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Scientific evidence and public policy: a systematic review of barriers and enablers for evidence-informed decision-making

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Introduction: This systematic review synthesizes empirical research on the integration of scientific evidence into public policy formulation across diverse governance contexts. While global support for evidence-informed policymaking is increasing, persistent institutional barriers, political resistance, and limited science-policy interaction continue to constrain the effective use of research in decision-making.

Methods: Guided by the PRISMA 2020 framework, the review identified 119 peer-reviewed articles from Scopus and Web of Science databases. Eligible studies included empirical analyses on the mobilization, translation, and institutionalization of scientific knowledge in policy processes. A thematic synthesis was conducted, classifying studies into six categories: science-policy participation, institutional capacity, political dynamics, trust and legitimacy, political support, and international collaboration.

Results: Major barriers included fragmented advisory systems, limited data infrastructures, and weak communication between researchers and policymakers. Key enabling factors comprised dedicated scientific advisory bodies, knowledge brokerage mechanisms, international cooperation, and co-production of knowledge. Most studies focused on the health policy sector, with a geographic concentration in high-income countries such as the United Kingdom, the United States, and Canada.

Discussion: Findings highlight the urgent need to institutionalize scientific evidence in policy formulation through formal governance frameworks, sustained stakeholder engagement, and robust science-policy interfaces. Advancing transparent, inclusive, and evidence-based governance will require cross-sector collaboration, epistemic trust, and political leadership committed to bridging the gap between research and public policy.

KEYWORDS

evidence-informed policymaking, scientific knowledge transfer, policy formulation, institutional barriers, knowledge brokerage, public governance, political will, international networks

1 Introduction

In a global context shaped by intersecting crises such as climate change, public health emergencies, growing inequalities, and the erosion of public trust in institutions policymaking increasingly demands robust, reliable, and context-sensitive evidence. Scientific evidence plays a critical role in public policy formulation by providing a foundation for informed decision-making. The integration of scientific data into political processes can enhance both the effectiveness and efficiency of policies, particularly in domains such as public health, safety, and environmental regulation. Nevertheless, the application of scientific evidence in policymaking is inherently complex, requiring careful consideration of various factors, including the hierarchies of evidence, stakeholder engagement, and the balance between scientific rigor and practical applicability.

Scientific evidence contributes to the effective identification and resolution of public problems, as illustrated by the formulation of child road safety policies in Panama, which involved collaboration between scientists, civil society, and policymakers (Núñez-Samudio and Landires, 2020). Ensuring that policies are grounded in reliable data is essential, as demonstrated by the use of national basic indicators in policy decisions at the state level in the United States (Moseley et al., 2013).

Despite its importance, a persistent gap often exists between the production of scientific evidence and its application in policy processes, prompting the need for frameworks that can bridge this divide (Straf et al., 2012). Moreover, normative objectives may influence the hierarchy of evidence that is considered relevant, as seen in the regulation of chemicals and pharmaceuticals, where different evidentiary standards are applied depending on the perceived stakes involved (Luján, 2023). The imperative to adopt evidence-based policies can, at times, lead to a paralysis in political processes, underscoring the importance of finding an appropriate balance between evidence-informed and value-driven approaches (Willemsen, 2018).

Several practical examples highlight the potential of evidence-informed policymaking. The Netherlands exemplifies the successful implementation of public health policies grounded in scientific evidence, demonstrating how evidence can support effective political decision-making (Willemsen, 2018). Furthermore, the use of randomized controlled trials in economic policy, recognized by the 2019 Nobel Prize in Economics, emphasizes the significance of rigorous scientific methodologies in evaluating public policies (Luján, 2023).

While scientific evidence is a fundamental component of policymaking, it is not the sole determinant. Policymakers must also account for ethical, social, and economic factors, and remain aware of the limitations inherent in scientific data. The integration of diverse perspectives and methodological approaches can ultimately strengthen both the robustness and societal acceptance of public policy decisions.

Beyond normative assertions, empirical research highlights a range of institutional, political, and cultural conditions that either facilitate or hinder the systematic integration of scientific knowledge into policymaking. Studies have identified how the presence of dedicated advisory bodies, robust data infrastructures, and structured procedures can foster an environment conducive to evidence-informed decision-making (Makkar et al., 2018; Nutley et al., 2002).

Conversely, the absence of such institutional mechanisms especially in settings with limited resources can severely restrict the use of relevant and timely scientific information (El-Jardali et al., 2015; Orem et al., 2014).

Political ideologies and strategic interests often mediate the reception of evidence. In some cases, scientific data are selectively interpreted or marginalized when incongruent with prevailing political agendas, thereby undermining the role of evidence as a neutral input (Bozeman and Bozeman, 2022; Bromme et al., 2014). These patterns underscore the importance of political will and epistemic trust in ensuring the legitimacy and uptake of scientific contributions to policy.

In parallel, engagement in international networks and participation in transnational knowledge-sharing platforms have proven valuable in enhancing domestic capacities and aligning national strategies with global evidence standards. Such collaboration not only facilitates methodological innovation but also nurtures a culture of accountability and mutual learning among policymakers and researchers (Lester et al., 2020; Van Kammen et al., 2006).

In addition to these structural and contextual considerations, recent scholarship has emphasized the relevance of science-policy interfaces and knowledge brokerage as crucial mechanisms to bridge the gap between research production and its practical application. Rather than advocating for specific outcomes, knowledge brokers operate at the intersection of scientific communities and policymakers, facilitating mutual understanding, framing policy-relevant questions, and clarifying uncertainties to inform deliberation and action. This function is inherently dialogical, requiring both epistemic humility and political acuity to navigate the dynamic tension between evidence provision and normative decision-making processes (Gluckman et al., 2022).

Institutional frameworks that support brokerage such as chief science advisors, science advisory councils, or dedicated boundary organizations have emerged as effective structures to operationalize these functions. These bodies not only synthesize evidence across disciplines but also act as mediators to support trust, legitimacy, and timely access to decision-making processes (Gluckman et al., 2022). For example, Gluckman (2014) in 2014 argued that science advisors should act as “honest brokers” rather than policy advocates, maintaining independence while ensuring evidence-informed options are made available to political authorities.

Moreover, successful integration of scientific advice into governance systems depends on sustained engagement, clear communication strategies, and institutional independence to protect the integrity of the advice process. Cairney and Oliver (2020) further highlight that impactful academic engagement in policymaking is often contingent on relational strategies and iterative interactions, rather than the mere dissemination of evidence. The European Commission's recent development of an evaluation framework for national science-for-policy ecosystems also reinforces the importance of structural and cultural factors such as inclusivity, reflexivity, and access to policy windows in determining the functionality and credibility of advisory systems (Gluckman, 2014).

