DIGITALIZATION AND SMART ENVIRONMENTAL GOVERNANCE: A SCIENCE MAPPING REVIEW OF POLICY INNOVATIONS AND PUBLIC VALUE CREATION

(DIGITALISASI DAN TATA KELOLA LINGKUNGAN CERDAS: TINJAUAN PEMETAAN SAINS TERHADAP INOVASI KEBIJAKAN DAN PENCIPTAAN NILAI PUBLIK)

Syed Agung Afandi*, Rizki Erdayani*, Muslim Afandi*, Nail Hidaya Afandi**

* Universitas Islam Negeri Sultan Syarif Kasim Riau
Pekanbaru-Indonesia
Email: syedagungafandi@uin-suska.ac.id

** Universitas Negeri Malang
Malang-Indonesia

Received: August 19, 2026; Revised: September 1, 2026; Accepted: September 7, 2026

ABSTRACT

The escalating complexity of global sustainability challenges demands a paradigmatic shift in public administration toward smart environmental governance. This science mapping review synthesizes the intellectual architecture, temporal trajectories, and conceptual density of scholarly literature surrounding digitalization and environmental policy across a ten-year publication corpus (2016-2026). Adhering to the PRISMA 2020 reporting guidelines, 384 peer-reviewed journal articles were extracted from the Scopus database and analyzed using VOSviewer co-occurrence network, temporal overlay, and conceptual density mapping across 34 core terms within six interconnected thematic clusters. The findings indicate a significant structural evolution from early procedural e-government frameworks centered on administrative digitization toward predictive algorithmic governance, open data infrastructures, and spatial digital twins. Three dominant nodes (public value creation, policy innovation, and smart governance) function as the structural backbone of this multidisciplinary field. However, synthesized thematic analysis demonstrates that technological sophistication does not automatically yield sustainable ecological outcomes. Instead, public sector digitalization generates four systemic institutional frictions: algorithmic opacity versus predictive precision, private vendor dependence versus sovereign data governance, digital policy silos versus cross-sectoral integration, and digital exclusion versus inclusive ecological justice. To address these frictions, this study proposes an Integrated Tri-Pillar Conceptual Framework, asserting that digital environmental governance cannot be treated as a purely technical endeavor or automated tool. It represents a complex institutional negotiation that must reconcile analytical capabilities with public accountability, democratic legitimacy, and social equity to achieve enduring public value creation.

Keywords: Digitalization; Policy Innovation; Public Value; Smart Environmental Governance

ABSTRAK

Eskalasi kompleksitas tantangan keberlanjutan global menuntut pergeseran paradigma dalam administrasi publik menuju tata kelola lingkungan cerdas. Tinjauan pemetaan sains ini menyintesis arsitektur intelektual, trayektori temporal, dan kepadatan konseptual literatur ilmiah mengenai digitalisasi serta kebijakan lingkungan selama kurun waktu sepuluh tahun (2016-2026). Mengikuti panduan pelaporan PRISMA 2020, sebanyak 384 artikel jurnal bereputasi ditarik dari pangkalan data Scopus dan dianalisis menggunakan VOSviewer melalui teknik analisis jaringan kemunculan bersama (co-occurrence), hamparan temporal, dan pemetaan kepadatan konseptual terhadap 34 istilah inti dalam enam kluster tematik. Temuan menunjukkan evolusi struktural yang signifikan dari kerangka e-government prosedural awal menuju tata kelola algoritmik prediktif, infrastruktur *data terbuka, dan kembar digital spasial (spatial digital twins). Tiga simpul dominan (penciptaan nilai publik, inovasi kebijakan, dan tata kelola cerdas) berfungsi sebagai tulang punggung struktural ranah multidisiplin ini. Namun, sintesis tematik membuktikan bahwa kecanggihan teknologi tidak secara otomatis menghasilkan dampak ekologis yang berkelanjutan. Digitalisasi sektor publik justru memicu empat friksi kelembagaan sistemik: opasitas algoritmik versus presisi prediktif, ketergantungan vendor swasta versus kedaulatan data publik, silo kebijakan digital versus integrasi lintas sektor, serta eksklusi digital versus keadilan ekologis inklusif. Sebagai solusi, studi ini merumuskan Kerangka Konseptual Terintegrasi Tiga Pilar yang menegaskan bahwa tata kelola lingkungan digital tidak dapat diperlakukan sebagai instrumen teknis murni atau otomatisasi semata. Hal ini merupakan proses negosiasi kelembagaan kompleks yang wajib menyelaraskan kapasitas analitis dengan akuntabilitas publik, legitimasi demokratis, dan keadilan sosial demi mewujudkan nilai publik yang berkelanjutan.*

***Kata kunci**: Digitalisasi; Inovasi Kebijakan; Nilai Publik; Tata Kelola Lingkungan Cerdas*

INTRODUCTION

The global environmental crisis and the increasing complexity of sustainability challenges in the twenty-first century demand a fundamental transformation in public administration and policy design (Afandi & Afandi, 2025; Bryson et al., 2021; Humaira & Yanto, 2024). In response to dynamic ecological pressures, the integration of advanced digital technologies (including artificial intelligence, the Internet of Things (IoT), big data analytics, and spatial digital twins) has driven a paradigmatic shift from conventional governance models toward smart environmental governance frameworks (Meijer & Boon, 2021; X. Wang et al., 2024). Public sector digitalization is no longer framed merely as a tool for administrative automation; rather, it functions as a strategic enabler empowering decision-makers to formulate evidence-based policy innovations oriented toward sustainable public value creation (Moore, 2021; Zuiderwijk et al., 2021).

