Sarcouncil Journal of Engineering and Computer Sciences

ISSN(Online): 2945-3585

Volume- 05| Issue- 02| 2026

Research Article

Received: 10-01-2026| Accepted: 05-02-2026 | Published: 20-02-2026

Integrating Wellsite Geochemical Indicators into Data-Driven Environmental Risk Screening for Abandoned U.S. Oil and Gas Wells

Stanley Uchenna Opara

Diversified Well Logging, LLC, Odessa, USA

Abstract: Abandoned oil and gas wells represent a widespread and persistent environmental challenge in the United States, posing risks to climate, groundwater resources, and public health. Many legacy wells suffer from progressive integrity degradation, enabling methane emissions and subsurface fluid migration that are difficult to identify using inventory-based or inspection-driven approaches alone. This review synthesizes current knowledge on integrating wellsite geochemical indicators into data-driven environmental risk screening frameworks for abandoned U.S. oil and gas wells. Drawing on 25 peer-reviewed studies, the review examines well integrity failure mechanisms, methane emissions and source attribution, groundwater contamination pathways, and the application of geochemical tracers such as methane isotopes, major ion chemistry, halide ratios, and organic contaminants. The findings demonstrate that environmental impacts are highly heterogeneous, with a small subset of wells responsible for disproportionate methane emissions and contamination risks. While data-driven screening approaches, including GIS-based and machine-learning methods, have improved large-scale risk identification, geochemical indicators remain underutilized within these frameworks. Integrating geochemical evidence enhances risk discrimination, reduces uncertainty associated with incomplete well inventories, and improves prioritization for monitoring and remediation. This review highlights methodological gaps, policy-relevant uncertainties, and opportunities for advancing scalable, geochemically informed screening tools. By explicitly integrating wellsite geochemical indicators into data-driven screening workflows, the proposed framework alters risk classification outcomes by reducing false negatives associated with spatial proxy-based models and improving differentiation between low- and high-risk abandoned wells. This integration enhances prioritization accuracy for methane mitigation and groundwater protection, supporting more targeted and cost-effective remediation strategies at basin to national scales.

Keywords: Wellsite, Geochemical Indicators, Data-Driven, Environmental Risk, Abandoned U.S. Oil and gas.

INTRODUCTION

Abandoned and orphaned oil and gas wells represent a long-standing environmental legacy of hydrocarbon development in the United States. Many of these wells were drilled before standardized regulations governing well construction, documentation, and abandonment were established, leading to incomplete records, uncertain locations, and ambiguous plugging status (Zhang *et al*., 2019; Thomas & Norman, 2023). As a result, historical inventories substantially underestimated the true number of abandoned wells across U.S. basins. Recent efforts to reconcile state regulatory databases with historical drilling archives, land-use records, and spatial modeling have significantly revised national estimates. Updated assessments indicate that known abandoned and orphaned well counts have increased by more than 30% following the inclusion of undocumented wells (Kang *et al*., 2023; Raimi *et al*., 2022). This growing inventory underscores the scale of the challenge facing regulators and land managers, particularly as federal and state remediation programs operate under limited financial and logistical capacity.

Well Integrity Degradation and Environmental Pathways

The environmental risks associated with abandoned wells arise primarily from the progressive degradation of well integrity over time. Aging wells commonly experience casing corrosion, cement shrinkage, debonding at casing-cement interfaces, and microannulus formation, all of which compromise subsurface containment (Umejuru & Ochulor, 2020; Jafarli, 2025). These processes are exacerbated by pressure cycling, geochemical interactions, and prolonged exposure to formation fluids. Integrity failures create preferential pathways for upward methane migration to the surface and for vertical or lateral transport of fluids into surrounding formations and shallow aquifers (Aghdam *et al*., 2025; Shaheen *et al*., 2022). Empirical field studies and laboratory investigations consistently demonstrate that such leakage pathways can persist for decades after production ceases, with failure rates increasing with well age and varying across geological settings (Kessler *et al*., 2022; Sharma *et al*., 2024).

Methane Emissions and Climate Implications

Methane emissions from abandoned and orphaned wells have emerged as a significant component of regional and national greenhouse gas budgets.

*Corresponding Author: Stanley Uchenna Opara

DOI- https://doi.org/10.5281/zenodo.18711120

Field measurements across multiple U.S. basins reveal extreme heterogeneity in emission rates, with a small fraction of wells acting as super-emitters that dominate cumulative methane fluxes (Milton-Thompson, 2019). This variability complicates emission estimation and challenges traditional inspection-based approaches. Both thermogenic and microbial methane sources have been identified at abandoned well sites. Notably, microbial methane occurs more frequently than previously assumed, particularly in shallow, water-saturated environments, and can contribute substantially to overall emissions (Laaouar *et al*., 2022). Integrated modeling studies further demonstrate that incomplete well inventories systematically bias methane budgets downward, with undocumented wells increasing estimated emissions by approximately 8% in some national-scale assessments (Senger *et al*., 2025; Kang *et al*., 2023).