Against this backdrop, the present study undertakes a comprehensive synthesis of the academic and applied literature to explore the multiple factors that shape the incorporation of scientific evidence into public policy formulation. By systematically reviewing a wide array of international sources, this work seeks to identify the

most commonly reported barriers and enabling conditions that affect evidence use in the policy process. Particular attention is paid to how institutional architectures, political cultures, and contextual variables influence the uptake, adaptation, or rejection of scientific knowledge within governmental decision-making. In doing so, the study contributes to a deeper understanding of the mechanisms through which research informs or fails to inform public policies, and highlights pathways to foster more responsive, inclusive, and knowledge-based governance.

2 Materials and methods

A systematic review approach was employed to explore how scientific evidence is incorporated into public policymaking. The review process adhered to the PRISMA 2020 guidelines (Page et al., 2021), ensuring methodological rigor and transparency during the identification, screening, eligibility assessment, and inclusion of studies. Although the protocol was not prospectively registered, it was developed prior to data analysis and it's publicly available on Mendeley Data (DOI: <https://doi.org/10.17632/b73wm9852j.2>). This allows readers to assess the review process and analytical decisions in a transparent manner.

2.1 Adapted PICO framework

Population (P): Public sector institutions, government agencies, policy decision-makers, and science-policy interfaces at national or international levels.

Intervention (I): Use or promotion of scientific evidence in the formulation of public policy.

Comparison (C): Not applicable (no comparison group required; the study focuses on identifying conditions, barriers, and enablers).

Outcome (O): Identification of barriers, facilitators, and knowledge transfer mechanisms affecting the integration of scientific evidence into policymaking.

Type of Study (TS): Empirical studies (qualitative, quantitative, or mixed-methods), case studies, and policy reports with analytic frameworks published in peer-reviewed academic or institutional sources.

2.2 Inclusion criteria

Studies were eligible for inclusion if they presented empirical evidence whether qualitative, quantitative, or mixed-methods focused on the use of scientific evidence in public policy formulation. Research conducted in national, regional, or international public governance contexts was considered, provided it addressed how scientific findings were mobilized, translated, or institutionalized in policymaking. The review included studies that explicitly identified barriers, enabling factors, or knowledge transfer strategies between the scientific and policy spheres. Moreover, eligible publications were those that engaged with institutional, cultural, or political conditions influencing the science-policy relationship. Only peer-reviewed academic articles, official policy documents, or research reports produced by recognized organizations were included. "Recognized organizations" was considered as those

affiliated with national or international government agencies, multilateral institutions, or academic centers known for policy-relevant research.

The review was limited to sources published between 1990 and 2025 to ensure both historical perspective and contemporary relevance.

2.3 Exclusion criteria

Documents were excluded if they were theoretical essays, editorial commentaries, or conceptual frameworks that did not incorporate empirical analysis or application. Studies focused solely on clinical decision-making or biomedical evidence without reference to broader policy processes were also excluded. Additionally, literature addressing knowledge production or evidence dissemination within academic communities without connection to public policy formulation was not considered. "Public policy formulation" was defined as the process that includes agenda setting, evidence integration, consultation, and drafting of official documents leading to policy decisions, excluding implementation and evaluation stages.

Also were excluded, publications that were inaccessible in full text or lacked sufficient methodological transparency were removed from consideration. Duplicate entries and early-stage presentations of research that were later published in more complete formats were also excluded to avoid redundancy and preserve analytical rigor.

2.4 Search strategy and data sources

Systematic searches were conducted using two major bibliographic databases: Scopus and Web of Science. Search queries were formulated to retrieve literature situated at the intersection of public policy processes and the use of scientific evidence (Table 1). The search strategy incorporated a wide range of terms related to evidence-based decision-making, knowledge translation, research utilization, and science-policy interfaces. Filters were applied to include only peer-reviewed journal articles. The complete search strategies for each database were documented to ensure reproducibility.

Scopus, Web of Science were selected due to their interdisciplinary coverage and accessibility to both academic and policy-related literature. Additional other databases were considered but not included due to indexing overlap and limited relevance for capturing grey literature on global policy mechanisms. Databases such as PubMed and Embase, although highly reputable, were excluded as they are primarily focused on biomedical literature and were considered less suitable for identifying studies related to evidence-informed policymaking across diverse sectors.

2.5 Screening and eligibility criteria

The selection process involved multiple stages. After duplicate records were removed and initial irrelevant items were excluded using built-in filtering tools, titles and abstracts of the remaining studies were manually screened based on predefined inclusion criteria. Full-text reports were subsequently retrieved and assessed for eligibility. Studies were included if they explicitly addressed evidence-informed policymaking processes, either through empirical analysis, policy evaluation, or conceptual development.

TABLE 1 Queries in search strategy for each database used.

Database	Formulation	Filters
Scopus	TITLE-ABS-KEY ("public policy" OR "policy making" OR "policy process" OR "policy development" OR "policy formulation" OR "policy implementation" OR "policy decision-making" OR "policy planning" OR "policy adoption" OR governance OR "government policy" OR "public administration" OR "government decision-making" OR "public sector management" OR "political decision-making" OR "policy design" OR "evidence-informed policy-making" OR "evidence-based policy-making") AND TITLE-ABS-KEY ("evidence-based" OR "evidence-informed" OR "evidence-based decision-making" OR "evidence use" OR "research evidence" OR "scientific evidence" OR "knowledge transfer" OR "knowledge translation" OR "knowledge mobilization" OR "knowledge exchange" OR "knowledge uptake" OR "research-to-policy" OR "science-policy interface" OR "science-policy relationship" OR "evidence-policy interface" OR "research utilization" OR "research impact" OR "science communication" OR "knowledge dissemination" OR "evidence synthesis" OR "evidence integration")	AND [LIMIT-TO (DOCTYPE, "ar")]
WoS	TS = ("public policy" OR "policy making" OR "policy process" OR "policy development" OR "policy formulation" OR "policy implementation" OR "policy decision-making" OR "policy planning" OR "policy adoption" OR governance OR "government policy" OR "public administration" OR "government decision-making" OR "public sector management" OR "political decision-making" OR "policy design" OR "evidence-informed policy-making" OR "evidence-based policy-making") AND TS = ("evidence-based" OR "evidence-informed" OR "evidence-based decision-making" OR "evidence use" OR "research evidence" OR "scientific evidence" OR "knowledge transfer" OR "knowledge translation" OR "knowledge mobilization" OR "knowledge exchange" OR "knowledge uptake" OR "research-to-policy" OR "science-policy interface" OR "science-policy relationship" OR "evidence-policy interface" OR "research utilization" OR "research impact" OR "science communication" OR "knowledge dissemination" OR "evidence synthesis" OR "evidence integration")	Refined by: document types: article

Screening was conducted independently by two reviewers (ACG & ISG) at both the title/abstract and full-text levels. Discrepancies were resolved through discussion, and when necessary, a third reviewer (MS) was consulted. Studies were excluded if full-text access was unavailable, if methodological detail was insufficient, or if there was a lack of relevance to science-policy linkages. Specifically, studies were excluded for insufficient methodological transparency when they lacked clear descriptions of their study design, data sources, or analytical strategies, thereby limiting the ability to assess their credibility and validity.

