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Review

The precautionary principle and fracking: a systematic review of environmental risk governance of hydraulic fracturing

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Abstract: In this systematic review, we synthesized research on the application of the precautionary principle to the complex environmental and ecological risks associated with hydraulic fracturing. Following PRISMA guidelines, the search was conducted across five major academic databases, resulting in the analysis of thirteen high-quality, peer-reviewed studies and authoritative reports. The findings indicated a significant and persistent gap between the formal legal adoption of the precautionary principle and its practical implementation within regulatory frameworks. Evidence showed that although some jurisdictions have incorporated the principle into legislative mandates, they often rely on traditional, hazard-based risk assessments in practice. In contrast, other regions exhibit varied applications of the principle, shaped by enforcement capacities, political contexts, and governance structures. Furthermore, the analysis suggests that the precautionary principle is frequently employed as a strategic tool in contentious public debates, serving more as a rhetorical device than as a binding legal standard. This instrumental use complicates its function within evidence-based policy. In conclusion, effective precautionary governance requires more than legislative commitments. Managing technologies characterized by significant environmental uncertainty requires developing robust institutional capacity, enhancing transparency in decision-making, and implementing proactive measures such as comprehensive, long-term baseline environmental monitoring. Transitioning from symbolic legal declarations to operationalized, science-informed oversight enables authorities to better mitigate the ecological risks of hydraulic fracturing and promote resilient environmental protection strategies.

Keywords: discursive framing; environmental governance; environmental risk; hydraulic fracturing; institutional capacity; precautionary principle; regulatory frameworks

1. Introduction

Governing technologies that carry significant environmental risks amid scientific uncertainty is a major challenge in contemporary environmental law and policy. Hydraulic fracturing, or fracking, exemplifies this issue. This method, which injects water, sand, and chemicals at high pressure into underground rock to extract oil and natural gas, has seen widespread adoption in the United States and Canada over the past two decades [1].

Proponents contend that fracking has unlocked substantial energy reserves, supported energy independence, and generated economic benefits through job creation and lower energy costs [2]. However, its rapid growth has led to growing evidence and public concern about significant environmental and ecological risks. These include groundwater and surface water contamination from chemical spills and methane emissions [3], induced seismic activity [4], air quality degradation from volatile organic compounds and particulates [5], and habitat fragmentation and ecosystem disruption.

To better understand the macro-trends and the evolution of the scientific discourse surrounding unconventional oil and gas, it is essential to consider foundational bibliometric analyses. For instance, Li among other authors demonstrates how scholarly attention and consensus regarding fracking risks have expanded historically [6]. This broad bibliometric baseline validates the structural necessity of a systematic review to synthesize the increasingly complex and fragmented scientific evidence available.

Scientific evidence regarding the scale, frequency, and long-term effects of these risks remains incomplete and contested [7], creating a policy dilemma: How should society regulate potentially hazardous activities when their dangers are not fully understood? In this context, the precautionary principle has become a central, though debated, framework for environmental decision-making. The 1992 Rio Declaration states: “where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation” [8].

The precautionary principle supports proactive measures amid scientific uncertainty, shifting the burden of proof to those pursuing potentially risky activities. It is included in international treaties, such as the Convention on Biological Diversity, and it guides environmental law in the European Union. However, its application is complex. Critics argue it is vague, may justify trade protectionism, and could hinder innovation by imposing restrictive regulations without sufficient evidence [7].

Furthermore, the application of the precautionary principle extends beyond unconventional hydrocarbons, becoming increasingly relevant for uncertain technoscientific risks associated with other emerging technologies. The literature emphasizes the urgency of anticipatory regulatory frameworks for developments such as nanotechnology and new drugs. For example, Pabón-Romero highlights the need to adapt the precautionary principle to these fields, particularly in developing contexts [9], while Saldívar Tanaka stresses that managing nanomaterial risks requires moving beyond traditional impact assessments, positioning the precautionary principle as a vital governance axis [10].

The application of precaution in these contexts must be understood alongside complementary environmental frameworks, particularly the 'polluter pays' principle [11]. While the polluter pays principle operates as an ex-post liability mechanism to internalize environmental costs once harm occurs, the precautionary principle functions as an ex-ante barrier against irreversible damage, creating a complex interaction within risk governance that this review seeks to explore.

Applying the precautionary principle requires balancing potential risks, the costs of precaution, and the socio-economic benefits of the activity. Its use in hydraulic fracturing is a complex case study, as the fracking debate extends beyond technical risk assessment to encompass political, economic, and

social conflicts. In jurisdictions such as France, Germany, and Quebec, the precautionary principle has justified moratoria or bans on fracking.

In other regions, including the United States and the United Kingdom, regulatory frameworks claim to incorporate precautionary elements such as baseline water monitoring, chemical disclosure, and adaptive management strategies [12]. However, environmental groups and some scientists argue that these measures are insufficiently precautionary and do not fully address cumulative or irreversible harm [13]. This divergence highlights fundamental questions about the interpretation and implementation of the precautionary principle across political and legal contexts.

Despite the prominence of the precautionary principle in the fracking debate, the literature remains fragmented and lacks systematic synthesis. Research spans law, political science, environmental science, and sociology, but these perspectives have not been integrated into a cohesive body of knowledge. There is a significant gap in understanding the full range of applications of the precautionary principle to fracking, from legal codification to its rhetorical use in public discourse.

While there is a notable lack of empirical studies evaluating whether these precautionary measures effectively reduce environmental or ecological risks, an analysis of the literature reveals a highly varied regulatory landscape. In France, Germany, and parts of Canada, moratoria and bans have been enacted as precautionary measures in response to scientific uncertainty and public opposition. In contrast, the United States and the United Kingdom have adopted risk-based regulatory frameworks that claim to include precautionary elements such as baseline monitoring and adaptive management.

Discursive dynamics are significant: Opponents of fracking invoke precaution to emphasize uncertainties, while proponents emphasize economic benefits and evidence-based decision-making. Institutional factors, such as regulatory authority and the roles of industry and civil society, are critical in determining whether precaution is applied. This review highlights major research gaps, particularly the lack of empirical evaluations of the effectiveness of precautionary measures. We conclude that applying the precautionary principle to fracking is neither uniform nor straightforward.

This situation reflects a complex interplay of scientific uncertainty, political dynamics, legal traditions, and stakeholder interests. Effective application requires legal mechanisms, robust public participation, transparent decision-making, and institutional capacity to monitor emerging risks. These findings have broader implications for governing other technologies with uncertain environmental impacts.

