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Review

What do we know about innovation in water governance?

Bruno Damásio[1], Cátia Miriam Costa[2], Andrea Vezzulli[3], Miguel Damásio[4,5] and Sandro Mendonça[6,7,8]

Water governance faces compounding pressures from climate variability, ageing infrastructure, and rising demand for environmental performance. The knowledge base that informs governance responses, the body of expertise that policy instruments mobilise, has not been mapped systematically across decades. The object of analysis here is precisely that knowledge base, not policy capacity itself: we characterise the body of scientific and engineering expertise on which governance choices can draw. We analyse 11 186 peer-reviewed articles indexed in Web of Science (1980–2024) drawn from six structured queries covering treatment, recharge, contaminant control, biological reactors, resource recovery, and sensing methods. Latent Dirichlet Allocation identifies six thematic streams; Hirschman-Herfindahl and Revealed Technological Advantage indices trace concentration over time and national specialisation. Treatment-process engineering remains the mainstream, but the field has diversified since 2018, with contaminant control and sensing-and-detection methods growing fastest, while resource-recovery knowledge, the core of the circular-economy transition, grows slowest and loses share. National portfolios track regulatory context and hydrological exposure. The paper provides a full field-level cartography that complements extant frameworks and shows that the knowledge base for circular water governance is broadening, while the institutional toolkit for steering the transition remains incomplete.

Addresses
[1] NOVA Information Management School (NOVA IMS), Universidade Nova de Lisboa, Campus de Campolide, Lisboa 1070-312, Portugal
[2] Instituto Universitário de Lisboa (ISCTE-IUL), Centro de Estudos Internacionais, Lisboa, Portugal
[3] InsIDE Lab - Department of Economics (DiEco), University of Insubria, , Italy
[4] Departamento Ingeniería Agroforestal, Escola Politécnica Superior de Enxeñaría, Universidade de Santiago de Compostela, Spain
[5] INIAV – Instituto Nacional de Investigação Agrária e Veterinária, I.P. Avenida da República, Quinta do Marquês, Oeiras 2780-159, Portugal
[6] Faculty of Business, City University of Macau, Macao
[7] ISEG, Universidade de Lisboa, REM – Research in Economics and Management, Portugal
[8] Instituto Universitário de Lisboa (ISCTE-IUL) and BRU/Business Research Unit, Portugal

Corresponding author: Damásio, Bruno (bdamasio@novaims.unl.pt)

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This review comes from a themed issue on **Accelerating Transition to Circular Economy in the Water Sector**

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Introduction

Water systems sit at the intersection of climate variability, resource security, and public health [1,2]. Water governance, the political, social, economic, and administrative structures that determine access to and control over water resources and services [3], must address this complexity while engaging adjacent transitions in energy, food, and circular production [4–6]. Effective responses require coordinating sectors, scales, and instruments [7–9]. Over the past two decades, policy priorities in water governance have shifted toward integrated and adaptive arrangements that span sectors, scales, and time horizons [1,2]. Progress has come through people-centric principles that clarify who holds the rights and responsibilities for which water services [53], and through circular-oriented approaches that recast water as a recirculatable resource managed end-to-end rather than a free input discharged after use [54].

Recent contributions propose governance frameworks for the circular water economy that move beyond technical reuse toward integrated coordination [10–13,14], building on the broader framing of water as a global common good set out by the Global Commission on the Economics of Water [15]. Those advances rest on an assumption that this paper interrogates: the knowledge base that governance can mobilise, the body of scientific and engineering expertise from which policy instruments draw, is sufficient and well-distributed. Whether

that assumption holds is an empirical question. Scoping studies to date have mapped narrow slices: 50 articles screened via PRISMA [16], 223 cases linked to governance paradigms [9], or single-country surveys [17,14]. None has tracked the full cross-domain knowledge base over four decades, linked thematic shifts to specific policy instruments [18,19], or read national specialisation against the regulatory and hydrological context.

We address two research questions: (RQ1) what thematic clusters characterise the water governance knowledge base, and how has their relative weight changed since 1980?; (RQ2) which clusters exhibit the strongest momentum and which are underrepresented relative to documented policy demand [20,21,2,1]? The paper does not claim to measure governance outcomes directly; it characterises the body of expertise on which governance rests [22–24]. Governance capacity is constrained by the knowledge it can mobilise: when the base is concentrated in particular heuristics or thin in particular regions, governance responses inherit those limits.