During the full-text screening phase, a structured assessment was conducted to determine whether each study provided sufficient methodological detail to enable interpretability, appraisal of quality, and replication. This process involved evaluating the presence and clarity of key elements such as the study’s design, data sources, sampling strategies, analytical procedures, and theoretical or conceptual frameworks. Studies that failed to report these components in a coherent or traceable manner were excluded. Reviewers independently applied a checklist to identify omissions or inconsistencies in methodological reporting, and disagreements were resolved through consensus. The decision to exclude a study was made only when the available information did not allow for a reliable understanding of how results were generated or interpreted.

2.6 Analytical framework

A thematic analysis was carried out to categorize the included studies according to their primary conceptual contributions. Six thematic categories were established based on the literature’s focus and theoretical framing:

Structured Science-Policy Participation: This category included studies analyzing mechanisms for formal engagement between researchers and policymakers, such as advisory bodies, science-policy dialogues, and knowledge co-production models.

Institutional Deficit and Limited Access to Evidence: Articles in this group addressed systemic barriers within public institutions, including

poor data infrastructures, fragmented policy processes, and limited research capacity.

Political Conflicts and Resistance to the Use of Evidence: This theme captured studies discussing how political ideologies, administrative turnover, and selective use of research undermine consistent evidence use in policy decisions.

Trust, Knowledge Creation, and Legitimacy: These studies examined trust-building processes between scientific and political actors, emphasizing participatory research, deliberative engagement, and local relevance of evidence.

Political Support and Institutionalization of Counseling: Studies in this category explored the presence or absence of political will, formal mandates for scientific advice, and the institutionalization of expert consultation in policy systems.

International Networks and Collaborative Platforms: This theme encompassed research on transnational policy learning, participation in international evidence-sharing platforms, and the influence of global best practices on national policy development.

This framework enabled a comparative synthesis of the different approaches, contexts, and enabling conditions under which scientific evidence was translated into policy.

Each study was classified based on the primary government sector it addressed. The classification included six predefined ministries: Health, Education, Environment, Economy, Interior or Governance, and Other/Undetermined. This allowed the identification of sector-specific patterns in the integration of evidence into policymaking. Studies were also geographically mapped according to the country of origin of the policy initiative or research setting, enabling a comparative view across national contexts.

In some cases, ministries were explicitly referenced in the texts; in others, thematic alignment was used to determine the relevant sector. The geographic distribution highlighted the prevalence of research output from high-income countries and pointed to disparities in documentation of evidence-informed policymaking in different world regions.

2.7 Data extraction

Data extraction was conducted systematically using a structured Excel spreadsheet developed for this review. For each included study, the following variables were recorded: Auth_Year (first author and year of publication), authors (full author list), year (publication year), title (article title), and DOI (Digital Object Identifier). Additionally, contextual and content-related variables were documented, including language of publication, country where the study was conducted or focused, and the methodology employed (e.g., qualitative, quantitative, or mixed-methods approaches).

Each study was also categorized by its branch of science relevant to the policy domain it addressed. Thematic variables were extracted to capture the presence of barriers and opportunities (or facilitators) for evidence-informed policymaking. Furthermore, the review recorded the transfer mechanisms used to facilitate science-policy interaction, the political context within which the initiative took place, and the institution involved in leading or supporting the work.

Each entry included a summary of recommendations derived from the study and the outcome of the initiative, where applicable.

2.8 Justification for not conducting a risk of bias assessment

A formal risk of bias assessment was not conducted in this study due to its descriptive and exploratory nature. The primary objective was to map and synthesize existing literature on the barriers and facilitators influencing the integration of scientific evidence into public policy formulation. The majority of included sources did not consist of primary studies with experimental or quasi-experimental designs, but rather comprised policy reports, qualitative inquiries, narrative reviews, and conceptual essays. As such, the use of conventional bias assessment tools (such as ROB 2, ROBINS-I, or CASP) was neither methodologically appropriate nor applicable.

Furthermore, the methodological and conceptual heterogeneity of the included studies would have impeded the consistent application of bias assessment criteria and may have led to misleading or artificial evaluations. Instead, a critical appraisal approach was employed, focusing on methodological transparency and thematic relevance to ensure the robustness of the synthesis.

2.9 Data analysis

When applicable, both qualitative and quantitative data analyses were conducted to examine patterns, distributions, and thematic relationships across the included studies. Qualitative data, such as narratives related to barriers, opportunities, recommendations, and institutional roles, were analyzed through thematic coding and categorization. This process allowed the identification of recurrent concepts and their classification under predefined analytical dimensions relevant to science-policy interaction.

Quantitative variables such as year of publication, country of origin, and frequency of specific transfer mechanisms or methodological approaches were analyzed using descriptive statistics

to generate summary metrics and visualize trends over time and across geographic regions.

All analyses and visualizations were carried out using RStudio® 2024.12.1 Build 563, which served as the primary environment for data processing, statistical summarization, and the creation of representative figures. Graphs and tables were produced to support the interpretation of key findings and enhance the clarity of the results section.

All extracted data were cross verified by two reviewers to ensure consistency and accuracy. The complete-detailed dataset is publicly available in the Mendeley Data repository (<https://doi.org/10.17632/b73wm9852j.2>).

3 Results

The study selection process was carried out in accordance with the PRISMA 2020 guidelines, focusing exclusively on sources retrieved from bibliographic databases and registers. Initially, a total of 17,890 records were identified through systematic searches conducted in Scopus ($n = 10,883$) and Web of Science ($n = 7,007$). Prior to the screening phase, several records were excluded due to various factors: 5,406 duplicate records were removed, 11,949 records were marked as ineligible by automated tools, and 170 were excluded for other reasons not specified in the report.

Following this initial refinement, 365 records remained and were subjected to title and abstract screening. From these, 170 records were excluded for not meeting the eligibility criteria based on preliminary information. Subsequently, 195 full-text reports were sought for retrieval. However, 24 of these could not be retrieved despite exhaustive efforts, and thus were not considered in the eligibility assessment.

A total of 171 full-text reports were assessed for eligibility. Of these, 76 were excluded for the following reasons: 59 did not meet the predefined inclusion criteria, 12 had no full-text version available, and 5 presented missing data critical for analysis. After this thorough selection process, a final set of 119 studies was included in the systematic review, constituting the basis for the synthesis of evidence presented (Figure 1).

Although the review protocol allowed for the inclusion of studies published in any language, the final set of included articles consisted predominantly of publications in English. Two studies were published in Portuguese (Scavuzzi et al., 2023; Gaiotto et al., 2023), and one study was published in German (Bromme et al., 2014). No studies published in Spanish met the inclusion criteria. All non-English articles were analyzed using reliable translation tools to ensure accurate interpretation and extraction of data.