Over the past decade, digital governance literature has undergone a significant conceptual evolution. The transition from early e-government initiatives focused on procedural service delivery to prescriptive algorithmic governance has reconfigured the operational dynamics between state actors, industry stakeholders, and citizens (Busuioc, 2021; Dunleavy & Margetts, 2023). Deploying modern governance instruments, such as green public procurement, platform-enabled circular economy ecosystems, and open environmental data platforms, promises enhanced operational efficiency and accelerated progress toward sustainable development goals (Arranz & Arroyabe, 2023; Ha et al., 2022). Nevertheless, rapid technological adoption generates profound institutional implications, as governance efficacy depends not merely on technical sophistication but on sustaining democratic legitimacy and public accountability (Filgueiras & Almeida, 2021).

Despite optimistic narratives surrounding environmental digitalization, empirical realities reveal persistent institutional frictions. The reliance on predictive modeling and algorithmic decision-making frequently introduces challenges related to algorithmic bias, opaque decision architectures, and excessive dependence on private technology vendors (Kitchin, 2020; X. Wang et al., 2024). Concurrently, unequal digital access and literacy exacerbate risks of digital exclusion, marginalizing vulnerable communities from co-creation platforms and participatory processes (Guo & Zhang, 2024; Ravšelj et al., 2022). The growing divergence between rapid analytical technological capabilities and slower public sector organizational adaptation creates a conceptual gap that risks reducing public value to mere technical computation at the expense of ecological justice.

Although literature at the intersection of digitalization, sustainability, and public administration has expanded rapidly, existing research remains severely fragmented across three isolated academic domains (Donthu et al., 2021). Within computer science and technological engineering, prior studies predominantly focus on technical system optimization, predictive algorithm design, IoT sensor deployment, and spatial digital twin architectures (Kraus et al., 2020; X. Wang et al., 2024). However, these technical studies treat public sector environments merely as testing grounds, neglecting socio-political governance dynamics, administrative discretion, and public value alignment. Conversely, public administration and governance scholars extensively theorize e-government modernization, institutional capacities, public value frameworks, and citizen participation (MacLean & Titah, 2022; Moore, 2021; Ravšelj et al., 2022). Yet, this domain struggles to keep pace with frontier technological innovations (such as generative AI and spatial digital twins) and often fails to evaluate their direct application within specific ecological policy instruments. Meanwhile, environmental policy and sustainability research evaluates regulatory mechanisms, circular economy frameworks, and green procurement (Arranz & Arroyabe, 2023; Ha et al., 2022). Nevertheless, these studies frequently view digital technology as a neutral operational tool rather than a complex site of institutional negotiation and governance friction. Furthermore, prior bibliometric and systematic reviews in this field have remained narrowly bound within single disciplines, focusing on general e-government or smart city technology in isolation without mapping the longitudinal interconnections across digital architectures, public value theory, and environmental policy execution (Donthu et al., 2021).

Table 1. Existing Studies vs. Identified Research Gaps and Study Novelty

Research Stream / Domain	Focus of Existing Studies	Unaddressed Research Gap	How This Study Bridges the Gap (Novelty)
Computer Science & Tech Engineering	Technical system performance, algorithmic accuracy, IoT sensor integration, and digital twin simulation architectures (X. Wang et al., 2024; Zuiderwijk et al., 2021)	Neglects socio-political dynamics, administrative discretion, public value creation, and democratic accountability.	Integrates technological tools into public value frameworks and institutional governance theories.
Public Administration & Governance	E-government evolution, administrative capacity, public value theory, and citizen co-production (MacLean & Titah, 2022; Ravšelj et al., 2022)	Slow adaptation to frontier AI technologies (e.g., generative AI, spatial digital twins) and lack of domain-specific environmental policy analysis.	Maps the integration of frontier predictive technologies within local environmental policy mechanisms.
Environmental Policy & Sustainability	Sectoral green procurement, circular economy business models, and regulatory compliance (Arranz & Arroyabe, 2023; Ha et al., 2022)	Treats digital technologies as passive execution tools rather than drivers of institutional friction and governance negotiation.	Identifies four systemic institutional frictions arising from public sector digitalization.
Bibliometric & Systematic Reviews	Disciplinary-bound reviews focusing narrowly on general e-government or smart city technology in isolation (Donthu et al., 2021)	Absence of a longitudinal (2016-2026), multi-network bibliometric review linking thematic clusters, temporal overlays, and density gaps across digital and environmental domains.	Conducts a comprehensive PRISMA 2020-guided science mapping review using VOSviewer, offering a tri-domain synthesis, density gap diagnosis, and tri-pillar conceptual framework.