Groundwater Contamination Risks and Geochemical Evidence

Beyond atmospheric emissions, abandoned wells pose substantial risks to groundwater quality. Wells intersecting shallow or unconfined aquifers can function as long-term conduits for methane, brines, volatile organic compounds, and trace metals, particularly where cement integrity has been compromised (Chapman *et al*., 2021; Shaheen *et al*., 2022). Hydrogeological modeling and field investigations indicate that contaminant migration can persist over decadal timescales, with transport behavior strongly controlled by stratigraphy, fracture networks, and hydraulic gradients (Raimi *et al*., 2021; Rashid *et al*., 2022). Wellsite geochemical anomalies documented near legacy wells include elevated methane concentrations, distinct stable isotope signatures ($\delta^{13}C\text{-}CH_4$ and $\delta D\text{-}CH_4$), increased chloride and bromide ratios, and the presence of BTEX compounds (Raimi *et al*., 2022). These indicators provide direct evidence of subsurface leakage processes and offer valuable diagnostic information that extends beyond surface observations or administrative classifications.

Role of Wellsite Geochemical Indicators in Environmental Risk Assessment

Wellsite geochemical indicators offer a process-based framework for evaluating environmental risk from abandoned wells. Methane isotopic compositions enable differentiation between thermogenic and microbial sources, while major ion chemistry and halide ratios constrain mixing between formation waters and shallow groundwater systems (Rashid *et al*., 2022). Trace hydrocarbons and dissolved metals further refine interpretations of leakage pathways, residence times, and contaminant origins (Aghdam *et al*., 2025). Despite their diagnostic value, geochemical indicators have historically been applied primarily in site-specific investigations rather than systematically incorporated into regional or national risk screening efforts. This limitation restricts their broader utility for prioritizing remediation across large well inventories and heterogeneous geological settings.

Emergence of Data-Driven Environmental Risk Screening Approaches

In response to data scarcity and spatial uncertainty, environmental risk assessment for abandoned wells has increasingly shifted toward data-driven and computational approaches. Recent studies integrate geographic information systems, probabilistic emission modeling, hydrogeological simulations, and machine-learning algorithms to improve detection of undocumented wells and characterize spatial risk patterns (Ali *et al*., 2024; Kang *et al*., 2023).

Machine-learning models trained on geological attributes, land-use variables, and known well characteristics have demonstrated substantial improvements in identifying undocumented wells and reclassifying national risk profiles, nearly doubling the proportion of wells identified as high-risk in some analyses (Kang *et al*., 2023). These methods support scalable screening and enable risk-based prioritization under limited remediation budgets.

Gaps, Challenges, and Need for Integrated Frameworks

Despite methodological advances, most existing data-driven screening frameworks underutilize wellsite geochemical information, relying instead on spatial proxies and infrastructure attributes (Alsubaih *et al*., 2025). This omission limits their ability to distinguish between structurally intact wells and those actively leaking contaminants. Furthermore, integration of heterogeneous datasets including groundwater chemistry, isotopic measurements, emissions data, and regulatory records remains inconsistent, complicating model transferability and uncertainty quantification (Chapman *et al*., 2021; Okosun *et al*., 2025; DiGiulio, 2024). Additional challenges include incomplete historical documentation, geological heterogeneity across U.S. basins, and climate-driven changes in groundwater recharge and

Publisher: SARC Publisher

subsurface redox conditions that may alter methane generation and migration dynamics over time (Ali *et al*., 2024; Mohan *et al*., 2020). Addressing these challenges requires integrative frameworks that combine geochemical process understanding with flexible, data-driven analytics.

Limitations of Existing Screening Frameworks and Bias from Missing Geochemical Data

Existing environmental risk screening frameworks for abandoned U.S. oil and gas wells primarily rely on spatial proxies such as well density, drilling era, depth, land use, proximity to receptors, and basin-scale geological attributes (Mohan *et al*., 2020). Although effective for broad national-scale assessments, these approaches assume spatial uniformity of risk within proxy-defined classes, overlooking well-to-well variability driven by localized integrity failure, subsurface connectivity, and active leakage processes (Shaheen *et al*., 2022). The exclusion of geochemical data introduces systematic model bias, leading to underestimation of risk at isolated or undocumented wells with strong methane or groundwater contamination signals and overestimation in densely developed areas where wells remain intact or effectively plugged (Kang *et al*., 2023; Raimi *et al*., 2022). Without geochemical constraints, screening models cannot reliably differentiate dormant legacy wells from those actively transmitting hydrocarbons or formation fluids, causing risk rankings to diverge from observed environmental outcomes (Raimi *et al*., 2022). Integrating geochemical indicators helps correct these biases and strengthens screening-based decision support

Scope of This Review

Given the scale of the abandoned well problem, the demonstrated diagnostic power of wellsite geochemical indicators, and the rapid growth of data-driven environmental screening methods, a systematic synthesis is urgently needed. While prior studies have examined methane emissions, groundwater contamination, or machine-learning detection of undocumented wells in isolation, no comprehensive review has focused on integrating geochemical indicators into data-driven environmental risk screening for abandoned U.S. oil and gas wells.

This review addresses that gap by synthesizing evidence from field measurements, geochemical analyses, and computational risk assessments. Specifically, it aims to (i) evaluate the types and diagnostic value of wellsite geochemical indicators, (ii) assess their incorporation into existing data-driven screening frameworks, (iii) identify methodological limitations and uncertainties, and (iv) outline future research directions for developing robust, scalable, and process-informed environmental risk screening tools to support abandoned well management in the United States.

