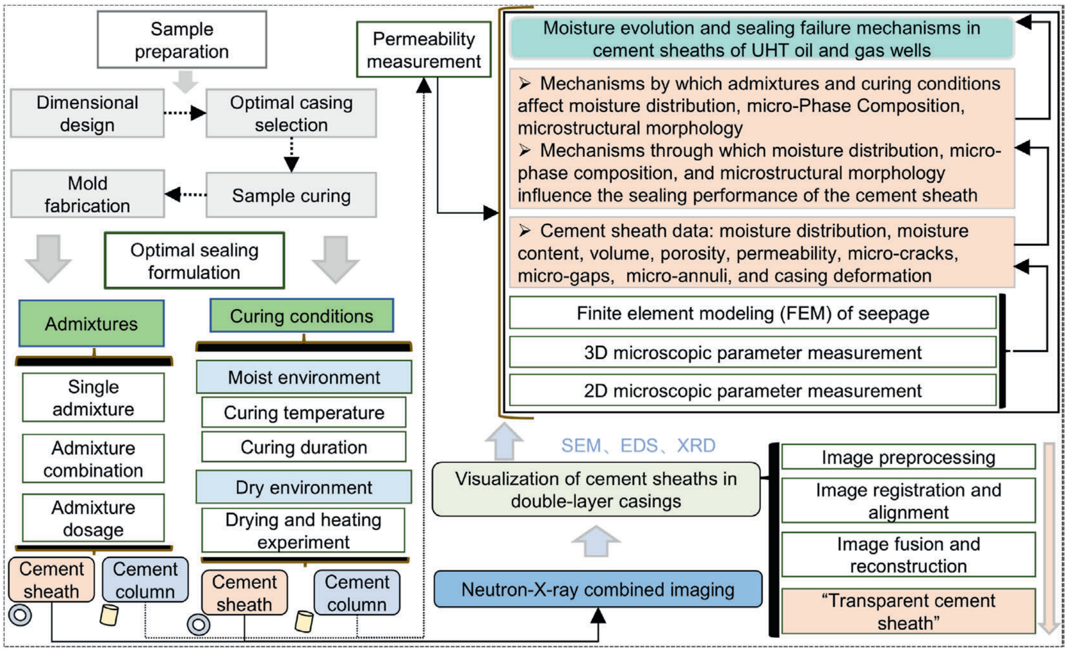


**Fig. 11.** Schematic illustration of the technical roadmap for investigating internal moisture evolution and sealing failure mechanisms in UHT cement sheaths.

distribution, content, and volume; porosity and pore volume; permeability; microfractures and micro-gaps; micro-annulus size and distribution; and casing deformation.

Upon completion of the above steps, most key information concerning cement sheaths under UHT conditions can be obtained. Based on this, further efforts can focus on clarifying two essential questions: (1) how admixtures and curing conditions influence moisture distribution, microphase composition, and microscopic morphology; and (2) how these factors, in turn, affect the sealing performance of the cement sheath. Clarifying these mechanisms can contribute to a better understanding and mitigation of sealing failures in UHT oil and gas wells. Consequently, whether focusing on the intrinsic properties of cement materials and casing components, or applying external interventions such as intelligent monitoring and compensation strategies, more precise data will be available to support targeted technical responses.

## 6. Challenges, strategies, and prospects for NXDI in UHT cement sheath research

### 6.1. Principal technical challenges

(1) Limitations in neutron imaging quality. Due to the intrinsic physical properties of neutrons and current technical constraints, images produced by neutron imaging systems often exhibit limited resolution and accuracy, potentially omitting critical structural details. In addition, background noise remains a persistent issue, requiring image preprocessing procedures such as denoising and smoothing. These steps may lead to the unintended loss of valuable original information, resulting in incomplete image representation.

(2) Challenges in Neutron-X-ray Image Fusion. Image fusion serves as a vital component in integrating the complementary strengths of NXDI. However, existing fusion methods generally lack universality, making it difficult to apply them effectively under varying conditions or for different imaging requirements. Most approaches do not provide image-specific guidance, and fusion outcomes are often uncertain due to the absence of standardized evaluation criteria. In some cases, the fused image may contain less useful information than the original input images, complicating subsequent analysis. As a result, significant effort is often required for method selection, result validation, and performance optimization during image processing.

(3) Effectively eliminating interference from irrelevant factors and ensuring the relevance of research outcomes to actual engineering applications. The study involves multiple variables, including the cement sheath, its internal moisture, admixtures, and curing conditions. The diversity of experimental methods may introduce unexpected or irrelevant signals during the testing process. Identifying and minimizing such external interferences is essential for creating a reliable experimental environment and ensuring the accuracy of results. In addition, the practical implementation of research outcomes in real oil and gas well cementing operations remains challenging, particularly in ensuring the engineering relevance of experimental findings. For example, maintaining the sample's condition during scanning and imaging consistent with that under real engineering conditions (including internal microstructure and moisture distribution information), thereby ensuring that the measured data match those of the downhole target.