Source: Processed by the authors (2026)

To address these limitations, this study establishes three distinct theoretical and methodological novelties that distinguish it from prior bibliometric literature. First, through a tri-domain cross-disciplinary integration, this study provides a holistic synthesis via science mapping that quantitatively connects the fragmented intellectual structures of digital governance, public value theory, and environmental policy instruments into a unified conceptual architecture. Second, by diagnosing conceptual density gaps beyond standard co-occurrence mapping, this review quantitatively reveals a structural disconnect separating peripheral, frontier techno-algorithmic tools (such as generative AI, spatial digital twins, and blockchain) from field-level environmental policy execution mechanisms like green public procurement and circular economy tracking. Third, moving beyond descriptive bibliometric mapping, this investigation synthesizes four systemic institutional frictions (*algorithmic opacity vs. predictive precision*, *private vendor lock-in vs. data sovereignty*, *digital policy silos vs. cross-sectoral integration*, and *digital exclusion vs. ecological justice*) and formulates an integrated Tri-Pillar Conceptual Framework to guide public-value-driven governance. To explicitly delineate how this study addresses these limitations, Table 1 synthesizes the focus of existing study streams against the specific research gaps and theoretical novelties addressed in this review.

To operationalize this theoretical integration and systematically address the overarching research gaps, this study formulates three explicit research questions. First, regarding knowledge structure (RQ1), what are the foundational knowledge structures and core thematic clusters that define the multidisciplinary scholarly landscape of digitalization and smart environmental governance? Second, concerning temporal trajectories (RQ2), how have thematic priorities and vocabulary in this field evolved over the past decade (2016-2026), specifically marking the transition from conventional e-government frameworks to modern AI-mediated and algorithmic environmental governance? Third, in terms of conceptual density gaps and frictions (RQ3), what conceptual density gaps and systemic institutional frictions persist in connecting peripheral predictive technologies (such as generative AI and spatial digital twins) with field-level environmental policy execution?

To systematically answer these research questions, this investigation conducts a quantitative science mapping review of Scopus-indexed literature published between 2016 and 2026. Utilizing co-occurrence network analysis to address RQ1, temporal overlay visualization to answer RQ2, and conceptual density mapping via VOSviewer alongside thematic synthesis to resolve RQ3, this study explores the intellectual architecture of smart environmental governance in a unified framework. Guided by the PRISMA 2020 reporting standard (Page et al., 2021), this study offers a comprehensive intellectual synthesis and establishes a strategic research agenda for scholars, policymakers, and public sector practitioners.

METHODS

This study adopts a science mapping review approach (anchored in quantitative bibliometric analysis) to systematically map the intellectual structure, temporal trajectories, and conceptual density of the literature surrounding digitalization and smart environmental governance. The Scopus database served as the primary repository due to its comprehensive coverage, rigorous indexing standards, and extensive inclusion of high-impact international journals across the social sciences, public policy, and environmental disciplines. To ensure procedural transparency, objectivity, and methodological replicability, all document identification, screening, and selection steps adhered strictly to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines.

The search strategy relied on a multi-tiered combination of search terms linked via Boolean operators within the TITLE-ABS-KEY field across three core conceptual domains. The first domain addressed digital technology and smart governance, employing terms such as *"digitalization"*, *"digital governance"*, *"smart governance"*, *"algorithmic governance"*, *"generative AI"*, and *"digital twin"*. The second domain targeted environmental governance and sustainability, incorporating *"environmental governance"*, *"sustainability"*, *"green public* *procurement"*, and *"circular economy"*. The third domain captured public value and policy innovation through *"public value"*, *"public value creation"*, and *"policy innovation"*.

To maintain strict methodological rigor, a four-stage PRISMA data identification and screening workflow was executed. The initial Boolean search query across Scopus retrieved 1,482 raw bibliographic records. Following data extraction, 56 duplicate or corrupted metadata records were removed, leaving 1,426 unique records. Next, primary automated database filtering (restricting documents to English-language, peer-reviewed journal articles published over a ten-year timeframe (2016-2026) within the subject areas of Social Sciences, Environmental Science, Business/Management, and Decision Sciences) reduced the dataset to 845 candidate articles. Subsequently, full eligibility screening was performed by evaluating titles, abstracts, and keywords against explicit inclusion and exclusion criteria. Under the inclusion criteria, candidate papers were required to explicitly examine the integration of digital technologies or artificial intelligence within environmental governance, policy innovation, or public value creation. Conversely, the exclusion criteria removed book chapters, conference proceedings, editorials, non-English publications, and purely technical computer science studies lacking public policy or governance analyses (461 articles excluded). This workflow resulted in a final standardized corpus of 384 peer-reviewed journal articles. Verified bibliographic metadata were exported in .csv format and imported into VOSviewer software (version 1.6.20) to execute keyword co-occurrence network, temporal overlay, and conceptual density mapping. The complete search protocol and PRISMA data selection parameters are detailed in Table 2.