Methods and materials

Corpus and filters

Records were retrieved from the Web of Science Core Collection using six structured queries that reflect recent and recognised policy-driven literature (Supplementary Material, Section S1), combining domain terms with a cross-cutting filter on innovation, technology, management, and governance. Single-source use follows large-scale science-mapping practice [25]; macrolevel publication and citation indicators correlate at $R^2 \approx 0.99$ between WoS and Scopus [26,27]. The corpus is restricted to English peer-reviewed articles and reviews (1980–2024; 2025–2026 excluded to avoid partial-year effects). After deduplication, 11 186 records remain with metadata on year, abstract, first-author country, and institutional affiliation.

Text processing, topic modelling, and indices

Abstracts capture authors' core claims and correlate with full-paper content [28,29], a property verified for this corpus (Section S2). After tokenisation, removal of English stopwords, publisher boilerplate and measurement units, low-frequency trimming, and Porter stemming, a Latent Dirichlet Allocation (LDA) model with $k = 6$ topics was fitted on the 10,722 records with a non-empty abstract. The number of topics was selected jointly on held-out perplexity and topic coherence over $k \in \{4,\ldots,15\}$; both are optimised at $k = 6$, beyond which the topics become redundant (Section S3). LDA represents each document as a probability distribution over topics (the γ weights) and each topic as a distribution over stems (the β weights); topics are labelled from their highest-β stems and read through their highest-γ documents. Two indices summarise structure: $\mathrm{HHI}_t = \sum_k s_{kt}^2$ measures annual thematic concentration; $\mathrm{RTA}_{ck} = (n_{ck}/n_c)/(n_k/N)$ measures national specialisation relative to the corpus mean (values above one indicate comparative advantage).

Topic-to-instrument approach

Converting LDA clusters into governance content requires explicit interpretation. We report a transparent four-step approach. (i) Top-10 β terms anchor a provisional label. (ii) The ten highest-γ documents per topic are read in full. (iii) Each cluster is mapped onto policy-instrument families documented in OECD, EEA, and UNESCO frameworks [1,20,2]: effluent standards and permits; procurement and performance-based contracting; tariff and pricing instruments; monitoring, reporting, and data-sharing obligations; rights allocation and inter-jurisdictional coordination. (iv) The authors coded the mapping independently and reconciled disagreements by re-reading high-γ documents.

Results

Dynamics, originators, and networks

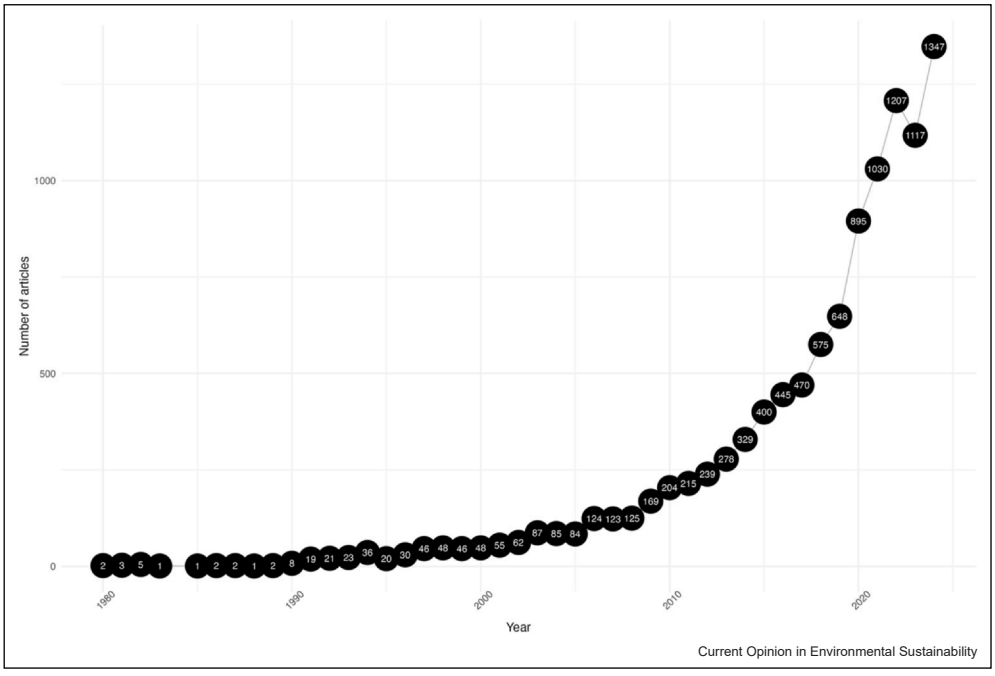
Annual output rose from a sparse set of items before the 1990s to over 1300 publications in 2024, with a marked acceleration after 2018 (Figure 1). Chinese, Dutch, Australian, and Indian universities lead in publication volume; citation leaders include Dutch, Swiss, and Danish institutions alongside major Chinese and US centres (Figure 2). The international co-authorship network is dense but asymmetric (Figure 3): China, the US, and the leading European producers (the Netherlands, Germany, the UK) form the backbone. Southern European countries, India, Iran, and Turkey act as connectors. African participation is fragmented (South Africa, Kenya, Nigeria as regional hubs), which signals a structural gap between knowledge production and the governance challenges of the most exposed regions [30].