The publication years of the studies included in the review ranged from 1999 to the most recent available at the time of the search.

A thematic analysis was conducted to classify scientific articles addressing the intersection of science and public policy. The literature was grouped into five major themes according to their conceptual focus and relevance.

For instance, studies classified under *Political Support and Institutionalization of Counseling* commonly focused on the establishment of CSA offices, the formalization of expert committees, and the creation of institutional platforms such as “what works” centers or evidence-use units within ministries. Several also explored

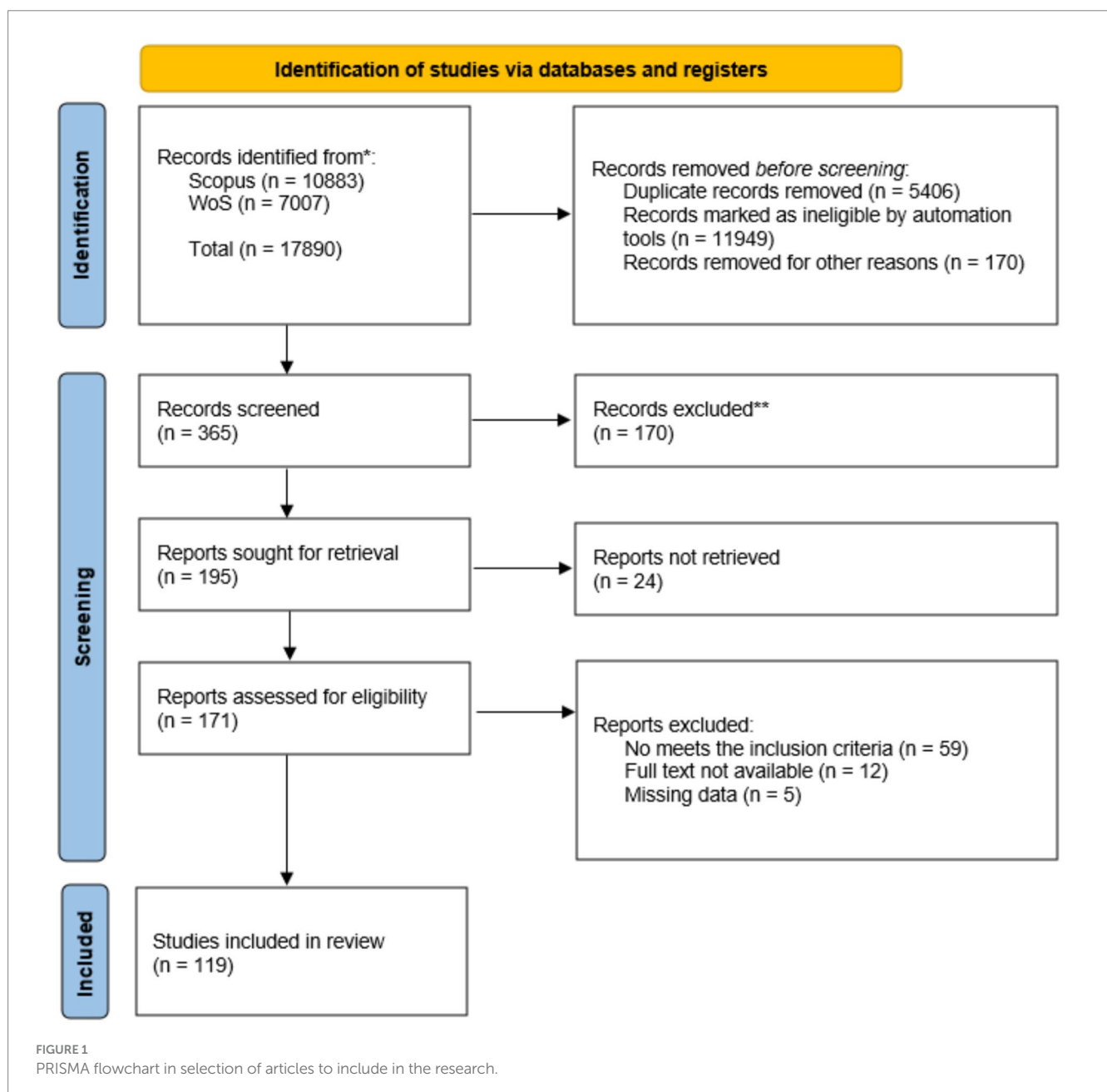
partnerships with non-governmental organizations to facilitate science-policy dialogue. In *Structured Science-Policy Participation*, the literature highlighted initiatives like science-policy dialogues, co-production processes, and participatory foresight exercises. Meanwhile, studies grouped under *Institutional Deficit and Limited Access to Evidence* frequently addressed issues such as fragmented information systems, low data interoperability, and the lack of technical capacity to produce or interpret evidence. These illustrative patterns provide a more nuanced understanding of how each thematic category is operationalized across contexts.

The first theme encompassed the structural and participatory dimensions of science-policy engagement. It included 19 studies that examined mechanisms through which scientific evidence was integrated or failed to be integrated into political decision-making processes.

The second theme addressed institutional deficits and limited access to scientific knowledge, gathering 33 articles. These studies emphasized systemic barriers, including capacity limitations and inequities in knowledge distribution, that hindered evidence-informed policymaking.

The third theme explored political conflicts and resistance to scientific evidence. A total of 24 articles in this group analyzed how political ideologies, power dynamics, and stakeholder interests shaped the acceptance or rejection of scientific input in policy agendas.

The fourth theme focused on trust, knowledge co-production, and the role of networks in shaping policy impact. This theme included 14 articles that highlighted how interpersonal and institutional trust, along with collaborative research practices, influenced the perceived legitimacy of scientific advice.



The fifth and final theme examined political support and the institutionalization of evidence-informed policymaking. Comprised of 18 articles, this group investigated how political will, formal frameworks, and long-term strategies contributed to the sustained integration of research into governance structures.

This thematic classification provided a comprehensive overview of the scholarly discourse on the challenges and enablers of science-policy interfaces across different socio-political contexts (Table 2).

The analysis revealed a strong thematic concentration of studies in the health sector. Out of the total corpus, 66 articles (approximately 58%) were thematically aligned with the Ministry of Health, indicating a predominant focus on evidence-informed policymaking within the health domain. This was followed by the Ministry of the Environment, which accounted for 18 articles (around 16%), and the Ministry of the Interior or Governance with 15 contributions (13%).

The Ministry of Education was associated with 10 studies (9%), while the Ministry of Economy was represented in 4 articles (4%). Finally, 6 articles (5%) could not be clearly classified and were grouped under "Other/Undetermined." These findings suggested that most research efforts have concentrated on the health and environmental sectors, potentially reflecting global policy priorities or stronger institutional mechanisms for integrating evidence into decision-making in these fields (Table 3).