2. Materials and methods

2.1. Review protocol

A systematic literature search was conducted across five electronic databases chosen for their relevance to environmental policy, legal scholarship, energy studies, and risk governance. Scopus was selected for its broad interdisciplinary coverage and strong indexing of international environmental policy journals. Web of Science was included to ensure access to high-impact, peer-reviewed research and specialized conference proceedings in environmental sciences and policy. ScienceDirect was used for its extensive collection of full-text articles from Elsevier journals, which focus on energy and environmental regulation.

SpringerLink was added to access additional books and journal articles in environmental law and governance. Google Scholar was used as a supplementary source to identify grey literature, government reports, and studies not indexed in major subscription databases. For searches, we used a

combination of keywords and Boolean operators, tailored to each database's syntax. The core search string targeted the intersection of the precautionary principle, hydraulic fracturing, and environmental or ecological risk.

The base query was: ("precautionary principle" OR "precautionary approach") AND ("hydraulic fracturing" OR "fracking") AND ("environmental risk" OR "ecological damage" OR "environmental hazard" OR "environmental impact"). For Web of Science and Scopus, field codes limited the search to titles, abstracts, and keywords. For ScienceDirect and SpringerLink, the same terms were used in full-text searches. The search included documents published from 2016 onward, in English only, as specified in the protocol. The final search was completed in January 2026, and records were exported to reference management software for deduplication and screening.

2.2. Analytical dimensions

To synthesize findings from the included studies, we developed an analytical framework that categorizes the literature along two interrelated dimensions, reflecting the main ways the precautionary principle is applied in hydraulic fracturing. The first dimension considers the precautionary principle as a procedural and regulatory framework. It includes studies analyzing its legal codification, implementation through policy instruments such as moratoria, bans, or adaptive management requirements, and its role in risk assessment and decision-making within governance institutions.

The second dimension examines the precautionary principle in public discourse and political framing. It includes studies on how stakeholders, such as industry groups, environmental organizations, policymakers, and the media, invoke, contest, and use the principle to support or oppose regulatory outcomes. These dimensions are complementary and together provide a comprehensive view of the institutional and discursive applications of the precautionary principle in fracking.

2.3. Inclusion and exclusion criteria

Inclusion and exclusion criteria were defined in advance to ensure the selected studies were relevant and consistent. Studies were included if they explicitly examined the application of the precautionary principle or approach to hydraulic fracturing, focusing on environmental or ecological risks such as water contamination, air pollution, seismic activity, or habitat disruption. Eligible studies comprised empirical research (quantitative or qualitative), policy analyses, legal reviews, risk assessments, and systematic reviews. To prevent the double-counting of data or redundant analysis of identical primary sources, cross-references within included systematic reviews were carefully mapped, ensuring that only distinct analytical arguments or novel empirical data were extracted for our synthesis. These studies were included provided they were published in a peer-reviewed journal, book, or official report from a recognized governmental or intergovernmental body (e.g., EPA and EU Commission).

The full text of each study had to be available in English. Studies were excluded if they referenced only fracking or the precautionary principle without substantive analysis of their intersection, or if they were opinion pieces, editorials, news articles, blog posts, or conference abstracts without a full paper. Studies focusing solely on economic impacts, energy security, or public health without a direct connection to ecological or environmental risk were also excluded, as were technical studies (such as chemical analyses of fracking fluid) that did not address the precautionary principle or risk governance. Duplicate publications and studies for which the full text could not be obtained after reasonable effort were also excluded.

2.4. Selection process

The study selection process was systematic and documented, with two independent reviewers to minimize bias. All records from database searches were imported into a reference management tool, and duplicates were removed. Unique records were screened by title and abstract using predefined inclusion and exclusion criteria. Records not meeting the criteria were excluded, while those potentially eligible or of uncertain relevance proceeded to full-text review.

We sought to obtain the full text of all potentially eligible studies. If the full text was unavailable through our institutional library, we made at least two attempts to contact the authors or obtain the document via interlibrary loan. Studies for which the full text could not be obtained were documented as "not retrieved" and excluded from the final synthesis. Both reviewers independently assessed the full texts of retrieved studies for eligibility using a standardized form.

Disagreements between reviewers were resolved through discussion or, if needed, by consulting a third reviewer. Studies meeting all inclusion criteria were included in the final review. Those not meeting the criteria were excluded, with reasons documented. The PRISMA flow diagram (Figure 1) illustrates the selection process and the number of records at each stage.

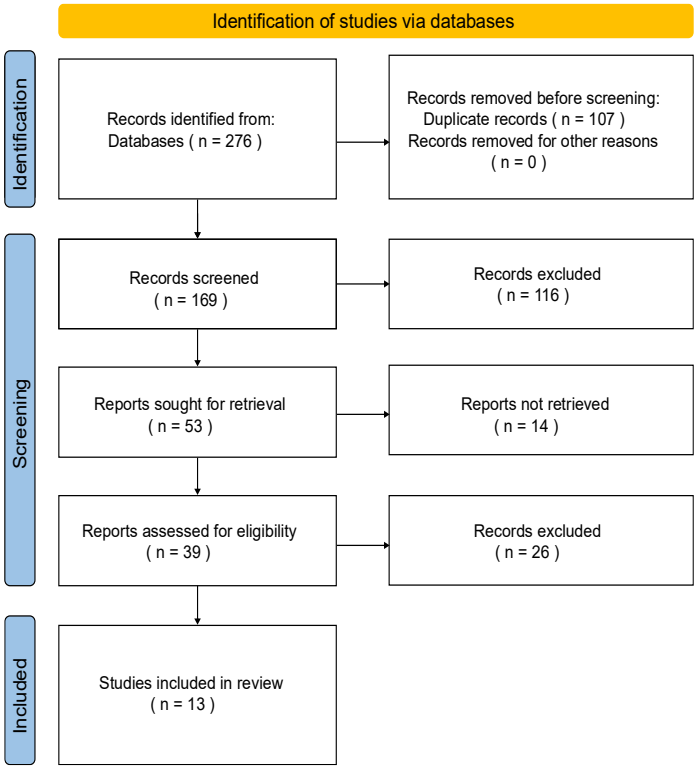


Figure 1. PRISMA 2020 flow diagram for systematic review of the application of the precautionary principle to hydraulic fracturing.

Figure 1 shows that the initial database search identified 276 records. After removing 107 duplicates, we screened 169 unique titles and abstracts. We excluded 116 records that did not meet the inclusion criteria, resulting in 53 reports for retrieval. Fourteen reports could not be retrieved in full, leaving 39 for full-text assessment. Of these, 26 were excluded: 12 lacked substantive analysis of the precautionary principle in relation to fracking, 8 focused only on economic or public health impacts

without an ecological perspective, and 6 were non-peer-reviewed opinion pieces.