Six emergent thematic streams in the knowledge base

LDA yields six thematic streams (Figure 4). For each, we report dominant terms, the policy-instrument family it maps onto under the approach in Section 2.3, and representative exemplars from the high-γ reading set:

i. *Treatment and process technologies* (Topic 1): wastewater treatment, process upgrades, system optimisation [31–33]. Maps onto effluent permits, performance standards, and public procurement for plant upgrading.
ii. *Recharge, irrigation, and decentralised supply* (Topic 2): groundwater recharge, rainwater harvesting, aquifer management, irrigation [34–36]. Maps onto allocation rights, abstraction permits, and cross-sector coordination across land use, agriculture, and municipal water.
iii. *Contaminant removal and water-quality control* (Topic 3): pollutant removal, emerging contaminants,

Figure 1



Annual research articles published on water governance topics (1980–2024). Counts cover the six structured queries described in the section Corpus and filters after deduplication.

efficiency optimisation [37–39]. Maps onto discharge permits and the tightening water-quality standards set under the EU Water Framework Directive and its daughter Environmental Quality Standards Directive: environmental quality standards for the sum of 24 PFAS are being phased in through the 2026 revision, while microplastics remain on the watch list pending harmonised monitoring.

iv. *Biological treatment and activated sludge processes* (Topic 4): biological nutrient removal, membrane bioreactors, granular sludge, nitrogen and phosphorus removal [40–42]. Maps onto effluent standards for nutrient removal and procurement for municipal upgrades.

v. *Sludge management, digestion, and resource recovery* (Topic 5): anaerobic digestion, biogas, nutrient recovery, composting, sewage sludge utilisation [43–45]. Maps onto circular-economy obligations and performance-based contracting for energy and nutrient recovery, directly aligned with the agenda set out in Tortajada et al. [10] and Romano and Guerrini [11].