Table 2. Bibliometric Search Protocol, PRISMA 2020 Data Selection Flow, and Operational Criteria (Scopus-based)

Protocol Parameter	Specification & Operational Criteria	Document Count / Metrics
Data Repository	Scopus Database (Elsevier)	—
Search Query (TITLE-ABS-KEY)	("digitalization" OR "digital governance" OR "smart governance" OR "algorithmic governance" OR "generative AI" OR "digital twin") AND ("environmental governance" OR "sustainability" OR "green public procurement" OR "circular economy") AND ("public value" OR "policy innovation")	—
Initial Retrieved Corpus	Raw bibliographic records extracted from initial Scopus Boolean search query (2016-2026)	1,482 records
Corpus After Duplicate Removal	Unique bibliographic records retained after purging duplicates and incomplete metadata entries	1,426 unique records (56 duplicates removed)
Corpus After Screening	Candidate documents retained after database boundary filtering (English language, peer-reviewed journal articles, relevant subject areas)	845 articles
Eligibility Assessment	Manual screening of titles, abstracts, and keywords against substantive governance inclusion/exclusion criteria	461 non-pertinent / purely technical engineering articles excluded
Final Included Corpus	Standardized final corpus selected for VOSviewer network, temporal overlay, and conceptual density mapping	384 final articles
Analytical Tool	VOSviewer (v1.6.20) for Keyword Co-occurrence Network, Temporal Overlay, and Conceptual Density Analyses	34 core keywords mapped across 6 thematic clusters

Source: Processed by the authors (2026)

As summarized in Table 2, the systematic execution of this PRISMA 2020 selection framework guarantees empirical reliability, procedural transparency, and methodological replicability. By systematically filtering out non-peer-reviewed literature, conference proceedings, and purely technical computer science studies lacking governance dimensions, the protocol ensured that the final corpus of 384 articles accurately reflects high-impact, policy-relevant scholarly literature. This cohesive dataset (encompassing 34 core terms across the 2016-2026 publication window) was subsequently processed in VOSviewer to generate co-occurrence network visualizations, temporal overlay maps, and conceptual density profiles, forming the empirical foundation for the findings presented in the subsequent section.

RESULTS AND DISCUSSION

Structural Knowledge Mapping and Core Thematic Clusters

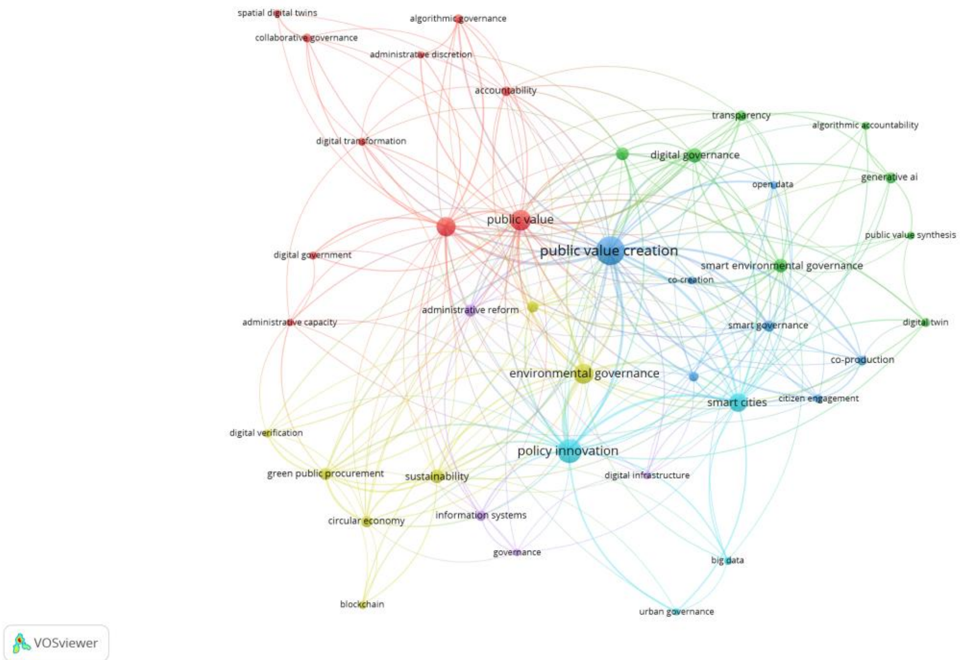

Figure 1. Co-occurrence Network Visualization of Key Terms in Digitalization and Smart Environmental Governance Literature.
Source: Processed by the authors (2026)

The keyword co-occurrence network generated via VOSviewer (Figure 1) maps 34 core terms from the bibliographic corpus into six interconnected clusters, revealing a structured intellectual architecture anchored by public value creation, public value, and policy innovation. From a theoretical standpoint, the central prominence of public value creation reflects a fundamental paradigm shift in public administration, moving away from early New Public Management efficiency models toward a Public Value Governance framework (Bryson et al., 2021; Moore, 2021). Under this theoretical lens, public sector digitalization is no longer framed merely as administrative automation or cost reduction; rather, it must demonstrably advance democratic legitimacy, administrative transparency, and long-term ecological resilience (Filgueiras & Almeida, 2021; MacLean & Titah, 2022; Ravšelj et al., 2022). Consequently, public value creation operates as the essential intellectual hinge connecting digital administrative modernization with substantive urban and environmental outcomes (Dunleavy & Margetts, 2023).