Integrating Wellsite Geochemical Indicators into Data-Driven Environmental Risk Screening

The proposed conceptual framework links wellsite geochemical indicators with data-driven analytical approaches to enable systematic environmental risk screening of abandoned U.S. oil and gas wells. The framework is designed to bridge the gap between site-specific geochemical evidence of leakage and scalable, regional-to-national risk assessment tools. It integrates subsurface process indicators, spatial and infrastructural datasets, and computational analytics to support risk-based prioritization for monitoring and remediation.

At its core, the framework recognizes that environmental risk from abandoned wells is governed by three interacting domains:

1. Well integrity and subsurface processes,
2. observable geochemical signals, and
3. data-driven screening and decision-making systems.

By explicitly connecting these domains, the framework advances beyond traditional inventory-based approaches and enables more accurate identification of high-risk wells.

Publisher: SARC Publisher

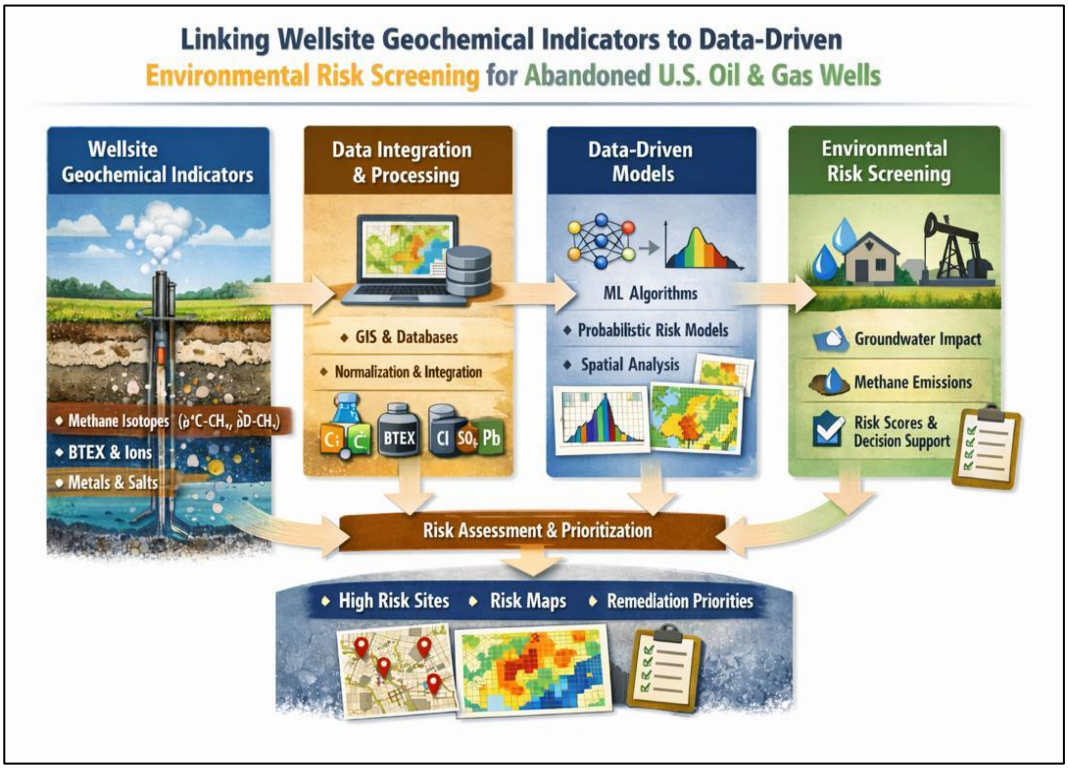

Figure 1.1: A Conceptual Framework Integrating Wellsite Geochemical Indicators into Data-Driven Environmental Risk Screen*ing*

MATERIALS AND METHODS

This study adopts a structured narrative review approach to synthesize research on integrating wellsite geochemical indicators into data-driven environmental risk screening frameworks for abandoned oil and gas wells in the United States. The review is designed to bridge site-scale geochemical evidence with regional- and national-scale screening methodologies, reflecting the need for scalable tools capable of prioritizing environmental risk under limited remediation resources. The analytical approach is guided by a conceptual framework linking legacy well characteristics, geochemical signals, data integration workflows, and computational screening outputs. Emphasis is placed on screening-level methodologies that support early-stage decision-making rather than on evaluating individual remediation technologies.

Literature Sources and Scope of Reviewed Materials

The review synthesizes findings from 25 peer-reviewed journal articles and technical studies selected for their relevance to abandoned or orphaned oil and gas wells in the U.S. context or for presenting methodologies transferable to U.S. geological and regulatory settings. The reviewed literature spans multiple disciplines, including hydrogeology, geochemistry, environmental science, petroleum engineering, and data science. Studies were included if they addressed abandoned well inventories, well integrity degradation, methane emissions, groundwater contamination, geochemical tracer applications, or data-driven risk screening. Studies focused exclusively on active wells or lacking methodological transparency were excluded to maintain relevance to legacy well risk assessment.

Summary of Reviewed Studies and Data Types

To provide transparency and facilitate comparison across studies, a summary table was developed to categorize reviewed literature by basin or region, primary data types, and analytical approaches. This classification highlights disciplinary patterns and reveals the extent to which geochemical data are incorporated into screening methodologies.