We recognize several limitations in our selection process. Limiting the review to English-language publications may have introduced language bias and excluded relevant studies in French, German, or Spanish, especially from regions where fracking is actively debated. Focusing on peer-reviewed journals and official reports may have omitted valuable grey literature from non-governmental organizations or industry-funded research centers. Our search terms may have missed studies using alternative terminology for the precautionary principle or hydraulic fracturing, such as "tight gas development" or "shale gas extraction." Despite the use of two independent reviewers, some subjectivity in applying the inclusion and exclusion criteria, particularly regarding the threshold for "substantive analysis," is unavoidable. These limitations should be considered when interpreting our findings.

3. Results

3.1. Research trends

The distribution of publications over time indicates modest but steady scholarly interest at the intersection of the precautionary principle and hydraulic fracturing, as shown in Figure 2. The earliest studies appeared in 2016, with three publications; this figure was repeated in 2017 and again in 2023.

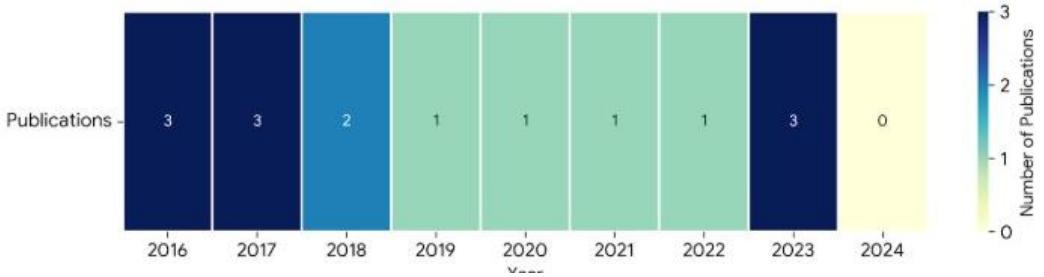


Figure 2. Distribution of publications over time (2016-2024).

This temporal distribution shows no clear trend. With only 13 studies published between 2016 and 2024, this remains a niche area rather than a rapidly growing field. We attribute this to the topic's specificity and contested nature. While the precautionary principle is well established in environmental law and hydraulic fracturing is widely studied, their explicit combination remains a narrow focus of research.

The peaks in 2016, 2017, and 2023 may correspond to regulatory events or high-profile controversies, such as fracking bans in parts of Europe or major scientific reports on associated risks. However, the consistently low number of studies per year indicates that the scholarly community has not engaged with this topic in a sustained or systematic way, highlighting opportunities for further research.

3.2. Overview of included studies

Table 1 presents the main characteristics of the included studies. The extracted information include study identification, study design, fracking context, application of the precautionary principle, key

environmental risks addressed, and main findings, where applicable. The included studies differ in geographic focus, regulatory context, and methodology. These variations are important for interpreting the review's findings and identifying potential sources of heterogeneity. The characteristics table provides a structured summary and serves as the basis for the subsequent narrative or quantitative synthesis.

Table 1. Characteristics of included studies.

Study Id	Study design	Context	Precautionary principle application	Key environmental risks addressed	Main findings
[15]	Document review of different sources on these activities and their consequences, as well as an analysis of legislation regarding the precaution and prevention principles	Mining and fracking environmental regulation in Latin America	The way in which these regulatory tools have been applied has no long-term effects on the prevention of other risks		Both institutional weakness and dependence on these activities in the region lead to a lack of comprehensive policies that guarantee long-term socio-environmental well-being.
[16]	Hypothetical-inductive methodology with analytical and explanatory procedures	The inclusion by the National Petroleum, Natural Gas and Biofuels Agency (ANP) of unconventional exploration blocks in the 12th Licitation Round in 2013, involving fracking operations and similar ventures with high social and environmental risks.	The research proposes adapting the Brazilian decision-making framework to the precautionary principle, with procedures better suited to mitigating serious or irreversible environmental risks.	High environmental risk; uncertainties subject to environmental and strategic study and evaluation; threats to sensitive environmental areas; and indigenous traditional use territories.	There is a need to reformulate the Brazilian decision-making model for high-risk energy projects. The institutional framework needs to evolve to adapt to the precautionary principle, expand access to information and transparency, and strengthen public participation.
[17]		Shale gas production in Brazil, with reference to the US shale boom and international examples (e.g., France and US states).	Applied in Brazil through public civil actions (PCA) that put unconventional resources on hold due to scientific uncertainties and possible irreversible negative impacts on human health and the environment.	Structural building failures, wastewater disposal, and fugitive emissions.	Some risks may be less of a concern when technical standards are rigorously followed; orderly risk management, supported by specific standards, may induce a precautionary principle ease, alongside additional geological studies.
[18]	The article theoretically and empirically describes a frame shift in Dutch decision-making on shale gas, analyzing frame contests and boundary work.	The Netherlands, where a policy controversy developed over hydraulic fracturing for shale gas, reframed its approach from 'business as usual' to a potential environmental risk.	The shift in meaning transformed the issue into a planning matter that requires greater caution.	Potential environmental problems and environmental impact associated with hydraulic fracturing for shale gas.	The technology of hydraulic fracturing for shale gas acted as a boundary object, creating a sphere of engagement for actors who negotiated a common but soft meaning. Discursive strategies of framing and boundary work enabled opponents to create uncertainty about economic benefits and environmental impact, leading to a shift in meaning from an economic issue to a planning issue requiring more precaution.
[19]	Legal and regulatory	Hydraulic fracturing	Recommends incorporating core	Environmental	Private litigants in the United States