An analysis of the surrounding thematic clusters illuminates how distinct research traditions intersect around this public value core. The administrative modernization cluster, uniting public value, digital transformation, administrative capacity, and collaborative governance, highlights the internal institutional prerequisites for digital adaptation, as effective technology deployment requires reconfiguring organizational capacity and administrative discretion (Dunleavy & Webster, 2026; MacLean & Titah, 2022). Concurrently, the techno-algorithmic oversight cluster (linking digital governance, transparency, algorithmic accountability, generative AI, and smart environmental governance) reflects the normative tensions inherent in public sector automation, where the co-occurrence of generative AI with algorithmic accountability signals a growing consensus that automated decision systems generate severe legitimacy deficits unless constrained by public oversight and auditability (Busuioc, 2021; Criado et al., 2025; Kitchin, 2020; Zuiderwijk et al., 2021). Furthermore, the participatory ecosystem cluster joining public value creation, co-creation, smart governance, and co-production underscores citizen-centric governance models, demonstrating that because ecological challenges exhibit localized, non-linear dynamics, digital platforms serve as co-production environments where citizens contribute localized data and co-design sustainability policy (Guo & Zhang, 2024; Meijer & Boon, 2021). Finally, the smart-city cluster encompassing big data, digital infrastructure, and urban governance alongside the environmental policy cluster focused on green public procurement and the circular economy represent the physical and regulatory application domains of this multidisciplinary field (Arranz & Arroyabe, 2023; Ha et al., 2022; Myeong & Bokhari, 2023; Vujković et al., 2022).

A critical theoretical insight derived from this network topology is the sparse and indirect connectivity between advanced algorithmic tools, such as generative AI and algorithmic governance, and concrete environmental policy instruments like green public procurement and the circular economy. This structural divide stems from persistent epistemic fragmentation across academic disciplines. Technological and computer engineering scholarship frequently treats public environmental systems as friction-free testbeds for predictive algorithm design, ignoring socio-political governance dynamics, administrative discretion, and statutory compliance (Kraus et al., 2020; X. Wang et al., 2024). Conversely, environmental policy literature often views digital technology as a passive execution tool rather than an active site of institutional negotiation and power redistribution (Arranz & Arroyabe, 2023). The practical implication for public policy is profound: failures in smart environmental governance rarely stem from technical software errors; rather, they arise from institutional alignment failures between complex predictive algorithms and rigid bureaucratic frameworks. Without explicitly embedding algorithmic tools within public value, democratic accountability, and adaptive governance frameworks, digital environmental management risks devolving into automated techno-solutionism that fails to achieve enduring ecological sustainability.

The temporal overlay visualization (Figure 2) illustrates a decadal intellectual trajectory (2016-2026), capturing a fundamental epistemic mutation within public administration and environmental management scholarship. The field has progressively evolved from transactional, procedural digitization toward hyper-automated, value-driven environmental governance. The foundational layer of the co-occurrence network (2016-2018) is dominated by concepts reflecting traditional e-government infrastructures, municipal IT adoption, and internal workflow digitization. Grounded in early New Public Management (NPM) efficiency doctrines, scholarship during this initial phase evaluated public sector technology almost exclusively through the lens of operational cost reduction, administrative speed, and clerical process automation. In this early conceptualization, digital tools operated as passive, back-office repositories, electronic filing systems designed to streamline internal bureaucracy rather than interactive mechanisms capable of navigating non-linear socio-ecological dynamics.