The studies were analyzed to extract recurrent barriers and facilitators related to the integration of evidence into policymaking. Barriers included institutional fragmentation, limited access to actionable data, political resistance to scientific inputs, and lack of incentives for researcher engagement. On the other hand, key facilitators identified included the presence of structured advisory mechanisms, stakeholder participation, political leadership, international collaboration, and the institutionalization of science-policy interfaces. These findings were organized according to the six thematic categories to support a deeper understanding of systemic challenges and opportunities across contexts.

A range of barriers and facilitators to evidence-informed policymaking were identified across the reviewed studies. Institutional and governance limitations were frequently reported, including the absence of formal frameworks, weak incentives, and fragmented structures that hindered intersectoral coordination. Political and ideological resistance also emerged, with evidence being selectively used or disregarded due to misalignment with prevailing agendas. Significant challenges were noted regarding access to relevant, timely, and actionable scientific evidence, exacerbated by inadequate data infrastructures and limited communication between researchers and policymakers. Furthermore, resource constraints and a lack of institutional or individual incentives were commonly cited as impediments to sustained science-policy integration.

In the area of structured science-policy participation, several studies reported fragmented advisory mechanisms and a lack of institutionalized policy analysis units. For instance, in Malawi and South Africa, the absence of dedicated analytical units, weak inter-ministerial coordination, and over-reliance on donor funding were repeatedly noted as structural shortcomings that hindered systematic evidence use. Similarly, one study highlighted how entrenched conflicting frames between government and civil society led to the instrumental use of evidence to delegitimize opposition voices and delay consultation processes.

Conversely, several facilitators were documented that helped promote the integration of scientific knowledge into policy. For example, partnerships with community organizations, access to localized data, and policy learning from peer municipalities enabled some governments to overcome knowledge gaps and align interventions with public needs. In Saudi Arabia, the presence of national support institutions, structured knowledge translation frameworks, and motivated participants trained in evidence-based medicine were seen to enhance the institutional capacity for policy uptake. Another study described how strong inter-professional relationships and trust-based environments allowed for the successful implementation of micro-level strategies that proved more effective than centralized directives.

These examples show that facilitators were not merely theoretical constructs such as "knowledge brokers" or "science advisors," but were embedded in concrete contexts that included academic partnerships, clinical opinion leadership, and community pressure each playing a distinct role in bridging the science-policy divide (Table 4).

Institutional deficits were highlighted through the lack of systematic frameworks, limited data access, and constrained institutional capacities. These were counterbalanced by the institutionalization of evidence-informed policy units, improved data systems, and procedural reforms.

Political resistance was characterized by ideological polarization, selective evidence use, and discontinuity due to shifting administrations. Facilitators included bipartisan leadership, political consensus, and strategic use of evidence in sensitive decisions.

Regarding trust and legitimacy, low confidence in scientific institutions and insufficient stakeholder engagement were underscored. Participatory research processes and transparent practices were cited as mechanisms to restore credibility.

Political support remained inconsistent, undermined by administrative turnover and weak formalization. Nonetheless, high-level backing, institutional mandates, and legislative requirements for expert consultation were identified as enablers.

Finally, international collaboration was impeded by institutional isolation and minimal participation in global platforms. However, engagement in international forums and alignment with best practices were recognized as vital pathways to foster cross-border evidence use (Table 4).

A total of 119 studies were identified across 32 countries. The highest number of studies originated from England (34 studies, 28.6%), followed by the United States (23 studies, 19.3%), Canada (7 studies, 5.9%), Brazil (4 studies, 3.4%), and Nigeria (4 studies, 3.4%). These five countries accounted for over 60% of all recorded studies.

Institutional involvement analysis revealed that references to ministries were relatively infrequent across cases. The Ministry of Health was the most commonly mentioned, appearing in 11 studies (9.2% of the total). This was followed by the Ministry of the Environment (1 mention), the Ministry of Education (1 mention), and the Ministry of the Economy and Ministry of the Interior or Governance (none). Notably, the vast majority of studies (104 cases, 87.4%) did not explicitly mention any of the six predefined ministries and were categorized as "Other/Undetermined."

This distribution highlighted both a concentration of research output in high-income countries and a generally low frequency of direct ministerial involvement in the documentation of evidence-informed policymaking processes (Figure 2).

TABLE 2 Thematic clustering of scientific articles on science-policy interfaces.

Thematic	Number of articles	Author, year
Structured science-policy participation	19	(Behague et al., 2009; Bozeman and Bozeman, 2022; Dagenais, 2021; Ellen et al., 2014; Erismann et al., 2021; Fisher and Milliken, 2022; Fobé et al., 2013; Gabbay et al., 2020; La Brooy et al., 2017; Lester et al., 2020; Mbachu et al., 2024; Meyerson et al., 2018; Reddel et al., 2022; Reddy and Sahay, 2016; Schepelmann et al., 2021; Wahabi et al., 2011; Walker et al., 2019; Wan et al., 2020; Webster et al., 2022)
Institutional deficit and limited access to evidence	33	(Adam et al., 2018; Aro et al., 2016; Braganza et al., 2022; El-Jardali et al., 2015; Godfrey et al., 2010; Hamalainen et al., 2015; Harding, 2003; Jack et al., 2010; Larned et al., 2022; Makkar et al., 2018; Manyuchi and Mugabe, 2018; Marchevska, 2024; Mathews et al., 2019; Mavoa et al., 2012; Meijers et al., 2022; Moat et al., 2014; Moura et al., 2023; Namdarian and Khedmatgozar, 2024; Nutley et al., 2002; Orem et al., 2014; Oronje et al., 2019; Parks et al., 2023; Purtle et al., 2022; Saric et al., 2022; Siyanbola et al., 2016; Uneke et al., 2011; Uneke et al., 2022; Vesely et al., 2018; Waqa et al., 2013; Waqa et al., 2013; Williamson et al., 2019; Wilson et al., 2007; Woodson and Boutilier, 2022)
Political conflicts and resistance to the use of evidence	24	(Arinder and Arinder, 2016; Barton, 2016; Bedregal and Ferlie, 2001; Biau et al., 2021; Botterill and Hindmoor, 2012; Bromme et al., 2014; Gaiotto et al., 2023; Hong et al., 2019; Ibarra et al., 2018; Jing and Hu, 2020; Knight, 2019; Koga et al., 2021; MacAulay et al., 2023; Munnich et al., 2017; Ongolo-Zogo et al., 2018; Persson et al., 2018; Saleh and Gamar, 2024; Sarkki et al., 2025; Shim and Shin, 2022; Stadelmaier et al., 2022; Turnpenny et al., 2009; Urcuqui-Bustamante et al., 2023; Weldon and Parkhurst, 2022; Wolf et al., 2017)
Trust, knowledge creation and legitimacy	14	(Bäumle et al., 2023; Broström and McKelvey, 2018; Brown, 2014; Byrne et al., 2018; Carpenter and Carpenter, 2016; Filograna et al., 2023; Gerber et al., 2020; Kleine, 2009; Langeveld et al., 2016; Mendell and Richardson, 2021; Sarkki et al., 2020; Silva et al., 2019; Siow et al., 2015; Whicher, 2021)
Political support and institutionalization of counseling	18	(Bax et al., 2010; Bullock et al., 2024; Ferlie et al., 2009; Koga et al., 2022; Lecesne et al., 2025; Lewis, 2011; Lim et al., 2021; Linke et al., 2014; Lu et al., 2018; Niño-Sandoval et al., 2023; Nutley and Davies, 1999; Pellegrini and Vivanet, 2021; Reed et al., 2023; Spiel et al., 2018; Strehlenert et al., 2015; Van Kammen et al., 2006; Wilcox, 2003; Yan et al., 2014)
International networks and collaborative platforms	11	(Angelou et al., 2024; Calnan et al., 2023; Lévesque et al., 2024; Mikton et al., 2013; Paing et al., 2021; Quinn et al., 2015; Rahai and Hosseinpoor, 2024; Rhodes et al., 2022; Sajadi et al., 2021; Scavuzzi et al., 2023; Tachino and Tachino, 2012)