Study Id	Study design	Context	Precautionary principle application	Key environmental risks addressed	Main findings
	analysis	(fracking) activities in Australia, particularly in Western Australia and South Australia, with comparative insights from the United States	elements of the precautionary principle and ecological sustainable development principles into regional management plans to strengthen protections for impacted communities	contamination of water	have failed to establish causation in fracking cases, highlighting the need for precautionary measures and baseline studies before large-scale fracking operations commence; regional management plans can help overcome causation problems and establish environmental harm.
[20]	Comparative analytical analysis of scientific policy regulation	fracking in the UK and the Netherlands	Both governments have adopted the precautionary principle into national law, but neither has directly invoked it in the field of fracking, relying instead on more conventional scientific understandings of risk.	water pollution and subsidence	While notionally subscribing to the precautionary principle, the UK and Dutch authorities have been reluctant to use it.
[21]	Discourse analysis and narrative network analysis of newspaper articles	Water-oil controversies, including fracking and oil spills, in Colombian media	Environmental narratives in Colombia emphasize the precautionary principle	Water impacts of oil extraction and transport, including fracking and oil spills	Environmental narratives in Colombia have transcended traditional political and ideological barriers by emphasizing issues of democracy, scientific uncertainty, and the precautionary principle, moving beyond unilateral economic and environmental debates
[22]	Tese de mestrado em Direito do Ambiente	Método de fraturação hidráulica (fracking) para exploração de gás de xisto no contexto energético europeu	Aplicação do princípio da precaução tendo em vista as incertezas e altas consequências ambientais envolvidas na atividade	Altas consequências ambientais envolvidas na atividade de fracking	Identificação da maneira mais eficiente de proteção ambiental desta atividade e verificação de como a regulação e a participação dos cidadãos podem contribuir para uma política de fracking mais justa, com base no princípio da precaução e na análise de casos na França, Espanha e Inglaterra
[23]	Comparative legal research methodology	Exploitation of shale gas in South Africa using hydraulic fracturing technology	The precautionary principle (mitigation) is used as a comparative theme in the assessment.	Environmental damage from shale gas development, including risks to the environment and contribution to climate change	The prevention, precautionary, and polluter-pays principles are already embedded in South Africa's environmental legal framework; an appropriate petroleum legal framework for shale gas development should provide for rigorous application of these principles in an integrated and complementary manner with close monitoring and enforcement; regulatory agency capacity must be enhanced for effective compliance monitoring and

Study Id	Study design	Context	Precautionary principle application	Key environmental risks addressed	Main findings
					enforcement.
[24]	argumentative discourse analysis	unconventional gas development (UGD) in Scotland, including shale gas	The government's evidence-based approach has drifted towards a precautionary approach that might lay the foundation for an extended moratorium.		Anti-UGD storylines appear more encompassing and have achieved greater resonance. The Scottish government established discursive dominance through a moratorium and cautious evidence-based approach, but its anti-Westminster storyline undermined this strategy. The interpretation of the evidence-based approach shifted from modestly reformed planning policy to scientific fact-finding with public consultation, and, arguably, to a precautionary approach.
[25]	Qualitative content analysis using constructed week sampling	Publication of a notice on proposed fracking regulations by the Minister of Forestry, Fisheries, and the Environment in South Africa	The precautionary principle lens (1992) was applied in the analysis of the proposed regulations for fracking in South Africa	Water resources and food security concerns resulting from the impact of fracking	The selected online media articles focused on resistance from the agriculture industry and civil society to the proposed regulations, revealed water resources and food security concerns, and findings centered on a cost-benefit analysis
[26]	The study uses an explanatory model grounded in the advocacy coalition framework to explore the characteristics of the German political debate on hydraulic fracturing.	Hydraulic fracturing has been practiced in Germany for decades, and several attempts to legalize and regulate new drilling methods ultimately led to the approval of a law that effectively banned the practice in 2016.	The uncertainty surrounding the use and effects of hydraulic fracturing prompts opponents to argue for the precautionary principle, which is typically invoked in German political discourse when the effects are highly uncertain.		Party competition takes place at the federal and state levels. The blurring of party competition boundaries typically leads to highly volatile advocacy coalitions.
[27]	Comparative contextual analysis using a science transplant model grounded in legal transplant theory, incorporating empirical analysis of public responses to parliamentary inquiries and consultation processes.	Regulation of hydraulic fracturing (fracking) as a transitional technology within multilevel legal systems.	In Australia, subnational-level perceptions of scientific uncertainties are integrated into regulatory decision-making, leading to divergent applications. In India, uncertainties are framed at the national level, resulting in uniform application.	Scientific uncertainty related to fracking, including climate change implications under the Paris Agreement and the basis of 'best available science'.	In Australia, subnational perceptions of scientific uncertainties related to fracking lead to divergent applications of the precautionary principle. In India, uncertainties are framed nationally despite subnational variations, resulting in uniform application. The science transplant model is transferable to other jurisdictions and transitional technologies such as carbon capture and storage.

3.3. The Precautionary principle as a procedural and regulatory framework for fracking

The application of the precautionary principle to hydraulic fracturing shows that legal adoption often does not lead to practical implementation. Studies reveal a gap between the principle's rhetorical use and its actual application within risk-based regulatory systems. In several jurisdictions, although the precautionary principle is part of national environmental law, governments have avoided applying it to fracking and have relied on conventional scientific risk assessments instead [20].

For example, in the United Kingdom and the Netherlands, both countries have adopted the precautionary principle in law but have not applied it directly to fracking regulation, choosing instead to use established risk management approaches [20]. This suggests that the precautionary principle, while symbolically important, can become ineffective when faced with the political and economic priorities of energy development. Its implementation as a procedural tool also depends heavily on the institutional structure of the regulating state.

A comparative study of India and Australia further illustrates this point, using a "science transplant model" to show how legal and institutional processes shape scientific uncertainty [27]. In Australia, regulatory authority is shared between national and subnational governments, enabling local perceptions of fracking-related uncertainties to influence regulatory decisions [18]. As a result, state governments can impose moratoria or strict conditions based on local concerns and risk assessments.

In contrast, India's centralized federal structure addresses uncertainties at the national level, leading to a uniform application of the precautionary principle that may not address local ecological or community-specific risks [27]. This comparison is crucial for our overall argument: It demonstrates that the precautionary principle is not a monolithic legal mandate, but a highly malleable framework whose practical impact is fundamentally dictated by the jurisdictional architecture, whether centralized or decentralized, that operationalizes it. This highlights that the procedural use of precaution depends more on how legal systems allocate authority and manage scientific information than on the principle.

This institutional context is further complicated when considering specific environmental liability architectures. For instance, as Muñoz Lancheros analyzed in the Latin American and Colombian context, the civil liability regime for high-risk activities like fracking operates under competing regulatory logic, where ex-post civil remediation requirements frequently conflict with the ex-ante preventive mandates of public law standards. This perspective is essential because it demonstrates that managing environmental damage depends not only on preventive administrative decisions but also on how the judicial sphere handles liability and remediation when precautionary measures fail [28].

Similarly, an analysis of mining and fracking regulation in Latin America finds that applying precautionary and prevention principles has not produced long-term risk prevention. The study attributes this to "institutional weakness and dependence on these activities in the region," indicating that precautionary language in legislation is ineffective without strong institutional capacity [15].