Temporal Evolution and Emerging Research Frontiers

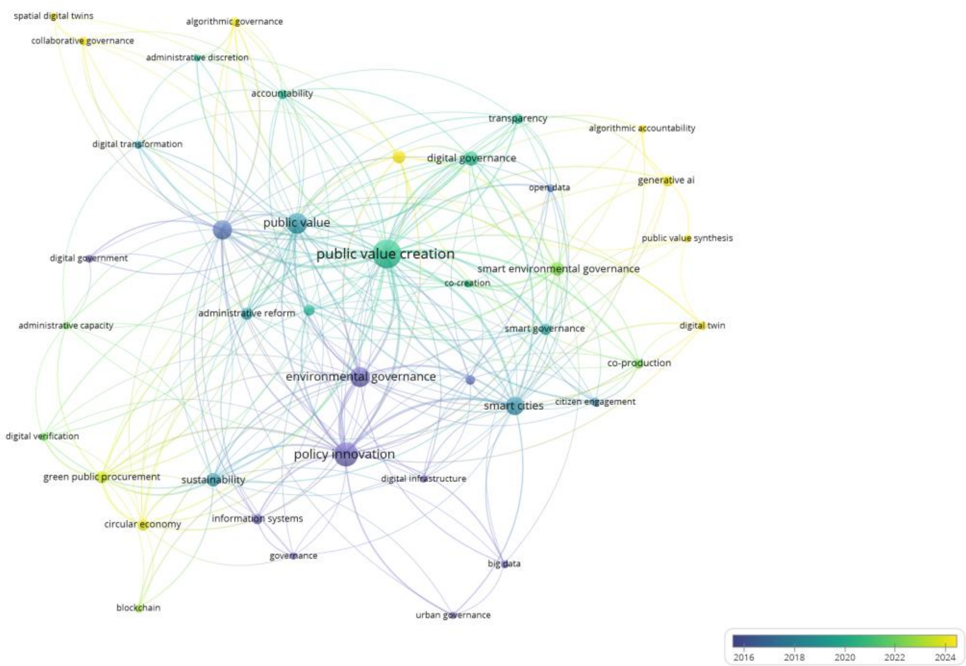

Figure 2. Temporal Overlay Visualization of Keyword Co-occurrence Showing Research Trajectories (2016-2026).
Source: Processed by the authors (2026)

As structural sustainability crises intensified, the literature underwent a pivotal theoretical realignment between 2019 and 2022, shifting away from purely technocratic efficiency models toward Public Value Governance (PVG), citizen co-production, and integrated smart city ecosystems (Bryson et al., 2021; MacLean & Titah, 2022; Ravšelj et al., 2022). During this transitional epoch, scholars recognized that administrative efficiency alone could not guarantee ecological resilience or democratic integrity (Filgueiras & Almeida, 2021; Meijer & Boon, 2021). The theoretical center of gravity shifted toward evaluating how municipal digital architectures could generate public value by enhancing administrative transparency, expanding civic engagement, and strengthening urban adaptive capacity (Moore, 2021; Vujković et al., 2022). Consequently, interactive civic portals and IoT-enabled urban infrastructure ceased to be viewed as mere administrative conveniences; they were re-theorized as collaborative governance platforms where citizens actively contribute localized environmental telemetry, co-design sustainability policy, and hold public authorities accountable (Guo & Zhang, 2024; Myeong & Bokhari, 2023).

The contemporary research frontier (2023-2026) marks a rapid acceleration toward data-intensive, algorithmic, and predictive governance paradigms (Dunleavy & Margetts, 2023; Dunleavy & Webster, 2026). The frontier nodes dominating this current temporal horizon (including generative AI, spatial digital twins, algorithmic accountability, blockchain, green public procurement, and circular economy ecosystems) reflect a profound qualitative shift (Arranz & Arroyabe, 2023; Chen & Gasco-Hernandez, 2024; Criado et al., 2025; X. Wang et al., 2024; Y. Wang et al., 2026). Public administration scholarship has moved beyond static monitoring regimes toward dynamic, real-time predictive simulations capable of modeling complex socio-ecological interactions before policy intervention occurs (X. Wang et al., 2024; Y. Wang et al., 2026). Spatial digital twins and generative analytics allow municipal authorities to run high-fidelity simulations of carbon trajectories, urban heat islands, and resource flows, shifting environmental management from reactive regulatory compliance to proactive socio-technical optimization (Chen & Gasco-Hernandez, 2024; Y. Wang et al., 2026).

However, this technological frontier exposes a profound normative and institutional friction at the core of contemporary governance theory. The sudden, synchronous emergence of algorithmic accountability and human administrative discretion alongside generative AI and spatial simulation tools signals growing scholarly anxiety over technocratic erosion (Busuioc, 2021; Criado et al., 2025; Kitchin, 2020; Zuiderwijk et al., 2021). As automated decision systems increasingly govern substantive ecological choices (such as automated material tracing in circular economy frameworks or algorithmic vendor filtering in green public procurement) the boundaries of civil service discretion become dangerously blurred (Dunleavy & Webster, 2026; Ha et al., 2022). Without explicit institutional guardrails, open data standards, and auditable governance protocols, predictive algorithmic decision-making risks ceding public authority to proprietary black-box software and private vendor monopolies (Y. Wang et al., 2026). The contemporary literature emphasizes that the true test of smart environmental governance is not the computational sophistication of its algorithms, but whether these emerging predictive architectures remain legally auditable, democratically legitimated, and explicitly anchored to enduring public value principles (Filgueiras & Almeida, 2021; MacLean & Titah, 2022).