TABLE 3 Classification of evidence-informed policy studies by relevant ministry sector.

Ministry	Number of articles	Authors, year
Ministry of Economy	4	(Harding, 2003; Reddel et al., 2022; Shim and Shin, 2022; Siyanbola et al., 2016)
Ministry of Education	10	(Bäumle et al., 2023; Bromme et al., 2014; Broström and McKelvey, 2018; Brown, 2014; Lewis, 2011; Moura et al., 2023; Niño-Sandoval et al., 2023; Pellegrini and Vivanet, 2021; Saleh and Gamar, 2024; Spiel et al., 2018)
Ministry of the Environment	18	(Godfrey et al., 2010; Kleine, 2009; Knight, 2019; Larned et al., 2022; Lévesque et al., 2024; Linke et al., 2014; Marchevska, 2024; Persson et al., 2018; Rahai and Hosseinpoor, 2024; Reed et al., 2023; Rhodes et al., 2022; Sarkki et al., 2020; Sarkki et al., 2025; Schepelmann et al., 2021; Siow et al., 2015; Urcuqui-Bustamante et al., 2023; Vesely et al., 2018; Wilson et al., 2007)
Ministry of Health	66	(Aro et al., 2016; Barton, 2016; Bedregal and Ferlie, 2001; Behague et al., 2009; Biau et al., 2021; Botterill and Hindmoor, 2012; Bozeman and Bozeman, 2022; Braganza et al., 2022; Bullock et al., 2024; Byrne et al., 2018; Calnan et al., 2023; Dagenais, 2021; El-Jardali et al., 2015; Ellen et al., 2014; Erismann et al., 2021; Ferlie et al., 2009; Gabbay et al., 2020; Gaiotto et al., 2023; Hamalainen et al., 2015; Ibarra et al., 2018; Jack et al., 2010; Jing and Hu, 2020; La Brooy et al., 2017; Langeveld et al., 2016; Lecesne et al., 2025; Lester et al., 2020; Lim et al., 2021; Lu et al., 2018; MacAulay et al., 2023; Makkar et al., 2018; Mathews et al., 2019; Mavoa et al., 2012; Mbachu et al., 2024; Meijers et al., 2022; Mendell and Richardson, 2021; Meyerson et al., 2018; Mikton et al., 2013; Moat et al., 2014; Munnich et al., 2017; Nutley and Davies, 1999; Nutley et al., 2002; Ongolo-Zogo et al., 2018; Orem et al., 2014; Oronje et al., 2019; Paing et al., 2021; Parks et al., 2023; Purtle et al., 2022; Quinn et al., 2015; Reddy and Sahay, 2016; Sajadi et al., 2021; Saric et al., 2022; Scavuzzi et al., 2023; Stadelmaier et al., 2022; Strehlenert et al., 2015; Turnpenny et al., 2009; Uneke et al., 2011; Uneke et al., 2022; Van Kammen et al., 2006; Wahabi et al., 2011; Wan et al., 2020; Waqa et al., 2013; Waqa et al., 2013; Webster et al., 2022; Weldon and Parkhurst, 2022; Williamson et al., 2019; Yan et al., 2014)
Ministry of the Interior or Governance	15	(Adam et al., 2018; Angelou et al., 2024; Arinder and Arinder, 2016; Filograna et al., 2023; Fisher and Milliken, 2022; Fobé et al., 2013; Koga et al., 2021; Koga et al., 2022; Manyuchi and Mugabe, 2018; Namdarian and Khedmatgozar, 2024; Walker et al., 2019; Whicher, 2021; Wilcox, 2003; Wolf et al., 2017; Woodson and Boutilier, 2022)
Other/Undetermined	6	(Bax et al., 2010; Carpenter and Carpenter, 2016; Gerber et al., 2020; Hong et al., 2019; Silva et al., 2019; Tachino and Tachino, 2012)

TABLE 4 Thematic barriers and facilitators for evidence-informed policymaking.

Thematic dimension	Barriers	Facilitators
1. Structured science-policy participation	<ul style="list-style-type: none"> Weak coordination and limited structured engagement between researchers and policymakers. Fragmented advisory mechanisms and persistence of linear knowledge transfer models. Limited academic incentives to engage in policy processes. Poor communication and lack of mutual understanding between researchers and decision-makers. 	<ul style="list-style-type: none"> Establishment of formal science advisory bodies and intersectoral coordination platforms. Use of knowledge brokers and structured communication mechanisms. Recognition of co-production models that align scientific outputs with policy needs.
2. Institutional deficit and limited access to evidence	<ul style="list-style-type: none"> Absence of institutional frameworks for systematically integrating evidence into policymaking. Restricted access to timely, relevant, and context-specific data. Inadequate data infrastructure and limited institutional capacity to manage evidence flows. Low perceived applicability of academic research to political realities. 	<ul style="list-style-type: none"> Institutionalization of evidence-informed policy units or governmental research departments. Improved data-sharing systems and standardized tools for evidence appraisal. Government reforms embedding evidence access into procedural norms.
3. Political conflicts and resistance to evidence use	<ul style="list-style-type: none"> Ideological resistance and politicization of evidence in highly polarized contexts. Selective use or dismissal of evidence to suit political agendas. Lack of political continuity that weakens long-term integration of evidence. Political priorities overriding evidence-based considerations. 	<ul style="list-style-type: none"> Political consensus on evidence-informed agendas. Leadership by influential or bipartisan actors advocating for science. Use of evidence to support politically sensitive decisions in early policy stages.
4. Trust, knowledge creation, and legitimacy	<ul style="list-style-type: none"> Low trust in scientific institutions among policymakers and the public. Limited stakeholder involvement reducing the perceived legitimacy of evidence. Disconnection between academic research and local policy contexts. 	<ul style="list-style-type: none"> Engagement of key stakeholders in research design and implementation. Transparent processes that enhance the credibility and legitimacy of evidence. Emphasis on participatory and deliberative knowledge creation models.
5. Political support and institutionalization of scientific advice	<ul style="list-style-type: none"> Lack of sustained political will to maintain scientific advisory mechanisms. Frequent administrative changes disrupting the continuity of evidence use. Unformalized role of science in policy decision-making. 	<ul style="list-style-type: none"> High-level political support for evidence-based governance. Institutional mandates formalizing scientific advice within government structures. Legislative frameworks requiring expert consultation.
6. International networks and collaborative platforms	<ul style="list-style-type: none"> Institutional isolation and low participation in global evidence platforms. Limited engagement in transnational networks and low capacity for international collaboration. 	<ul style="list-style-type: none"> Active participation in global policy forums and scientific exchange initiatives. Adoption of international best practices and shared learning mechanisms. Integration into regional or global evidence consortia.