(4) Lack of direct empirical guidance. This requires a certain amount of time and effort for exploration, which can affect the continuity and timeliness of research, as well as prolong the research cycle and progress.

### 6.2. Mitigation strategies and potential solutions

(1) Methods for improving the quality of neutron imaging continue to expand. At present, most imaging systems are being continuously upgraded, resulting in higher resolution and reduced imaging noise. These advancements expand the applicability of neutron imaging across various research fields. In addition, certain practical studies have broken through resolution limitations—such as centroid reconstruction (Hussey et al., 2017), optical enhancement (Hussey

et al., 2025), and deep learning-based super-resolution image optimization (Ma et al., 2025). Although these methods still require broader adoption, they have demonstrated the feasibility of enhancing neutron imaging resolution. Even when the quality of neutron imaging alone does not fully meet requirements, complementary information from X-ray imaging can be used to refine the results, potentially revealing details that are inaccessible through other analytical methods. For noise interference in neutron images, it can be addressed through targeted improvements during the image processing stage.

(2) Tackling image fusion challenges in dual-mode imaging from multiple angles. First, appropriate image processing software must be selected. While existing open-source tools meet most general image processing needs, they often lack specificity. Software selection should be based on the fusion requirements of neutron and X-ray images and aligned with the research focus on moisture evolution. Comparative and combined use of different tools can help identify the most effective software combinations, allowing each to be used for its strengths and facilitating collaborative processing. The resulting image data should be organized and documented for further analysis. Second, the use of suitable algorithm models is essential. Inappropriate algorithms may introduce distortions or degrade image quality. Third, emerging technologies such as artificial intelligence offer potential support. As AI continues to advance, its application in various research domains is expanding, and it may provide valuable assistance in improving neutron-X-ray image fusion.

(3) Addressing interferences arising from external factors and during the research process, and enhancing the relevance of the research to practical applications. For external interferences, the scanning environment should be kept consistent with that in actual oil and gas wells, and comparative analyses should be conducted to determine whether any additional information has practical value. For interferences generated during the research process, the procedures should be standardized, with careful monitoring and recording to promptly and accurately identify new sources of interference, followed by targeted screening and removal of irrelevant information. To tackle the challenge of ensuring consistency between laboratory sample information and that of the actual target, several approaches can be adopted, such as using sample chambers capable of simulating real wellbore environments while allowing both neutrons and X-rays to pass through without attenuation (Makowska et al., 2015), employing vapor-phase humidity control systems to maintain stable moisture content in the cement sheath (Smyl et al., 2016), reducing sample exposure time (Vigor et al., 2024), and applying post-measurement calibration and compensation (Oesch et al., 2019).

(4) Gradual approaches to address the lack of direct experiential guidance. Research can begin by exploring relatively simple related experiments or by learning from analogous methods adopted by other research teams facing similar challenges. For example, Li et al. (2024b) reported difficulties in image registration during dual-mode imaging of asphalt mixtures. By applying vertical mirroring, rotation, and edge cropping to the neutron images, alignment with X-ray images was achieved. A customized fusion method based on digital image processing was then developed.

### 6.3. Future perspectives

(1) Future work suggestions. 1) Explore the integration of image fusion techniques with intelligent algorithms. Stay informed of advancements in both NXDI and cement sheath research, and refine the experimental design accordingly. 2) Investigate UHT cementing challenges in oil and gas wells under different regional and geological conditions, and compile a comprehensive framework of sealing failure mechanisms. 3) Conduct preliminary applications of NXDI in simpler studies to further uncover its potential and operational considerations. Promote broader scientific collaboration to improve and extend theoretical and technical frameworks.

(2) Predicted development trends. With continuous equipment upgrades, technical advancements, and the accumulation of experience, particularly improvements in neutron imaging systems, the feasibility of the proposed research has been steadily increasing. Scientific research will benefit from diversified support, including artificial intelligence and big data resource sharing. A growing number of studies are expected, potentially leading to a complete characterization system for moisture evolution in cement sheaths and a robust framework for evaluating sealing failure mechanisms. These advancements may guide the development of high-temperature-resistant and leakage-preventive cementing materials, supporting the safe and sustainable extraction of UHT oil and gas wells.