Study Region / Basin	Primary Focus	Geochemical Data	GIS-Based Screening	ML / Statistical Modeling
Appalachian Basin	Methane leakage	✓	✓	✗
Permian Basin	Emissions screening	✗	✓	✓

Publisher: SARC Publisher

Midcontinent	Groundwater risk	✓	✗	✗
National (U.S.)	Well inventory risk	✗	✓	✓

Source: (Kang *et al*., 2023; Raimi *et al*., 2022; Zhang *et al*., 2019; Thomas & Norman, 2023)

Extraction of Legacy Well and Geological Information

From each study, information related to legacy well characteristics and geological context was systematically extracted. These data included well age, construction era, casing and cement materials, plugging status, and depth, as well as geological descriptors such as stratigraphy, permeability contrasts, fault presence, and aquifer connectivity. These parameters were treated as primary controls on well-integrity degradation and leakage potential. Where direct construction data were unavailable, proxy indicators such as drilling era or basin development history were used. This process established a baseline for linking physical well attributes and subsurface conditions to observed environmental impacts and geochemical signals.

Identification and Classification of Wellsite Geochemical Indicators

Wellsite geochemical indicators reported in the reviewed studies were compiled and classified according to their diagnostic function and environmental relevance. Gas-phase indicators included methane concentrations, emission fluxes, and stable isotopic compositions used to distinguish thermogenic from microbial sources. Aqueous indicators encompassed dissolved methane, major ion chemistry, and chloride-to-bromide ratios indicative of formation water intrusion or subsurface mixing. Where available, organic and inorganic tracers such as BTEX compounds and trace metals were also included. These indicators were evaluated for both their ability to confirm leakage and their suitability as screening-level inputs for large-scale risk assessment frameworks.

Environmental Risk Endpoints and Impact Classification

Environmental impacts associated with abandoned wells were classified into two primary risk endpoints: atmospheric risk and groundwater risk. Atmospheric risk was defined by methane emissions and their implications for greenhouse gas inventories and air quality, while groundwater risk encompassed contamination of potable aquifers and long-term degradation of subsurface water quality. This classification enabled consistent comparison across studies employing different monitoring techniques, spatial scales, and analytical objectives. Emphasis was placed on assessing how geochemical indicators directly inform these risk endpoints and support prioritization decisions.

Data-Driven Screening and Computational Methods

The review examined data-driven and computational approaches used for environmental risk screening of abandoned wells, including GIS-based spatial analysis, probabilistic emission modeling, and machine-learning techniques. These methods have been applied to identify undocumented wells, detect risk hotspots, and classify wells by emission or contamination potential. Extracted methodological details included model input variables, spatial resolution, treatment of missing or uncertain data, and validation strategies. Special attention was given to whether geochemical indicators were incorporated directly as predictive features, used for model calibration, or applied post hoc for validation.

Integration Assessment of Geochemical Indicators

To assess the extent of integration between wellsite geochemical indicators and data-driven screening frameworks, each study was evaluated along three dimensions: availability of geochemical data, analytical incorporation into screening models, and influence on risk classification outcomes. This assessment distinguished studies in which geochemical evidence functioned as a core analytical component from those where it played a supplementary role. The analysis also identified methodological gaps where strong geochemical signals are documented but not systematically incorporated into large-scale screening efforts.

Synthesis Strategy and Comparative Evaluation

A qualitative synthesis strategy was employed to compare methodologies across the reviewed studies, emphasizing integration strategies rather than quantitative aggregation. The synthesis evaluated consistency of geochemical indicators across geological settings, scalability of screening approaches, transferability of models between basins, and sources of uncertainty related to incomplete inventories and heterogeneous data

Publisher: SARC Publisher

quality. This comparative evaluation provided insight into current best practices and limitations in abandoned well risk screening.

Methodological Constraints and Framework Alignment

Common methodological constraints identified across the reviewed studies include incomplete historical records, spatial bias toward accessible regions, inconsistent geochemical sampling protocols, and limited temporal monitoring data. These limitations were explicitly considered to avoid overgeneralization of findings. All extracted data and analytical comparisons were mapped onto the proposed conceptual framework to ensure consistency between legacy well attributes, geochemical evidence, data integration processes, and screening outcomes. This alignment supports the development of integrated, scalable environmental risk screening approaches for abandoned oil and gas wells in the United States.

RESULTS AND FINDINGS

The 25 studies synthesized in this review collectively span major U.S. producing regions and legacy basins, including the Appalachian Basin, Midcontinent, Gulf Coast, Rocky Mountain region, and California. The literature demonstrates a strong concentration of empirical evidence on methane emissions and groundwater geochemistry near abandoned and orphaned wells, with increasing integration of spatial and computational analyses in more recent studies (Kang *et al*., 2023). Earlier studies emphasize well integrity degradation and contamination pathways (Barker, 1982; Harrison, 1992), while later work increasingly applies isotopic tools and data-driven screening frameworks. Evidence has evolved from site-specific case studies toward regional and national screening, but integration of geochemical indicators into data-driven models remains uneven.

Well Integrity Degradation and Observed Leakage Pathways

Across the reviewed studies, well integrity degradation is consistently identified as the primary driver of environmental risk from abandoned wells. Reported degradation mechanisms include casing corrosion, cement shrinkage, debonding at casing-cement interfaces, and microannulus formation, particularly in wells drilled prior to modern standards (Ali *et al*., 2024; Mohan *et al*., 2020). These integrity failures are directly linked to both upward methane migration and fluid transport into overlying formations and aquifers (Mohan *et al*., 2020).