The Brazilian case illustrates this issue: When the National Petroleum, Natural Gas and Biofuels Agency (ANP) included unconventional exploration blocks in a 2013 licitation round, it led to social mobilization and legal challenges. The judiciary required environmental and strategic studies before proceeding. The study concludes that the institutional framework must improve in two areas: Adapting procedures to mitigate serious or irreversible environmental risks better and increasing access to information, transparency, and public participation [16]. Both studies revealed the same procedural challenge: Without institutional maturity and genuine public engagement, the precautionary principle remains ineffective.

Some studies offer a different perspective, suggesting that the precautionary principle can be

operationalized through structured and technical approaches. One study showed that standardization and strict adherence to technical standards can improve risk management and reduce the need for judicial moratoria. This suggests that risks like structural failures, wastewater disposal, and fugitive emissions are less significant when technical standards are rigorously applied, potentially enabling shale gas operations to resume in Brazil [17].

Table 2. Regulatory frameworks, application of the precautionary principle, and identified barriers across jurisdictions.

Study id	Regulatory framework analyzed	Jurisdiction	Legal or institutional barriers identified
[15]	Precautionary and prevention principles in mining and fracking environmental regulation	Latin America	Institutional weakness and dependence on these activities in the region
[16]	Brazilian decision-making model for new exploitation horizons for energy resources in unconventional reserves, including the role of the National Petroleum, Natural Gas and Biofuels Agency (ANP)	Brazil	Gaps/limitations in the Brazilian decision-making model when approving fracking operations with high social and environmental risks; lack of environmental and social security generated by the ANP; damaging public management without agreement of those at risk
[17]	Brazilian regulatory regime for shale gas, including the precautionary principle and ANP bid rounds	Brazil, with references to the United States and France	Public civil actions putting unconventional resources on hold due to the precautionary principle; scientific uncertainties and possible irreversible negative impacts; public opinion's rejection and legal restraints to additional exploitation
[19]	Risk-based regulatory regimes applied to hydraulic fracturing activities	Australia (Western Australia and South Australia), United States	Failure of private litigants in the United States to establish causation in fracking cases; lack of baseline studies
[20]	Precautionary principle in national law	United Kingdom and Netherlands	Reluctance of authorities to directly invoke the precautionary principle for fracking, despite its formal adoption into law
[22]	Princípio da precaução in European energy context	France, Spain, England	The study focuses on identifying the most efficient way of environmental protection and how regulation and citizen participation can contribute to a fairer fracking policy.
[23]	South Africa's petroleum legal framework for shale gas development	South Africa, United Kingdom, Canada	South Africa lacks an effective legal framework to regulate shale gas exploration and production using hydraulic fracturing; the capacity of regulatory agencies needs enhancement.
[25]	Proposed fracking regulations by the Minister of Forestry, Fisheries, and the Environment	South Africa	Resistance from the agriculture industry and civil society; water resources and food security concerns
[27]	Hydraulic fracturing regulation, with a focus on the application of the precautionary principle	India and Australia	In Australia, subnational-level perceptions of scientific uncertainties lead to divergent applications. In India, national-level framing results in uniform application despite subnational variations.

This view positions the precautionary principle as a driver for best practices and higher safety standards, rather than a barrier to development. However, studies challenge this technical approach by highlighting the problem of causation. Moreover, an analysis of fracking in Australia recommends incorporating core elements of the precautionary principle into regional management plans, citing the difficulties private litigants in the United States face in proving causation in contamination cases. The study showed that without precautionary measures, such as baseline studies before large-scale operations, it is nearly impossible to prove that environmental contamination is caused by fracking, thereby undermining the polluter-pays principle [19].

Integrating precaution into planning and monitoring offers a more proactive approach than relying on judicial intervention. Table 2 summarizes the various ways the precautionary principle has been applied across jurisdictions, providing a comparative overview of regulatory frameworks and the legal or institutional barriers identified in the studies.

Several studies discussed in this review are not included in Table 2 but offer valuable complementary insights. For example, a study on the Dutch fracking debate showed how reframing the issue from 'business as usual' to a potential environmental risk led to the precautionary principle becoming central, redefining the technology as a planning issue that requires greater caution [18].

Similarly, researchers conducting a comparative study of shale gas and hydraulic fracturing in South Africa used the prevention, precautionary, and polluter pays principles as key themes. The study revealed that an effective legal framework must rigorously apply these principles in an integrated way, with close monitoring and enforcement [23].

Another study entailed the legal aspects of shale gas fracking in Europe, analyzing cases in France, Spain, and England to identify the most effective approach to environmental protection based on the precautionary principle [22]. Collectively, these studies show that applying the precautionary principle is not only a legal matter but is also shaped by political discourse, institutional capacity, and public participation.

3.4. The precautionary principle as a discursive and political framing device

In addition to its procedural and regulatory roles, the precautionary principle serves as a key framing tool in public debates on hydraulic fracturing. It is used not only as a legal guideline but also as a rhetorical resource by stakeholders to shape meaning, legitimize positions, and influence policy. The studies reviewed show that invoking the precautionary principle is often a strategic move. Opponents of fracking use it to emphasize scientific uncertainty and call for a halt to development, while proponents focus on economic benefits and advocate for "evidence-based" decision-making.

In this section, we summarize findings from four studies that examined the precautionary principle's role in public discourse and political framing: the Scottish debate on unconventional gas [24], the German political debate on hydraulic fracturing [26], Dutch shifts in shale gas decision-making [18], and Colombian media coverage of water-oil controversies [21]. Table 3 provides a comparative analysis of discursive strategies, key storylines, and coalition dynamics in these cases. It highlights how the precautionary principle is invoked and its impact on public narratives and the political landscape.

Table 3. Comparative analysis of the precautionary principle in public discourse and political framing.