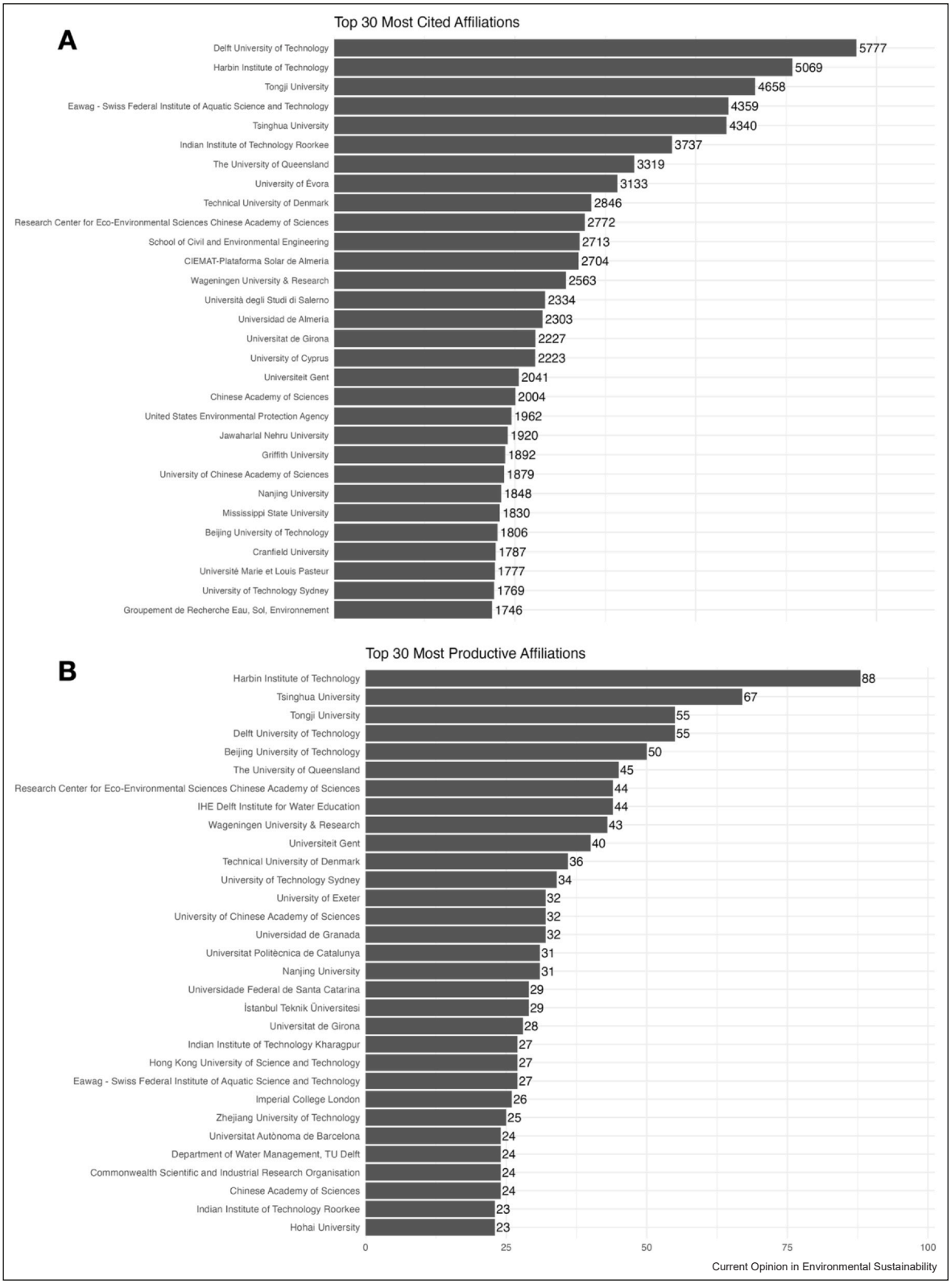
vi. *Detection methods and network simulation* (Topic 6): leakage detection, network simulation, early-warning systems [46,47]. The high-γ reading set indicates that this stream captures sensing-and-modelling methods developed primarily in water-utility contexts but also tested on adjacent pipeline networks (oil, gas), and reported under shared methodological vocabulary. The cluster maps onto monitoring, reporting and data-sharing obligations and onto procurement of predictive analytics; the multisector character should be kept in view when interpreting national-specialisation patterns below.

Structural diversity and specialisation

Streams 1 and 4 dominate long-term activity, consistent with regulatory compliance and infrastructure modernisation. Topic 3 expands progressively as standards for emerging contaminants tighten. Topic 6, among the fastest-growing after 2018, reflects the rising uptake of sensing, automation, and analytics. Resource recovery (Topic 5), the core of the circular-economy agenda, grows the most slowly and loses share, a gap between policy salience and research attention. The HHI trajectory (Figure 4c) shows a shift from concentrated to diversified attention.