Field and laboratory evidence indicates that leakage pathways can remain active for decades after abandonment and that failure likelihood increases with well age and exposure to chemically aggressive formation fluids (Kessler *et al*., 2022). Integrity degradation is ubiquitous across legacy wells and provides the physical basis for observed geochemical anomalies and emissions.

Methane Emissions: Magnitude, Variability, and Source Attribution

Methane emissions from abandoned wells show extreme spatial variability across the reviewed studies. Direct flux measurements reveal that a small subset of wells functions as super-emitters, disproportionately contributing to total methane emissions (Shaheen *et al*., 2022; Aghdam *et al*., 2025). This skewed distribution challenges uniform inspection-based screening approaches.

Stable isotope analyses consistently demonstrate the presence of both thermogenic and microbial methane. Importantly, microbial methane is frequently detected near abandoned wells, particularly in shallow or water-saturated environments, and is often underrepresented in emissions inventories (Laaouar *et al*., 2022). National-scale modeling studies indicate that incomplete inventories of abandoned and undocumented wells lead to systematic underestimation of methane emissions, with modeled increases of approximately 8% when undocumented wells are included (Kang *et al*., 2023). Methane emissions are highly heterogeneous, and isotopic geochemistry is essential for source attribution and accurate risk screening.

Groundwater Impacts and Diagnostic Geochemical Signals

Groundwater contamination associated with abandoned wells is documented across multiple basins, with studies reporting elevated methane concentrations, altered major ion chemistry, and detectable organic contaminants in proximity to legacy wells (Chapman *et al*., 2021). Chloride and bromide concentrations and ratios are repeatedly identified as effective indicators of formation water intrusion, particularly where wells intersect shallow aquifers (Umejuru & Ochulor, 2020; Raimi *et al*., 2022).

Stable isotopes of methane ($\delta^{13}C\text{-}CH_4$ and $\delta D\text{-}CH_4$) provide robust discrimination between biogenic and thermogenic sources, enabling differentiation between natural background

Publisher: SARC Publisher

conditions and well-related contamination (Raimi *et al*., 2021). BTEX compounds and trace metals are less frequently reported but serve as strong confirmatory indicators were detected (Raimi *et al*., 2022). Wellsite geochemical indicators consistently reveal subsurface leakage processes that are not detectable through surface inspections alone.

Synthesis of Wellsite Geochemical Indicators

Table 1 summarizes the primary geochemical indicators identified across the reviewed studies and their diagnostic relevance to environmental risk screening.

Table 1. Summary of wellsite geochemical indicators and associated risk relevance**.**

Indicator category	**Key parameters**	**Diagnostic value**	**Primary risk endpoint**
Gas-phase indicators	CH_4 concentration, $\delta^{13}C$-CH_4, δD-CH_4	Source attribution (thermogenic vs. microbial)	Atmospheric risk
Aqueous indicators	Dissolved CH_4, Cl^-, Br^-, Cl/Br ratio	Formation water intrusion, leakage pathways	Groundwater risk
Organic tracers	BTEX compounds	Hydrocarbon migration confirmation	Groundwater risk
Inorganic tracers	Trace metals	Subsurface interaction and transport	Groundwater risk

***Sources** : Raimi et al. (2022); Umejuru & Ochulor, (2020); Chapman et al. (2021); Raimi et al. (2021).*

Integration of Geochemical Indicators into Data-Driven Screening Frameworks

The reviewed literature reveals a clear imbalance between the availability of geochemical evidence and its incorporation into data-driven screening models. GIS-based and machine-learning approaches increasingly dominate national-scale assessments, particularly for identifying undocumented wells and spatial risk hotspots (Chapman *et al*., 2021; Okosun *et al*., 2025; DiGiulio, 2024). However, most models rely primarily on spatial proxies such as land use, drilling density, and geological attributes, with geochemical indicators used mainly for validation rather than as core predictive inputs.

Studies incorporating geochemical data demonstrate improved discrimination between high-risk and low-risk wells, especially when isotopic or groundwater chemistry data are available (Chapman *et al*., 2021). Machine-learning frameworks that include geochemical indicators show higher sensitivity to active leakage conditions, although such implementations remain limited in scope (Kang *et al*., 2023). Geochemical indicators are underutilized in data-driven screening despite strong evidence of their predictive value.

Comparative Performance of Screening Approaches

Table 2: compares environmental risk screening approaches identified in the reviewed literature.

Screening approach	**Spatial scale**	**Use of geochemistry**	**Key strengths**	**Key limitations**
Site-specific investigations	Local	Extensive	High diagnostic accuracy	Limited scalability
GIS-based screening	Regional-national	Limited	Broad coverage, low cost	Weak process resolution
ML-based screening	National	Minimal–moderate	Identification of undocumented wells	Underutilizes geochemical data
Integrated frameworks	Regional	Moderate-high	Improved risk discrimination	Data availability constraints

***Sources**: Okosun et al., (2025); DiGiulio (2024); Kang et al. (2023); Chapman et al. (2021).*

Conceptual Integration and Screening Outcomes

Figure 3.1 illustrates how legacy well characteristics drive integrity degradation, which produces measurable geochemical signals that can be integrated into data-driven screening systems. The reviewed studies collectively support this conceptual model, demonstrating that screening

Publisher: SARC Publisher

frameworks incorporating geochemical indicators are better positioned to identify active environmental risks rather than latent or inferred hazards.