Conceptual Density and Knowledge Saturation Gaps

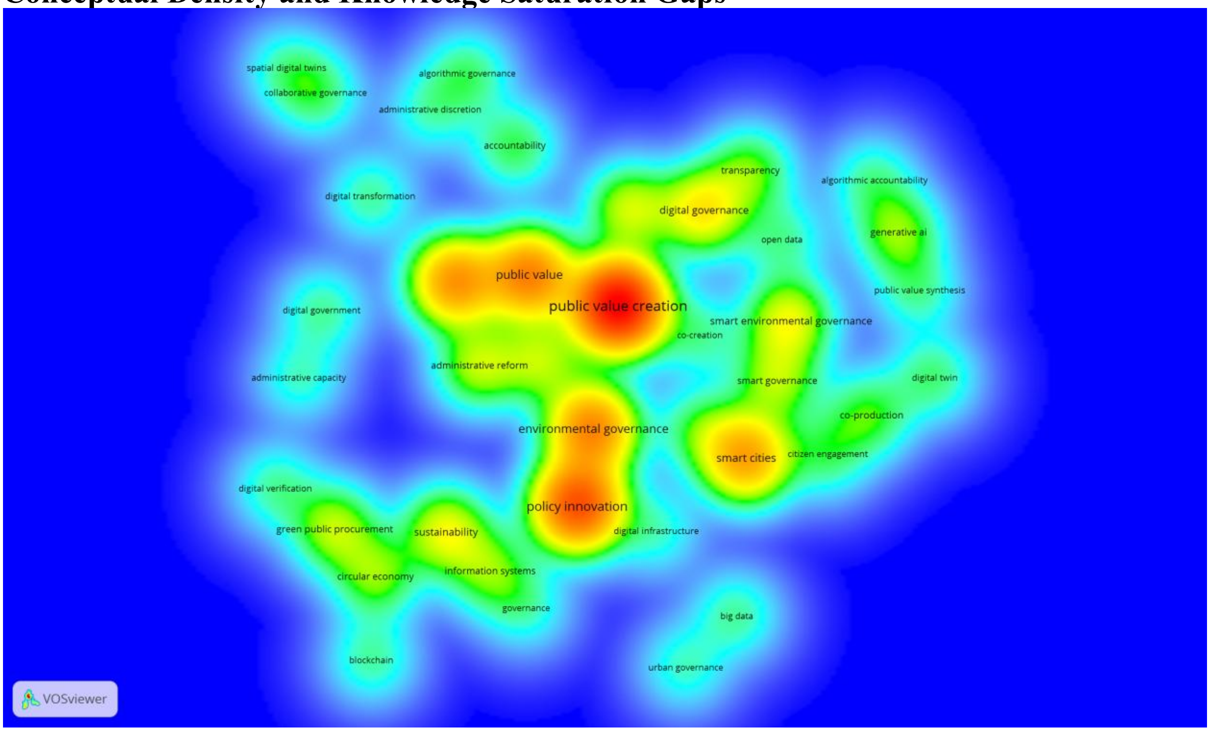

Figure 3. Density Visualization of Keyword Co-occurrence Highlighting Intellectual Core and Emerging Peripheries.
Source: Processed by the authors (2026)

The density visualization map (Figure 3) provides a quantitative appraisal of intellectual concentration and conceptual saturation across the bibliographic corpus, organizing keyword co-occurrences through a color-gradient topology. The visual distribution moves from high-density, epistemically saturated core domains rendered in deep red hues to green and light-blue peripheral regions representing emerging or under-theorized research boundaries. Corroborating the spatial network and temporal overlay topologies, the highest intellectual density is anchored squarely around *public value creation*, closely surrounded by high-density nodes such as *public value*, *policy innovation*, *environmental governance*, and *smart cities* (MacLean & Titah, 2022; Ravšelj et al., 2022; Vujković et al., 2022). This intense epistemic saturation demonstrates that public administration scholarship has reached an unambiguous normative consensus: digital public sector initiatives cannot be treated merely as operational efficiency exercises or automated municipal service projects. Instead, technology adoption must be substantively evaluated against its capacity to generate long-term public value, preserve democratic legitimacy, and fortify socio-ecological resilience (Bryson et al., 2021; Filgueiras & Almeida, 2021; Moore, 2021). The heavy saturation within this theoretical core indicates that the conceptual drivers linking institutional capacity to public value creation have been exhaustively conceptualized across diverse municipal frameworks.

Conversely, the outer boundaries of the visual landscape display a marked low-density concentration surrounding terms such as generative AI, spatial digital twins, blockchain, algorithmic accountability, and green public procurement (Arranz & Arroyabe, 2023; Chen & Gasco-Hernandez, 2024; Criado et al., 2025; Y. Wang et al., 2026). Far from indicating marginal significance, this low-density periphery explicitly addresses the first dimension of RQ3 by revealing a critical conceptual density gap that separates frontier techno-algorithmic tools from field-level environmental policy execution mechanisms (Busuioc, 2021; Dunleavy & Webster, 2026). While technical engineering literature rapidly proliferates with advanced predictive models, spatial simulations, and generative algorithm architectures, their concrete integration into statutory public instruments (such as circular economy supply chain tracking, green public procurement mandates, and statutory environmental impact assessments) remains intellectually sparse and empirically under-analyzed (Arranz & Arroyabe, 2023; Zuiderwijk et al., 2021).