4 Discussion

The results of this systematic review reveal a complex network of factors that influence the incorporation of scientific evidence into public policy formulation. Broadly speaking, multiple structural, institutional, and political barriers persist, hindering the systematic integration of scientific knowledge into governmental decision-making processes. Nonetheless, enabling conditions were also identified, allowing for the emergence of effective pathways to promote evidence-informed governance.

One recurring limitation is the weak linkage between the scientific community and decision-makers. The predominance of unidirectional knowledge transfer models has been widely questioned for their ineffectiveness in promoting meaningful use of evidence, a concern echoed in the existing literature that emphasizes the need for more

interactive and iterative mechanisms (Nutley et al., 2002; Dagenais, 2021; Suazo-Galdames and Saracosti, 2025). The lack of institutional incentives encouraging academics to engage in policy advisory processes contributes to this disconnect (Walker et al., 2019). However, experiences of knowledge co-production and the existence of permanent advisory bodies, and boundary organizations such as science-policy interfaces have been shown to improve the relevance, credibility, and legitimacy of public policies (Gabbay et al., 2020; La Brooy et al., 2017; Suazo-Galdames et al., 2024).

From an institutional perspective, deficits in data infrastructure, poorly standardized regulatory frameworks, and limited organizational capacities hinder the systematic integration of evidence (Makkar et al., 2018; El-Jardali et al., 2015). These findings align with previous studies that highlight similar challenges, particularly in low-income contexts, these limitations are exacerbated by the scarcity



of technical and human resources (Orem et al., 2014). Nevertheless, progress has been observed in countries that have institutionalized evidence-based policy units, developed interoperable analytical tools, and promoted procedural reforms aimed at facilitating the use of knowledge (Ferrigno et al., 2022; Shtatina et al., 2021; Fyfe and Richardson, 2018) as in the case of Indonesia in terms of reproductive health (Meijers et al., 2022). In Latin America, progress has been observed in the induction of science in public policies, especially in the field of education, where academic contributions are being systematically analyzed to improve the implementation of public policies, address inequalities, and address complex challenges in the education system (Torres-Bernal et al., 2024; Davyt, 2023); however, in this region there were not many studies included that focused their objective on how public policies can appropriate Science for their better performance, proposal and approach. Peña et al. analyze the governance of science, technology, and innovation in Latin American higher education institutions, highlighting how effective governance incorporates public policies that support scientific knowledge production and management, demonstrating progress in integrating science into public policy across countries like Argentina, Brazil, Chile, Mexico, and Colombia (Peña et al., 2022).

According to Mateos-Espejel and Estrada Rodríguez (2024) articles that highlight advances in the inclusion of science in public policies in Europe, Africa, and Asia include studies on Citizen Science and its application in sustainable agriculture. In addition, in these same regions, according to the study by Paz-Enrique (2023) spaces and forms of participation in the construction of public policies related to science, technology, and innovation were identified. These results are divergent and consistent with the outcomes of the present study, which revealed a little representation of countries that research on public policies and incorporated science in Asia and Africa.

Public policy communication and the appropriation of scientific knowledge have also been deeply affected by how science is publicly represented. During the COVID-19 pandemic, for example, studies have shown that poorly communicated, politically driven, or

exaggerated representations of scientific findings such as the hydroxychloroquine case can distort public understanding and undermine trust in institutions and evidence-based policymaking (Caulfield et al., 2021). Caulfield et al. (2021) warn that during health crises, poor scientific communication and politicized interpretations not only derail public trust, but also hinder the integration of research into public decisions. Similarly, Taschner et al. (2021) argue that in current media ecosystems, hype is no longer solely driven by media and scientific institutions but often originates in political and social media spheres, with the public actively contributing to the amplification of misinformation. These dynamics illustrate how scientific knowledge can be misappropriated or marginalized when public discourse and decision-making become detached from rigorous evidence, further underscoring the need for governance structures that protect scientific integrity and transparency.

Finally, a study by Espinoza Martínez (2019) reports that there is an induction of science in public policies in Europe, Africa and Asia.

These findings aligned with earlier syntheses emphasizing the structural disconnect between research production and policy implementation. However, while previous literature often focused on technical constraints, this review brought forward novel insights concerning epistemological mismatches and temporal misalignments between research and policymaking cycles. For instance, while some studies describe limited institutional capacity as the primary bottleneck, others highlighted the absence of trust-building mechanisms and collaborative governance processes that ensure continuity in evidence use.

The political dimension also plays an ambivalent role. On one hand, the politicization and strategic use of evidence can lead to selective uptake and instrumentalization, thereby weakening the integrity of the evidence-policy interface (Bozeman and Bozeman, 2022; Bromme et al., 2014). On the other, committed leadership, cross-party consensus, and institutional continuity have been recognized as key facilitators in the successful adoption of evidence-informed policymaking practices (Meyerson et al., 2018; Reddy and

Sahay, 2016). These findings corroborate earlier research pointing to the importance of political will and leadership stability in sustaining long-term policy change.

A cross-cutting theme identified in the literature is trust. The legitimacy of scientific evidence in the eyes of policymakers largely depends on the transparency of its production and the involvement of social actors. This has been extensively discussed in the field of deliberative policy analysis, where participatory methodologies and context-sensitive approaches are recognized as crucial to enhancing both the epistemic and democratic quality of policies (Moat et al., 2014; Mendell and Richardson, 2021; Suazo-Galdames, 2024; Suazo-Galdames and de Toro, 2024). In this regard, civil society has played a dual role as both consumer and producer of evidence by contributing community-based knowledge and exerting pressure for more accountable governance.

Several studies reviewed described the emergence of evidence networks collaborative structures connecting researchers, policymakers, and civil society actors that function as platforms for co-producing and contextualizing evidence. These networks often played a critical role in expanding the types of knowledge considered valid for policy, integrating lived experience, practitioner insights, and local data. Transdisciplinary platforms, particularly in Latin America and Sub-Saharan Africa, were highlighted for contributing to shared ownership of the policy process. In these contexts, the role of civil society has transcended consultation, becoming instrumental in validating evidence, setting policy agendas, and ensuring transparency in implementation (Schulz and Adams, 2025; Ochen-Ochen, 2025; Kauko, 2022; García, 2021; Hawkins and Parkhurst, 2016).