Figure 3.2 shows the relative contribution of well subsets to total methane emissions, illustrating super-emitter dominance based on field measurements (Kessler, 2022).

Figure 3.3 outline Spatial overlap between high-risk screening outputs and observed geochemical anomalies near abandoned wells, highlighting improved prioritization when geochemical data are integrated (Chapman *et al*., 2021).

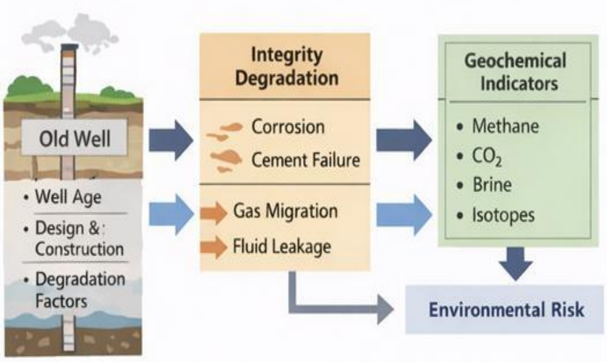

Figure 3.1: Legacy Well Integrity and Screening Framework

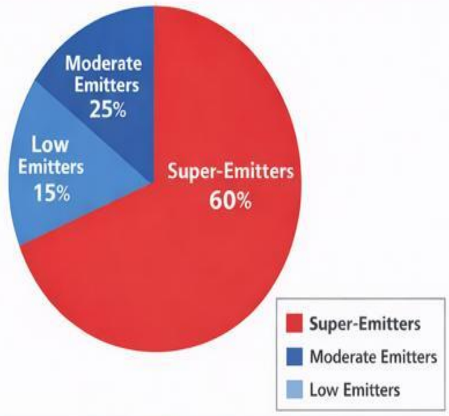

Figure 3.2: Methane Emission Contributions

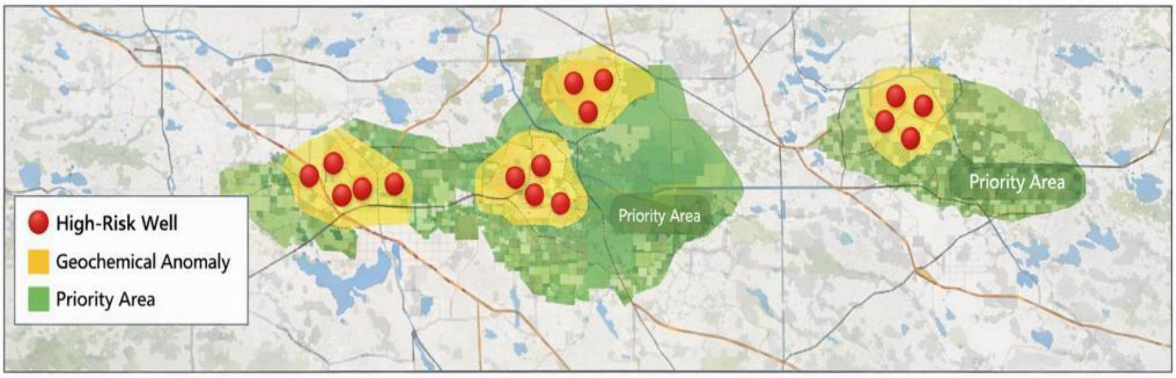

Figure 3.3: High-Risk Wells and Geochemical Anomalies

Key Findings and Implications

Collectively, the results demonstrate that (i) abandoned wells exhibit persistent integrity degradation and leakage pathways, (ii) wellsite geochemical indicators provide robust, process-based evidence of environmental risk, and (iii) current data-driven screening frameworks underutilize these indicators. Integrating geochemical data into screening models enhances risk discrimination, supports more accurate prioritization, and reduces uncertainty associated with incomplete well inventories. These findings directly support the need for integrated, geochemically informed data-driven environmental risk screening frameworks for abandoned U.S. oil and gas wells.

DISCUSSION

Advancing Screening-Level Understanding of Abandoned Well Risks

The findings synthesized in this review demonstrate that integrating wellsite geochemical indicators into data-driven environmental risk screening frameworks substantially improves identification and prioritization of high-risk abandoned oil and gas wells across the United States as evident in Table 2 and Figures 3.1-3.3 respectively. Across multiple basins and regulatory contexts, the reviewed literature consistently shows that environmental impacts from abandoned wells are highly heterogeneous, with a relatively small subset of wells responsible for disproportionate methane emissions and groundwater contamination risks. By linking

Publisher: SARC Publisher

legacy well construction attributes and geological controls to observable geochemical signals, the reviewed approaches advance beyond inventory-based or proximity-based screening methods toward mechanistically informed risk classification.