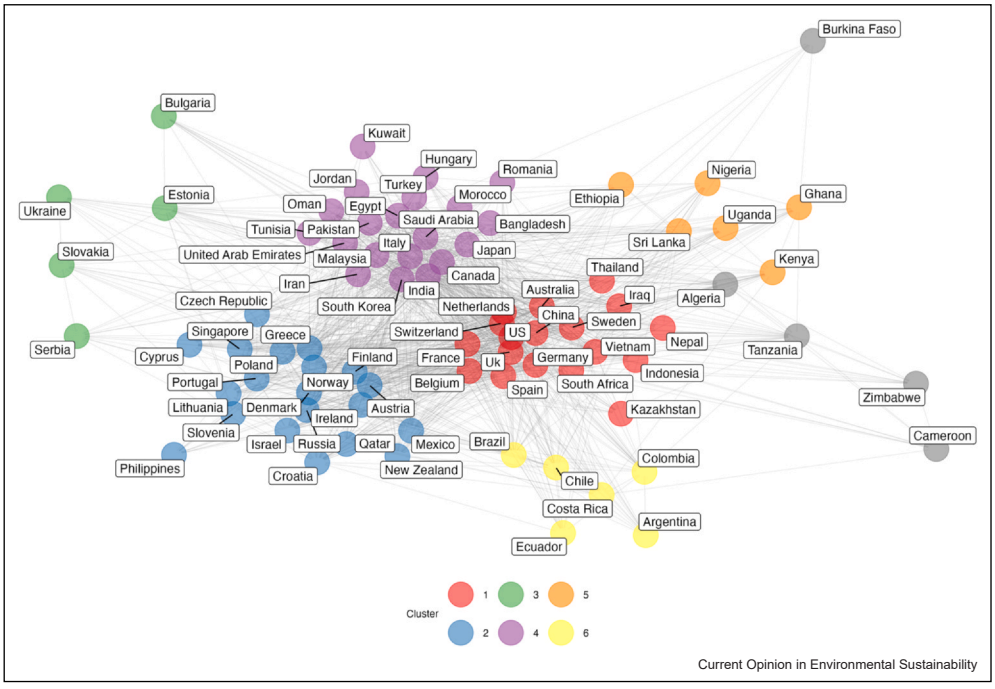
National RTA patterns track regulatory and hydrological context, not the size of the research base. China shows the highest advantage in Topic 4, consistent with the scale of biological wastewater treatment infrastructure. The US, India, and South Africa concentrate on Topic 2, consistent with groundwater stress. Poland, Turkey, Canada, and Brazil specialise in Topic 5, in line with circular-economy strategies. Portugal leads in Topic 3, reflecting contaminant-removal research. Iran, South Korea, and the UK are at the avant-guard of Topic 6

Figure 2



Leading institutions in water governance research: most productive and most cited affiliations.

Figure 3



International collaboration network (country nodes; modularity clusters). Node colour denotes the modularity cluster to which a country is assigned (Clusters 1–6). Grey nodes are countries that the modularity algorithm did not assign to any stable cluster, that is, isolates or weakly connected peripheries (e.g. Burkina Faso, Algeria, Iraq, Zimbabwe, Cameroon, and Tanzania); they are plotted for completeness but carry no cluster membership.

(Panel D), consistent with established analytics traditions in water-distribution research, although the cluster's multisector character points to broader pipeline analytics work.

Discussion

A field centred in treatment, branching into monitoring while circular recovery lags

Treatment-oriented learning dynamics (Streams 1 and 4) remain the mainstream and correspond to regulatory compliance and infrastructure modernisation [31,40]. The portfolio is diversifying: Topics 2 and 3 reflect a broader agenda linking resource security and quality protection [37,39], while detection (Topic 6) is among the fastest-growing post-2018 areas. The shift in research is toward the informational layer (sensors, anomaly detection, network simulation, predictive analytics), even as circular-economy infrastructure, a policy priority, outpaces its research base. The governance implication is that managing these systems requires interoperability standards, data-sharing arrangements, and procurement mechanisms that, in most jurisdictions, remain partially built [47,10]. The mainstream treatment focus also surfaces distributional questions absent from much of the technical literature: pricing instruments shape whether water reaches its highest-value use [48,49], while access depends on whether treatment improvements reach marginalised populations [30]. Governance responses that improve aggregate efficiency without addressing access or cost distribution may deepen rather than reduce inequality.