Another important aspect concerns nature and definition of “evidence” itself. The findings of this review highlight the persistent tension between formal scientific knowledge and alternative or experiential forms of evidence. This includes local knowledge, practitioner expertise, and values-based arguments, which are often dismissed or marginalized in technocratic models of policy design. A more pluralistic understanding of evidence is required one that reflects power asymmetries and acknowledges that knowledge production and use are inherently political processes.

The review further underscored how power dynamics influence what is considered credible or legitimate evidence. In many instances, quantitative data from formal institutions were privileged, while qualitative or community-generated evidence was downplayed, regardless of its contextual relevance. These hierarchies of evidence often mirrored broader inequalities in institutional voice and visibility. At the same time, informal and politically embedded evidence pathways such as advisory coalitions, epistemic communities, and issue networks were found to be particularly influential in shaping policy narratives, especially when formal mechanisms for evidence use were weak or absent.

The predominance of academic papers emerging from the UK, US, and Canada can be attributed to several intertwined factors, including established scientific advisory traditions in these nations, robust funding mechanisms, and significant historical investments in research infrastructures. This phenomenon can be analyzed through the lens of existing literature on evidence-based policy-making and the dynamics of advisory roles in government contexts.

Firstly, the legacy of science advisory structures in the UK, the US, and Canada has fostered an environment where scientific research is systematically integrated into policy-making processes. Tangney and

Howes (2016) highlight challenges in bridging the gap between scientific knowledge and policy decision-making, particularly in climate adaptation, emphasizing the critical role of evidence in shaping policies. The establishment of scientific advisory committees (SACs) in Britain serves to mobilize scientific knowledge directly into the policy arena, affecting various high-profile issues through a structured advisory network, as discussed by Page et al. (2018). This institutional support results in a higher output of papers, as researchers in these countries are often engaged in direct policy consultations and studies that warrant publication.

Moreover, boundary organizations, which serve as intermediaries between scientific expertise and policy-making, also play a crucial role in facilitating this trend. Pattyn et al. (2022) suggest that these organizations often embody a dual advice role, enhancing their credibility and effectiveness in governance contexts, which drives the influence of academic work on political decision-making in established democracies. The sophisticated policy-making environments in the UK, US, and Canada cultivate a niche for scholars to generate research that directly feeds back into the system, thus increasing publication frequency in reputable journals.

Additionally, funding structures in these countries enable a wide range of research initiatives that emphasize policy relevance and societal benefit. Demeritt (2010) notes that publicly funded research in the UK often aims at achieving tangible societal impacts, which incentivizes academic production aligned with government priorities. The interplay of academic ambition and governmental need in such ecosystems generates a high density of research outputs addressing pressing societal challenges, explaining why these sought-after publications proliferate in these nations.

Furthermore, the focus on engagement with the public and policy-makers is increasingly codified within UK policy discourse. The push for upstream public engagement, as examined by Rogers-Hayden and Pidgeon (2007), indicates a shift where scientists are expected to contribute more broadly to public understanding and policy articulation, thus leading to greater scholarly output reflecting these engagements. Such dynamics foster an atmosphere where academic discourse is frequently invigorated with fresh empirical insights, resulting in numerous publications that respond to real-world issues.

International cooperation also emerges as a powerful strategy to address structural barriers and promote institutional learning. Transnational networks such as EVIPNet, the International Network for Government Science Advice (INGSA), and the Alliance for Useful Evidence have proven effective in building local capacities, fostering trust between stakeholders, and diffusing best practices (Lester et al., 2020; Van Kammen et al., 2006). Nonetheless, unequal participation in these platforms exacerbates regional disparities in access to knowledge and its translation into policy, underscoring the need for more inclusive and equitable evidence ecosystems.

The increasing involvement of civil society in the context of evidence networks goes beyond mere consultation to profound engagement throughout the policy cycle. As elaborated by García (2021), civil society organizations have become instrumental in validating evidence, shaping policy agendas, and ensuring transparency in the implementation process. Their advocacy efforts help hold policymakers accountable and strengthen the democratic processes through which policies are enacted.

Moreover, as described by Ochen-Ochen (2025), the collaborative nature of these networks facilitates a direct line of communication

between marginalized communities and policymakers, amplifying voices that might otherwise be excluded from policy discussions. This democratization of evidence production plays a crucial role in addressing disparities and ensuring that the needs and rights of all stakeholders are represented.

In terms of practical implications, the findings highlight the need to move toward governance models that institutionalize the use of evidence through legal frameworks, sustained resources, and organizational structures that promote interaction between science and policy. From a theoretical standpoint, the urgency is noted to develop more integrative approaches that acknowledge the contextual, negotiated, and political nature of knowledge in decision-making.

4.1 Limitations and strengths

Among the limitations of this review is the methodological heterogeneity of the included studies, which prevents firm generalizations about the effectiveness of the various mechanisms analyzed. Moreover, the predominance of studies from high-income countries restricts the transferability of the findings to contexts with weaker institutional capacities. It should also be noted that much of the existing literature relies on descriptive accounts or case studies, limiting the scope for causal inference.

Nonetheless, the review provides a comprehensive synthesis of international experiences and incorporates diverse disciplinary perspectives, offering both breadth and depth in the analysis of barriers and enablers to evidence-informed policymaking. The inclusion of grey literature and reports from policy institutions further enriched the understanding of real-world policy dynamics.

5 Conclusions and future directions

In terms of practical implications, the findings emphasize the need to institutionalize evidence use through legal mandates, sustained financial and human resources, and dedicated organizational structures that promote interaction between science and policy. Moving beyond the linear model of knowledge translation, it is imperative to embrace iterative, dialogical, and politically informed approaches that reflect the contested and negotiated nature of policymaking.

From a theoretical standpoint, there is an urgent need to develop integrative frameworks that incorporate the political economy of knowledge, recognize the role of intermediary actors such as knowledge brokers, and capture the interplay between evidence, values, and interests in decision-making processes.

Future research should prioritize comparative analyses across countries and policy sectors, assess the long-term impact of scientific advisory mechanisms, and explore the contributions of non-traditional evidence sources. Investigations into how power relations shape what counts as legitimate evidence and how marginalized voices can be included are particularly relevant for advancing inclusive and democratic forms of evidence-informed governance.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: <https://doi.org/10.17632/b73wm9852j.1>.

Author contributions

IS-G: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MS: Formal analysis, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AC-G: Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that Gen AI was used in the creation of this manuscript. Artificial intelligence was used exclusively to enhance the accuracy, clarity, and fluency of English language and grammar. No content was generated or modified beyond linguistic refinement and stylistic improvement.

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