(3) Future application prospects. As conventional research approaches approach their performance limits, cross-disciplinary exploration through the adoption of emerging

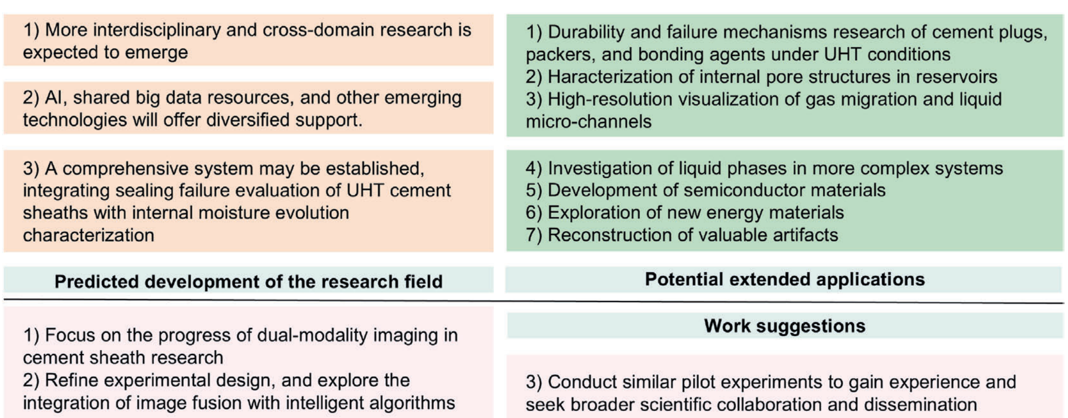


**Fig. 12.** Future perspectives: Predictions for the field development, potential applications, and proposed work.

technologies may result in unique insights. A visual summary is provided in Fig. 12. Based on the demonstrated potential of NXDI in prior applications, several prospective directions for future extension are proposed. 1) This technique may be applied to investigate the durability and failure mechanisms of oil and gas cementing components that operate under similar ultra-high temperature conditions as cement sheaths, including cement plugs, packers, and bonding agents. It can also support the characterization of pore structures in deep reservoirs, the evaluation of casing-cement interface bonding, and the visualization of gas channeling and liquid microchannels. 2) The technique may assist in the high-precision investigation of liquid-phase substances in various settings, such as tracing groundwater contamination in mining zones caused by resource extraction and detecting liquid water in extreme environments including deep-sea, polar, and extraterrestrial regions. 3) Its non-destructive microscopic reconstruction capability may contribute to semiconductor material research and the restoration or reconstruction of high-value artifacts. 4) In the field of new energy, this technique may provide valuable insights for the study of hydrogen storage materials, nuclear fuel systems, and energy storage batteries, offering new perspectives for technological advancement.

## 7. Conclusions

Focusing on the cementing challenges in oil and gas wells during deep and ultra-deep resource extraction, this paper outlines the current technical barriers in researching the sealing failure of UHT cement sheaths. This is a critical issue for safe and efficient upstream petroleum production, environmental protection, and sustainable low-carbon development. It provides a comprehensive review of the notable advantages and broad applications of NXDI, demonstrating its potential and feasibility in this field. Additionally, it offers application recommendations and future prospects. Based on a synthesis of current research and the content of this paper, the following conclusions are drawn.

- The failure mechanisms of cement sheath sealing under UHT conditions are complex, moisture is a significant influencing factor, and the roles of admixtures, while the roles of admixtures and curing conditions remain to be clarified. Effectively visualizing both microstructural information and moisture migration is essential for understanding the failure mechanisms. However, conventional techniques struggle to achieve both, making meaningful progress difficult.
- A comparative analysis was conducted on the adaptation mechanisms and characteristics of neutron and X-ray imaging, with particular emphasis on NXDI, which integrates the advantages of both techniques. From a mechanistic perspective, the advantages of NXDI over conventional single-modality imaging were demonstrated, particularly its potential to simultaneously provide information on light elements and microstructural features; moreover, it enables the extraction of additional insights via image fusion.
- By reviewing a wide range of practical applications of NXDI in multiple disciplines, its capabilities in non-destructive analysis and micro-level characterization of complex internal structures are highlighted—especially in accurately identifying liquid phases within materials like concrete. These application-based findings support the potential and suitability of NXDI for investigating the sealing integrity of cement sheaths under UHT conditions.
- The feasibility and rationale of applying NXDI to the study of sealing performance in UHT cement sheaths were demonstrated from both theoretical and practical perspectives. A comprehensive experimental framework was proposed to guide and support future research.
- In response to potential challenges and bottlenecks in future research, several coping strategies were proposed, and the application prospects of NXDI were discussed. Among them, achieving high-quality fusion of neutron and X-ray imaging data, as well as ensuring the relevance of research outcomes to real-world engineering practices, are critical challenges and areas of innovation. These goals require strong support in terms of technology, methodology, and practical experience. With continued technological progress and cross-sector collaboration, the sealing failure mechanisms of cement sheaths in UHT oil and gas wells will become increasingly well understood. NXDI is anticipated to emerge as a key enabling technology for advancing deep oil and gas resource development, mitigating methane emissions, enhancing wellbore safety and production efficiency, and supporting the UN Sustainable Development Goals.

## CRediT authorship contribution statement

**Yabing Wen:** Writing – original draft, Visualization, Investigation, Formal analysis. **Xinxiang Yang:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

## 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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