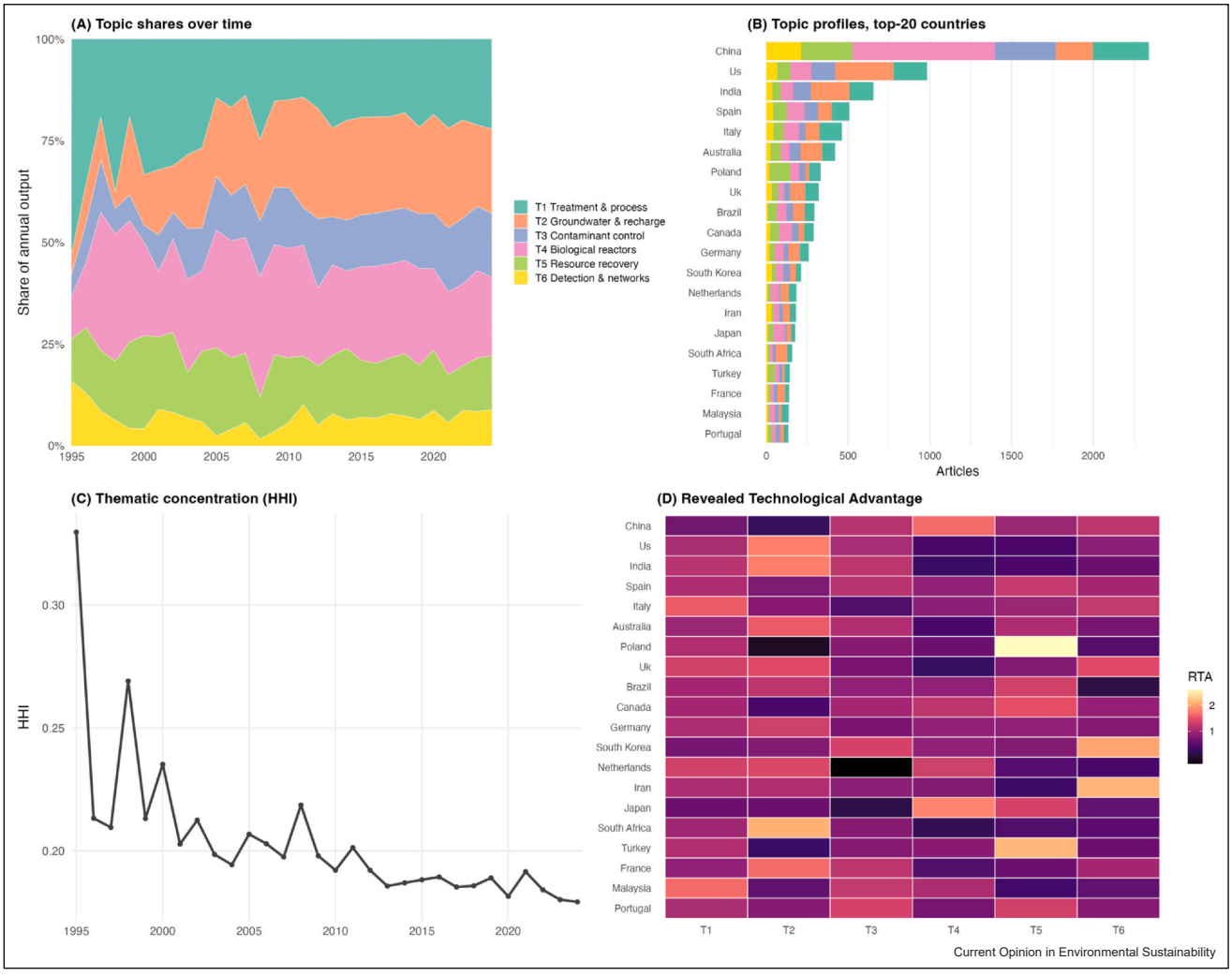
Geography and policy capacity shape thematic orientation

National specialisation tracks the regulatory and hydrological context, not research capacity. China's concentration in Topic 4 reflects municipal-scale biological treatment upgrading. India, the US, and South Africa focus on Topic 2 (groundwater and recharge), consistent with water-stress conditions [18,19]. Poland, Turkey, Canada, and Brazil specialise in Topic 5, aligned with circular-economy strategies [20,12]. Iran, South Korea, and the UK lead Topic 6, consistent with the multisector analytics traditions discussed above.

Cross-cluster relationships, system-level coordination, and methodological positioning

The six clusters are thematically distinct, and whether their themes combine within the same body of work is itself a governance question: a fragmented knowledge base steers differently from an integrated one. Three cross-instrument governance challenges sit at the seams between clusters and show where integration matters most: the regulated transition of conventional treatment

Figure 4



Topic modelling results: **(a)** topic shares of annual output (1995–2024), each year's documents allocated to their highest-γ topic and expressed as a share of that year; **(b)** topic profiles for the top 20 countries; **(c)** Hirschman-Herfindahl Index of thematic concentration; **(d)** Revealed Technological Advantage by topic. Panels **b** and **d** are computed on the 10 722 records with a non-empty abstract that received a topic assignment under the LDA model (Section Text processing, topic modelling, and indices), not on the full 11 186-record corpus of Figure 1; the national counts are therefore restricted to topic-assigned documents.