Study ID	Discursive strategy	Key storylines or frames	Role of the Precautionary Principle	Coalition dynamics
[24]	The Scottish government established a form of discursive dominance through a moratorium on all UGD and a cautious 'evidence-based approach', thereby minimizing electoral risks. Its anti-Westminster storyline, created in the run-up to the 2014 Scottish independence referendum, invoked Scottish resistance to the UK's pursuit of shale gas.	Anti-UGD storylines appear more encompassing and have achieved greater resonance. The government's 'evidence-based approach' is the preeminent storyline, which has 'drifted' from (1) a modestly reformed planning policy to (2) an exercise in scientific fact-finding combined with a public consultation, and (3) a precautionary approach that might lay the foundation for an extended moratorium.	The precautionary approach might lay the foundation for an extended moratorium, representing a 'drift' in the interpretation of the evidence-based approach.	Three discourse coalitions: anti-UGD coalitions, pro-UGD coalitions, and the Scottish government as a third discourse coalition. The anti-UGD storylines are more encompassing and resonant. The government's anti-Westminster storyline undermined its pragmatic strategy.
[26]	The study uses an explanatory model grounded in the advocacy coalition framework. Two key arguments are presented: (1) uncertainty about fracking's effects prompts opponents to argue for the precautionary principle, and (2) party competition takes place at both the federal and state levels.	Opponents invoke the precautionary principle due to high uncertainty. The blurring of party competition boundaries leads to highly volatile advocacy coalitions.	The precautionary principle is typically invoked in German political discourse when effects are highly uncertain, and fracking opponents used it to argue against the technology.	Party competition takes place at the federal and state levels. The blurring of party competition boundaries typically leads to highly volatile advocacy coalitions.
[18]	Discursive strategies of framing and boundary work enabled opponents to create uncertainty about economic benefits and environmental impact, leading to a shift in meaning. The technology of hydraulic fracturing acted as a boundary object.	The meaning of fracking shifted from 'business as usual' to a potential environmental risk, and from an economic issue to a planning issue needing more precaution.	The shift in meaning transformed the issue into one that requires greater caution.	Opponents created a sphere of engagement in which they negotiated a common yet soft meaning of the technology.
[21]	Discourse analysis and	Environmental narratives in	Environmental narratives in	Competing coalitions

Study ID	Discursive strategy	Key storylines or frames	Role of the Precautionary Principle	Coalition dynamics
	narrative network analysis revealed how debates are shifting away from an economic-environmental binary towards nuanced discussions surrounding complexity, uncertainty, and the role of expert knowledge.	Colombia emphasize issues of democracy, scientific uncertainty, and the precautionary principle, moving beyond unilateral economic and environmental debates.	Colombia have transcended traditional political and ideological barriers by emphasizing the precautionary principle.	were characterized, and the relative prominence of discourse frames and links among them was quantified and visualized using network analysis methods.

The Scottish case illustrates how the precautionary principle emerges in public discourse as a product of dynamic political processes rather than as a fixed legal doctrine. The study revealed that the Scottish government, by imposing a moratorium on all unconventional gas development (UGD) and adopting a cautious, evidence-based approach, established discursive dominance and minimized electoral risks [24]. The government positioned itself as a rational, scientific decision-maker.

However, the government also advanced an 'anti-Westminster storyline,' portraying the UK's shale gas policy as an external threat to Scottish sovereignty. This approach strengthened pro-independence credentials before the 2014 referendum but weakened the government's evidence-based stance by appealing to a sense of national resistance. The study revealed three phases in the evolution of the government's evidence-based approach: starting as a modest planning policy reform and progressing to scientific fact-finding.

Over time, many interpreted this as a precautionary approach that could justify an extended moratorium [24]. This shift shows how the precautionary principle can arise from policy processes, even without explicit reference, as growing uncertainty and political risks lead to a de facto precautionary stance. The German case, analyzed using the advocacy coalition framework, provides a complementary view of the political dynamics surrounding the precautionary principle.

The study showed that uncertainty about the impacts of hydraulic fracturing leads opponents to invoke the precautionary principle, a common theme in German environmental discourse [26]. This use of precaution is a political strategy within a complex system of multi-level party competition. Party competition occurs at both federal and state (Länder) levels, and blurred boundaries between these levels create volatile advocacy coalitions [26].

For example, a federal party may adopt a strong anti-fracking position to attract green voters, while its state-level counterpart in a shale-rich region may be more cautious. This volatility enables actors to use the precautionary principle tactically, depending on electoral considerations. The 2016 law effectively banning hydraulic fracturing in Germany reflects a prolonged political struggle, with the precautionary principle serving as its moral and intellectual foundation.

The Dutch case details how a frame shift can change the perceived meaning and risks of a technology. The study showed that hydraulic fracturing for shale gas in the Netherlands functioned as a "boundary object," flexible enough for varied interpretations yet consistent in identity across groups [18]. Initially, fracking was framed as 'business as usual,' a routine practice governed by standard regulations.

However, through framing and boundary work, fracking opponents redefined its meaning. They

questioned the economic benefits and emphasized potential environmental risks [18]. This re-framing shifted fracking from an economic issue to a planning issue requiring greater precaution. Here, the precautionary principle emerged as the logical outcome of effective discourse, rather than as a legal mandate.

The study demonstrated that this shift resulted from complex negotiation within a "sphere of engagement," where a shared but flexible understanding of the technology developed [18]. This highlights that the precautionary principle in public discourse often results from effective rhetorical strategy rather than solely from scientific uncertainty. The Colombian case further shows how the precautionary principle can be woven into broader narratives that cross political and ideological boundaries.

Moreover, the study analyzed Colombian media coverage of water-oil controversies, including fracking, from 2017 to 2021 [21]. Narrative network analysis revealed that environmental narratives have moved beyond the economic-environmental divide, now focusing on democracy, scientific uncertainty, and the precautionary principle [21]. This suggests the precautionary principle can unify diverse groups.

The network analysis offered a structural view of each coalition's narrative, enabling researchers to measure the prominence and connections of different discourse frames [21]. The anti-fracking coalition's narrative was more integrated, with the precautionary principle linking concerns about water contamination, indigenous rights, and democratic participation. This integration may have contributed to the success of environmental narratives in Colombia [21].

Collectively, these four studies showed the precautionary principle as a dynamic and contested discursive tool. Rather than a static legal rule, it serves as a framing device that can be strategically used, challenged, and reshaped through political debate. Its effectiveness depends on factors such as political culture, governance structures, actors' ability to redefine technology, and the strength of narrative coalitions.

These findings show that applying the precautionary principle in public discourse is closely tied to broader political and social dynamics. Examining different national contexts reveals that the principle serves less as a scientific guideline and more as a rhetorical tool shaping policy in complex, uncertain environments. This underscores the importance of considering socio-political factors in environmental governance.

4. Discussion

In this systematic review, we synthesize scholarly literature on the application of the precautionary principle to hydraulic fracturing and its associated environmental and ecological risks. The studies reviewed reveal critical insights that extend beyond fracking, informing broader issues of environmental governance amid scientific uncertainty. The evidence shows that the precautionary principle is not a uniform or self-executing legal standard; its meaning, application, and effectiveness depend on the institutional, political, and discursive contexts in which it is used.