Implications for Methane Mitigation and Climate Policy

The skewed methane emission distributions identified in the reviewed studies have direct implications for greenhouse gas mitigation policy. Several investigations demonstrate that a minority of abandoned wells account for the majority of observed emissions, supporting targeted remediation rather than uniform plugging strategies in Figure 3.3. Incorporation of gas-phase geochemical indicators, including methane concentration and isotopic composition, improves the identification of active leakage pathways and reduces uncertainty in emissions attribution. These findings reinforce the value of geochemically informed screening frameworks for improving national methane inventories and supporting cost-effective emissions reduction programs administered at both state and federal levels.

Groundwater Protection and Environmental Justice Considerations

The reviewed literature also highlights persistent groundwater risks associated with abandoned wells, particularly in regions with shallow aquifers and extensive legacy infrastructure outlined in Table 1. Dissolved methane, major ion chemistry, and tracer-based indicators provide direct evidence of subsurface connectivity and contamination pathways that are not captured by surface-based screening alone. Importantly, spatial analyses reported in several studies reveal overlap between high-risk wells and rural or historically underserved communities, raising environmental justice concerns. Data-driven screening frameworks that integrate geochemical indicators offer a means of identifying these risks systematically, even where monitoring infrastructure and historical documentation are limited.

Value of Integrated Data Frameworks for Regulatory Prioritization

A central finding of this review is that geochemical indicators are most effective when embedded directly within integrated screening frameworks rather than applied solely as site-confirmation tools. Studies combining geochemical measurements with spatial analysis, well attributes, and machine-learning classification show improved risk differentiation and greater confidence in prioritization outcomes. For regulatory agencies managing large inventories of abandoned wells, such frameworks enable scalable prioritization of inspection and remediation activities, supporting tiered regulatory workflows that balance cost, urgency, and environmental benefit.

Uncertainty, Data Gaps, and Policy-Relevant Limitations

Despite methodological advances, the reviewed studies consistently identify limitations related to incomplete well records, inconsistent sampling protocols, and spatial bias in geochemical data availability. These uncertainties influence screening outcomes and must be explicitly considered in policy applications. However, the findings suggest that probabilistic, data-driven screening informed by geochemical indicators remains more informative than deterministic approaches based solely on well counts or proximity metrics.

Comparative Performance of Spatial Proxy-Based and Geochemistry-Informed Screening Models

Screening frameworks relying exclusively on spatial proxies demonstrate scalability but limited diagnostic power. These models perform well in identifying regional hotspots but fail to capture localized leakage driven by well-specific integrity failure. In contrast, studies incorporating even limited geochemical indicators such as methane concentrations, isotopic signatures, or groundwater chemistry demonstrate improved discrimination between inactive and actively leaking wells.

Comparative evidence across reviewed studies indicates that spatial-only models prioritize risk based on probability of occurrence, whereas geochemistry-informed models prioritize risk based on confirmed impact. This distinction is critical for remediation planning, as it shifts screening outputs from predictive likelihood toward evidence-based prioritization. Although geochemical integration remains limited, studies that include these signals report reduced uncertainty in classification and improved alignment with observed environmental outcomes. The lack of systematic comparison in existing literature highlights a methodological gap. Future screening frameworks would benefit from hybrid approaches that retain the scalability of spatial

Publisher: SARC Publisher

models while anchoring risk classification in geochemical evidence.

Implications for Future Policy and Remediation Practice

The reviewed findings support expanded use of standardized geochemical monitoring, improved inter-agency data integration, and routine incorporation of geochemical variables into national screening tools. Adaptive screening frameworks that update risk classifications as new geochemical data become available offer a pathway for improving remediation efficiency and accountability. Ultimately, integrating geochemical indicators into data-driven screening systems strengthens the scientific foundation for methane mitigation, groundwater protection, and equitable allocation of remediation resources.

CONCLUSION

This review shows that integrating wellsite geochemical indicators into data-driven screening frameworks significantly improves identification and prioritization of high-risk abandoned U.S. oil and gas wells. By linking legacy well characteristics with geochemical evidence, these approaches better capture heterogeneous methane and groundwater risks, support cost-effective remediation, and strengthen policy decisions for methane mitigation, groundwater protection, and equitable resource allocation.