plants into circular-economy assets (made explicit by the 2024 recast of the EU Urban Wastewater Treatment Directive), which couples treatment (Topic 1) with resource recovery (Topic 5); the pairing of decentralised aquifer management (Topic 2) with abstraction telemetry; and early-warning systems for emerging contaminants, which join contaminant control (Topic 3) with detection (Topic 6). Each challenge spans clusters that the corpus treats largely separately, so the integration they require is still more agenda than achievement. The broader implication is a needed transition from isolated innovations to systems integration [3,8,13]: governance gains come from how water systems are coordinated, monitored, and anticipated, not from standalone devices. Three knowledge gaps stand out, all institutional rather than technical: the water-energy-food nexus is underrepresented relative to its policy salience; African water systems are thinly represented in detection-related research despite high exposure; and small island developing states face distinct challenges largely absent from the corpus [50,24].

Recent contributions map sector-specific slices of the circular water economy at the small-N scale: Pichis-García and Cueva-Rodríguez [16] synthesise 50 PRISMA-screened items on water governance, and Biswas and Barua [14] review 34 case studies on the circular economy in India's water sector. Each derives

governance implications through structured coding of abstracts and keywords against policy categories. The present paper applies this approach on the basis of 11 186 records and provides a full field-level cartography that situates such contributions, a field-level overview from which practical positions can be derived.

Governance implications and policy priorities

Four strategic implications follow. (i) Support the digital transition: regulatory sandboxes for prediction-oriented technologies, procurement frameworks that allow utilities to trial data-rich solutions, and a dashboard culture that turns continuous monitoring into accountability [46,47]. (ii) Consolidate circularity in established infrastructure: standardised monitoring protocols, quality controls for reuse, and contractual mechanisms that reward energy- and emission-intensity reductions [44,11,10]. (iii) Enable coordination for decentralised solutions, which cut across land-use planning, environmental licensing, and municipal finance [34,51]. Operational toolkits for local authorities and basin-situated organisations are needed [36]. (iv) Build research-and-innovation diplomacy by matching differentiated profiles; divergent specialisation between economically linked countries signals structural coordination challenges for transboundary systems.

Conclusions, limitations and avenues for the future

Since the early 1990s, the knowledge base for water governance innovation has broadened: from a treatment-dominated portfolio toward groundwater protection, decentralised supply, contaminant control, and data-driven monitoring. Specialisation patterns track national problem structures: countries with advanced regulatory infrastructure lean toward Topics 5 and 6; rapidly industrialising systems concentrate in Topics 1 and 4; hydrologically stressed regions show comparative strength in Topic 2. The frontier is moving toward circular and digitally empowered systems [52,11]. The implication for the governance frameworks proposed elsewhere in this special issue is that the empirical base on which they can draw is broadening; the governance toolkit must broaden in step.

Three limitations bound the inference. First, abstract clustering compresses technical detail and may lose granularity on actor constellations and regulatory particulars. Our framework-guided topic-to-instrument approach mitigates this through structured authorial coding (Supplementary Material, Sections S1 and S2, which are indeed methodological contributions of this paper). Second, LDA imposes soft topic boundaries; $k = 6$ is selected on both held-out perplexity and topic coherence rather than perplexity alone, since perplexity correlates only weakly with human judgements of topic quality [55] (Section S3), yet the high-γ reading set shows residual cross-sector content in Topic 6 (sensing methods used across pipeline types), which we acknowledge in the body. Third, WoS (or Scopus, for that matter) may undercount contributions from regions with different publication channels.

Two major directions for further development follow. First, patents and start-up data would surface the entry of AI and specialised systems intelligence providers into utility-scale infrastructures. Second, extended geographic coverage of Sub-Saharan Africa and Southeast Asia is needed to map innovation trajectories where governance demand is highest and research output is lowest.

Supplementary material

Supplementary material associated with this article, comprising the Web of Science search strategy (Section S1), the abstract-versus-body robustness check (Section S2), and the model-selection, topic-coherence, and temporal-dynamics diagnostics (Section S3), is available in the online version.

Data Availability

Data will be made available on request.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cosust.2026.101701.

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