A key finding is the gap between the formal adoption of the precautionary principle in law and its practical implementation in regulatory decisions. Studies of the United Kingdom, the Netherlands, and several Latin American countries show that while governments may include precautionary language in statutes, they often hesitate to apply it directly to fracking, relying instead on traditional risk assessments [20,15]. This challenges the assumption that legal adoption ensures protective action, indicating that the precautionary principle often serves as a symbolic gesture, easily overridden by

priorities such as energy security, economic growth, or industry influence.

Institutional weakness in Latin America, where reliance on resource extraction limits the implementation of comprehensive precautionary policies [15], shows that the principle's effectiveness depends on a state's enforcement capacity. Without strong institutions and political will, precautionary measures may remain ineffective. Comparisons between federal and centralized governance add another dimension: In Australia, subnational authority allows for varied, often more precautionary approaches, whereas India's centralized system yields uniform but potentially less context-sensitive outcomes [27]. These findings have important implications for the design of precautionary governance.

This suggests that the distribution of regulatory authority is a key factor in whether precautionary measures can be adapted to local ecological conditions and community needs. Federal systems with independent state or provincial powers may enable more tailored precautionary responses to local uncertainties and public concerns. In contrast, centralized systems may offer consistency but are less responsive to regional differences in risk and vulnerability. This insight is especially relevant for policymakers in multilevel jurisdictions managing emerging technologies with region-specific risks.

Studies on Scotland, Germany, the Netherlands, and Colombia [24,26,18,21] highlight the discursive and political aspects of the precautionary principle, prompting a broader understanding of its role in environmental governance. Rather than being only a legal or technical tool, the principle also serves as a rhetorical resource used strategically in political debates. The Scottish case, where an evidence-based approach led to a de facto precautionary stance without formally invoking the principle [24], shows how discourse can drive precautionary outcomes even without legal mandates.

This suggests that factors such as political legitimacy, public support for anti-fracking narratives, and electoral considerations can be as influential as scientific risk assessments in shaping precautionary policy. In Germany, the principle is often used in multi-level party competition, serving political strategies as much as environmental goals [26]. These findings challenge the view of the precautionary principle as a neutral rule, instead highlighting its inherently political nature, shaped by negotiations among competing advocacy groups.

These findings have significant practical implications for policymakers and regulators. Effective application of the precautionary principle to fracking requires more than legal adoption; it also needs institutional capacity for monitoring, enforcement, and adaptive management. Proactive measures such as comprehensive baseline studies before operations [19], public participation in decision-making [16], and consistent technical standards [17] can operationalize precaution without relying on blanket bans or moratoria.

These procedural measures help address the challenge of proving causation in litigation, as seen in the United States, where communities have struggled to link environmental contamination to fracking [19]. By requiring baseline environmental data and transparent monitoring, regulators can establish evidence that supports enforcement of the polluter-pays principle. The findings also highlight the need for transparent, inclusive decision-making that incorporates diverse stakeholder views and builds public trust, as shown in Colombia, where the precautionary principle was linked to broader themes of democratic accountability and scientific uncertainty [21].

However, several limitations affect the generalizability and completeness of this review. Limiting the review to English-language publications is a significant constraint, as the precautionary principle is widely debated in non-English-speaking jurisdictions. For example, studies from France, Germany, and Spain were included only if published in English, potentially excluding valuable analyses in other languages.

Excluding grey literature, such as reports from NGOs, industry groups, or government advisory bodies, may have omitted practical perspectives on how the precautionary principle is interpreted outside academia. The search strategy, though comprehensive, may also have missed studies using alternative terms for the precautionary principle or hydraulic fracturing, such as "tight gas development," "shale gas extraction," or "foresight principle," potentially omitting certain research traditions or policy contexts.

Although we assessed the quality of included studies, evaluating qualitative policy analyses and legal reviews is inherently subjective so that some interpretive bias may remain. These limitations should be considered when evaluating the robustness and transferability of our findings. In this review, we identify significant research gaps, particularly the lack of empirical studies that systematically assess whether precautionary measures reduce environmental or ecological risks from fracking.

While researchers have examined the political and legal aspects of moratoria, bans, and regulatory frameworks, there is a need for research that entails rigorous causal inference to determine whether these interventions lead to measurable improvements in water quality, air quality, seismic stability, or ecosystem integrity. In future studies, researchers should compare jurisdictions with precautionary approaches to those using conventional risk-based frameworks while accounting for differences in geology, industrial activity, and enforcement capacity.

The review also highlights the need for comparative, longitudinal studies tracking how the precautionary principle is interpreted and applied throughout the policy cycle. The Scottish case [24] shows that the meaning and use of precaution change with political circumstances, new scientific evidence, and public opinion. Researchers should examine how precautionary approaches are sustained, modified, or abandoned over time. Other understudied areas include the role of judicial review, public participation in decision-making, and the influence of international legal frameworks on domestic policy, particularly in developing countries where institutional capacity constraints and competing development priorities create unique challenges.

5. Conclusions

In this systematic review, we consolidate fragmented evidence on the application of the precautionary principle to hydraulic fracturing and its associated environmental and ecological risks. The findings reveal significant variation, ongoing debate, and institutional differences. The precautionary principle is not a uniform legal standard or a simple decision-making rule. Its interpretation and implementation depend on scientific uncertainty, political context, legal traditions, and stakeholder interests in each jurisdiction.

A key finding is that formal legal codification of the precautionary principle does not ensure its practical application. For example, authorities in the United Kingdom and the Netherlands have been reluctant to apply it to fracking. This challenges the assumption that legal norms directly translate into regulatory outcomes. These insights are important for policymakers and regulators managing technologies with uncertain environmental risks.

Our findings indicate that effective precautionary governance requires more than symbolic legal commitments; it depends on strong institutional capacity for monitoring and enforcement, transparent decision-making with public participation, and proactive measures such as baseline studies and adaptive management. The analysis also shows that the distribution of regulatory authority, whether federal or centralized, can either support or limit the adaptation of precautionary measures to local ecological and community needs.

These insights are also relevant for the governance of other emerging technologies, such as carbon capture and storage or geoengineering, where scientific uncertainty and the risk of irreversible harm challenge traditional regulatory approaches. Researchers should focus on empirical evaluations of how precautionary measures reduce environmental risks, as it is important to assess whether jurisdictions with moratoria or strict regulations have achieved measurable improvements in water quality, air quality, or ecosystem integrity.

Long-term studies on how precautionary approaches change with political shifts and new scientific findings could offer important insights. Exploring how the precautionary principle shapes public narratives and political coalitions is another promising area for interdisciplinary research that connects legal analysis, political science, and science and technology studies. Addressing these research gaps will help build a stronger evidence base for governing risky technologies amid significant environmental uncertainty.