REFERENCES

1. Aghdam, S. R., Ignatov, D., Voynilenko, V., & Manikin, A. G. "Innovative Integration of Cutting Analysis and LWD Data for Geosteering Optimization." *Abu Dhabi International Petroleum Exhibition and Conference*. SPE, (2025).
2. Ali, M., Zhu, P., Huolin, M., Jiang, R., Zhang, H., Ashraf, U., & Hussain, W. "Data-driven machine learning approaches for precise lithofacies identification in complex geological environments." *Geo-spatial Information Science* 28.4 (2025): 1722-1742.
3. Alsubaih, A. A. S., Sepehrnoori, K., Delshad, M., & Alsaedi, A. "A Comprehensive review of well integrity challenges and digital twin applications across conventional, unconventional, and storage wells." *Energies* 18.17 (2025): 4757.
4. Barker, J. F. “Migration of petroleum hydrocarbons in groundwater systems.” *Journal of Hydrology*, 56.1–2 (1982): 1–17.
5. Chapman, E. C., Capo, R. C., Stewart, B. W., Kirby, C. S., Hammack, R. W., Schroeder, K. T., & Edenborn, H. M. “Geochemical and isotopic evidence of fugitive methane contamination in groundwater from legacy wells.” *Environmental Science & Technology*, 55.6 (2021): 3492–3501.
6. DiGiulio, D. "Understanding, Evaluating, and Remediating Leakage from Abandoned Oil and Gas Wells During Geological Storage of Carbon Dioxide." *Center for Applied Environmental Science, Environmental Integrity Project, https://environmentalintegrity. org/wpcontent/uploads/2024/03/20240318_DiGiulio_report_Final. pdf* (2024).
7. Harrison, S. S. “Evaluation of abandoned oil and gas wells as contamination pathways.” *Ground Water Monitoring & Remediation*, 12.2 (1992): 70-80.
8. Jafarli, A. "Numerical and Analytical Modelling of Wellbore Integrity During CO_2 Injection." (2025).
9. Kang, M., *et al*. “Machine learning-based identification of undocumented orphaned wells.” *Environmental Science & Technology*, 57.4 (2023): 1734-1743.
10. Kessler, J. D., *et al*. “Long-term behavior of methane leakage from legacy wells.” *Nature Energy*, 7 (2022): 937-946.
11. Laaouar, Z. L., Kalbaza, Y. R., & Merzougui, I. “Well Integrity Management: Annulus Pressure, Causes and Solutions.” *Diss*. (2022).
12. Mohan, R., Hussein, A., Mawlod, A., Al Jaberi, B., Vesselinov, V., Salam, F. A., ... & El Yossef, B. "Data driven and ai methods to enhance collaborative well planning and drilling risk prediction." *Abu Dhabi International Petroleum Exhibition and Conference*. SPE, (2020).
13. Okosun, A., Ojeh-Oziegbe, O., Adubi, O., Ugoh, O., & Onafeso, O. "Impact of Planning and Experience in Well Abandonment-Lessons Learned from Complex Well Abandonment in Bonga Deepwater Field." *Offshore Technology Conference*. OTC, (2025).
14. Rashid, A., Ayub, M., Ullah, Z., Ali, A., Khattak, S. A., Ali, L., ... & Kaushik, P. "Geochemical modeling source provenance, public health exposure, and evaluating potentially harmful elements in groundwater: Statistical and human health risk assessment (HHRA)." *International Journal of Environmental Research and Public Health* 19.11 (2022): 6472.
15. Raimi, O. M., Ezekwe, C. I., & Bowale, A. "Statistical and multivariate techniques to trace

Publisher: SARC Publisher

the sources of ground water contaminants and affecting factors of groundwater pollution in an oil and gas producing wetland in rivers state, Nigeria." *medRxiv* (2021): 2021-12.

16. Raimi, M. O., Ezekwe, C. I., & Bowale, A. "Hydrogeochemical and multivariate statistical techniques to trace the sources of ground water contaminants and affecting factors of groundwater pollution in an oil and gas producing wetland in rivers state, Nigeria." *Open Journal of Yangtze Gas and Oil* 7 (2022): 166-202.
17. Senger, K., Betlem, P., Braathen, A., Olaussen, S., & Sand, G. "Longyearbyen CO2 lab project—from a vision of a CO2-neutral Svalbard to a geoscience data eldorado." *Arctic Science* 11 (2024): 1-26.
18. Shaheen, S. W., Wen, T., Herman, A., & Brantley, S. L. "Geochemical evidence of potential groundwater contamination with human health risks where hydraulic fracturing overlaps with extensive legacy hydrocarbon extraction." *Environmental science & technology* 56.14 (2022): 10010-10019.
19. Sharma, S. K., Rani, A., Bakhariya, H., Kumar, R., Tomar, D., & Ghosh, S. "The role of IoT in optimizing operations in the oil and gas sector: A review." *Transactions of the Indian National Academy of Engineering* 9.2 (2024): 293-312.
20. Milton-Thompson, O. “Developing a risk assessment model using fuzzy logic to assess groundwater contamination from hydraulic fracturing.” *University of Exeter (United Kingdom),* (2019).
21. Thomas, T. J., & Norman, B. J. "Quantifying Well Integrity Risk at Scale: A Repeatable & Data Driven Analysis of Well Integrity in Unconventional Gas Fields." *SPE Annual Technical Conference and Exhibition?*. SPE, (2023).
22. Umejuru, J. M., & Ochulor, O. J. "Integrated Risk Assessment Model for Well Integrity and Abandonment Operations." (2020).
23. Yang, J., Li, S., Zeng, J., Yang, Z., Li, X., He, T., ... & Kong, B. "Data-driven assessment of well stimulation in unconventional gas reservoirs." *Scientific Reports* 14.1 (2024): 31133.
24. Zhang, L., Wang, Y., Li, M. W., Yin, Q. Z., & Zhang, W. "Relative sorption coefficient: Key to tracing petroleum migration and other subsurface fluids." *Scientific Reports* 9.1 (2019): 16845.
25. Zhdaneev, O. V., Frolov, K. N., & Petrakov, Y. A. "Predictive systems for the well drilling operations." *Cyber-Physical Systems: Design and Application for Industry 4.0*. Cham: Springer International Publishing, 2021. 347-368.

Source of support: Nil; **Conflict of interest:** Nil.

Cite this article as:

Opara, S. U. “Integrating Wellsite Geochemical Indicators into Data-Driven Environmental Risk Screening for Abandoned U.S. Oil and Gas Wells” *Sarcouncil Journal of Engineering and Computer Sciences* 5.2 (2026): pp 1-11.

Publisher: SARC Publisher