Use of AI tools declaration

The author used Artificial Intelligence (AI) tools, specifically Gemini and Grammarly, only to check and improve grammar, syntax, style, and orthography. The author reviewed and edited the article and takes full responsibility for its final content.

Conflict of interest

The author declares no conflicts of interest, financial or otherwise, that could have influenced the work reported in this article.

References

1. Vengosh A, Jackson RB, Warner N, et al. (2014) A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environ Sci Technol* 48: 8334–8348. https://doi.org/10.1021/es405118y
2. Gilje E, Ready R, Roussanov N (2016) *Fracking, drilling, and asset pricing: Estimating the economic benefits of the shale revolution*. National Bureau of Economic Research. https://www.aeaweb.org/conference/2016/retrieve.php?pdfid=20835&tk=3tYTTn52
3. Osborn SG, Vengosh A, Warner NR, et al. (2011) Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proc Natl Acad Sci* 108: 8172–8176. https://doi.org/10.1073/pnas.1100682108
4. Showstack R (2012) Induced seismicity from fracking and carbon storage is focus of study and hearing. *Eos Trans Am Geophys Union* 93: 251–251. https://doi.org/10.1029/2012EO270003
5. Wilde S E, Hopkins J R, Lewis A C, et al. (2023) The air quality impacts of pre-operational hydraulic fracturing activities. *Sci Total Environ* 858: 159702. https://doi.org/10.1016/j.scitotenv.2022.159702
6. Li J, Jovanovic A, Klimek P, et al. (2015) Bibliometric analysis of fracking scientific literature. *Scientometrics* 105: 1273–1284. https://doi.org/10.1007/s11192-015-1739-7
7. Gardiner S (2006) A core precautionary principle. *J Polit Philos* 14: 33–60. https://doi.org/10.1111/j.1467-9760.2006.00237.x

8. Triana N, Khashogi L R, Turistiati A T, et al. (2023) Application of the precautionary principle in judge's legal considerations for pollution cases in Islamic law perspectives. *Al-'Adalah* 20: 61–90. https://doi.org/10.24042/adalah.v20i1.16660
9. Pabón-Romero LN (2026) El principio de precaución en materia de nanotecnología y de nuevos medicamentos en Colombia. *Chornancap Revista Jurídica* 4. https://doi.org/10.61542/rjch.229
10. Saldívar Tanaka L (2024) El principio de precaución ante los posibles riesgos de la nanotecnología y sus derivados. *Mundo Nano Revista Interdisciplinaria en Nanociencias y Nanotecnología* 17: e69762. https://doi.org/10.22201/ceiich.24485691e.2024.33.69762
11. Aczel MR (2020) Public opposition to shale gas extraction in Algeria: Potential application of France's 'Duty of Care Act'. *Extr Ind Soc* 7: 1360–1368. https://doi.org/10.1016/j.exis.2020.09.003
12. Brady WJ, Crannell JP (2012) Hydraulic fracturing regulation in the United States: The laissez-faire approach of the federal government and varying state regulations. *Vermont J Environ Law* 14: 39–70. https://doi.org/10.2307/vermjenvilaw.14.1.39
13. Kinchy A (2017) Citizen science and democracy: Participatory water monitoring in the Marcellus shale fracking boom. *Sci Cult* 26: 88–110. https://doi.org/10.1080/09505431.2016.1223113
14. Page MJ, McKenzie JE, Bossuyt PM, et al. (2021) The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* 372: n71. https://doi.org/10.26633/RPSP.2022.112
15. Azamar Alonso A (2021) Implications of the precautionary and preventive principles for the right to a healthy environment in Latin America. *Econ Soc* 26: 34–47. http://dx.doi.org/10.15359/eys.26-59.2
16. Melo Marques Mourão M (2025) *Constitucionalismo petrolífero brasileiro: o regime jurídico do petróleo no Brasil*. Editora Dialética.
17. Liaw C, Brito T L F, Costa H K M, et al. (2022) Standardization as key to precautionary principle handling: Risk mitigation for shale gas production in Brazil. *Res Humanit Soc Sci* 14: 10–20. https://doi.org/10.7176/RHSS/12-2-02
18. Metze T (2017) Fracking the debate: Frame shifts and boundary work in Dutch decision making on shale gas. *J Environ Policy Plann* 19: 35–52. https://doi.org/10.1080/1523908X.2014.941462
19. Murray T, Andre DE, Prasad K (2016) Holding fracking operations to account for environmental contamination in risk-based regulatory regimes: Insights from the United States. *Environ Plann Law J* 33: 222–236. https://ro.ecu.edu.au/ecuworkspost2013/2661/
20. Patterson A, McLean C (2018) The regulation of risk: the case of fracking in the UK and the Netherlands. *Sci Public Policy* 45: 45–52. https://doi.org/10.1093/scipol/scx036
21. Rinaldi PN (2023) Water science in the public sphere: A narrative network analysis of fracking and oil spills in Colombian media. *Extr Ind Soc* 13: 101215. https://doi.org/10.1016/j.exis.2023.101215
22. Raimi D (2017) *The fracking debate: The risks, benefits, and uncertainties of the shale revolution*. Columbia University Press.
23. Orthofer CL, Huppmann D, Krey V (2019) South Africa after Paris—fracking its way to the NDCs?. *Front Energy Res* 7: 20. https://doi.org/10.3389/fenrg.2019.00020
24. Stephan HR (2017) The discursive politics of unconventional gas in Scotland: Drifting towards precaution?. *Energy Res Soc Sci* 23: 159–168. https://doi.org/10.1016/j.erss.2016.09.006

25. Tarisayi KS (2023) Seeing through the lens of precaution: An analysis of South African online media coverage of fracking regulations. *Alternation* 30: 133–153. https://doi.org/10.29086/2519-5476/2023/v30n1a6
26. Tosun J, Lang A (2016) The politics of hydraulic fracturing in Germany: Party competition at different levels of government. *Policy Debates on Hydraulic Fracturing: Comparing Coalition Politics in North America and Europe*: 177–200. https://doi.org/10.1057/978-1-137-59574-4_7
27. Yadav SK (2026) *Regulating hydraulic fracturing as a transitional technology in India and Australia: A comparative contextual approach to the precautionary principle*. University of Surrey.
28. Muñoz Lancheros CA (2022) Régimen de responsabilidad civil ambiental por actividades de fracking en Colombia. *Anuario de Derecho Privado* 4: 1–48. http://dx.doi.org/10.15425/2022.656



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