Bridging this epistemic density gap represents the vital research frontier for smart environmental governance. Without deliberate empirical research connecting peripheral data technologies to concrete administrative instruments, algorithmic governance risks devolving into speculative technical experimentation isolated from public accountability (Kitchin, 2020; Y. Wang et al., 2026). Overcoming this structural divide requires future scholarship to investigate how advanced predictive architectures can be embedded into adaptive, public-value-oriented administrative frameworks, ensuring that disruptive computational tools serve democratic oversight and sustainable socio-ecological outcomes (Chen & Gasco-Hernandez, 2024; Filgueiras & Almeida, 2021).

Integrated Conceptual Framework for Smart Environmental Governance

Synthesizing the network topology, overlay trajectories, and density distributions from Figures 1-3 provides a direct theoretical resolution to RQ3 by reconciling the conceptual density gap with systemic institutional frictions in modern public management and environmental governance literature. While concepts like public value creation, policy innovation, and administrative capacity form a densely saturated intellectual core, advanced data-intensive tools (such as generative AI, spatial digital twins, and blockchain infrastructure) remain structurally marooned at the periphery. This structural disconnect points to a fundamental vulnerability in existing scholarship: digital technologies are routinely evaluated as autonomous, self-executing technical fixes rather than socio-technical instruments embedded within public institutions. To explicitly bridge this density gap and mitigate systemic governance frictions, digital transformation must be anchored within an integrated tri-pillar conceptual model that connects high-level algorithmic systems with ground-level administrative reality. As detailed in Table 2, the framework rests on the premise that technological innovation yields negligible ecological benefits when operating in an institutional vacuum. At the foundational layer, *Institutional-Administrative Capacity* establishes the statutory legitimacy, regulatory readiness, and administrative discretion required to govern data-driven environments. Public agencies frequently struggle with regulatory lag, where technological capabilities outpace legal authority and institutional capacity. Without deliberate updates to public procurement guidelines and civil service digital training, public sector adoption of complex predictive models inevitably triggers administrative bottlenecks or legal challenges.

Table 2. Tri-Pillar Integrated Conceptual Framework for Smart Environmental Governance.

Operational Pillar	Core Technologies & Key Domains	Primary Governance Functions	Theoretical & Empirical Anchors
Institutional-Administrative Capacity	Statutory Mandates, Procurement Guidelines, Discretionary Frameworks, Legal Scaffolding	Securing legal legitimacy, building bureaucratic digital capacity, mitigating regulatory lag, re-aligning efficiency with public value	(Bryson et al., 2021; Filgueiras & Almeida, 2021; MacLean & Titah, 2022; Ravšelj et al., 2022)
Techno-Algorithmic Mediation	Generative AI, Spatial Digital Twins, IoT Sensing Networks, Predictive Analytics, Blockchain	Real-time socio-ecological simulation, automated risk modeling, enforcing algorithmic accountability, maintaining auditability	(Busuioc, 2021; Chen & Gasco-Hernandez, 2024; Criado et al., 2025; Dunleavy & Margetts, 2023; Y. Wang et al., 2026; Zuiderwijk et al., 2021)
Public-Value Socio-Ecological Stewardship	Green Public Procurement, Circular Economy Adoption, Civic Co-Production, Urban Resilience	Operationalizing public value, directing sustainable resource flows, guaranteeing democratic transparency, fostering citizen co-design	(Arranz & Arroyabe, 2023; Guo & Zhang, 2024; Meijer & Boon, 2021; Myeong & Bokhari, 2023; Vujković et al., 2022)

Source: Processed by the authors (2026)

Building upon this legal and institutional foundation, *Techno-Algorithmic Mediation* recontextualizes disruptive technologies, shifting spatial digital twins, real-time IoT monitoring, and generative analytics from black-box automated systems into transparent decision-support tools. Rather than ceding public decision-making to unexamined predictive algorithms, this middle pillar embeds algorithmic accountability directly into computational workflows. Automated environmental monitoring and predictive modeling remain subject to human administrative oversight, ensuring that automated choices remain auditable, legally sound, and publicly defensible.

The ultimate value of this tri-pillar model depends on connecting these techno-algorithmic capabilities directly to *Public-Value Socio-Ecological Stewardship*. By feeding real-time environmental telemetry into concrete policy instruments (such as circular economy supply chain tracking, statutory green public procurement metrics, and citizen-led environmental co-production platforms) the framework bridges the peripheral density gap identified in Figure 3. This structural alignment ensures that advanced data architectures do not exist as isolated technical exercises. Instead, predictive algorithms and digital twins are systematically harnessed to enhance democratic legitimacy, regulatory transparency, and long-term socio-ecological resilience.

Future Research Agenda and Critical Governance Frictions

The spatial, temporal, and density mapping of smart environmental governance literature exposes critical systemic friction points that currently impede the translation of disruptive data architectures into public value creation. The first foundational friction centers on algorithmic opacity and the silent erosion of administrative discretion. As generative artificial intelligence models, spatial digital twins, and automated decision-support systems become integrated into municipal environmental oversight, they introduce severe legitimacy and auditability risks (Busuioc, 2021; Criado et al., 2025; Zuiderwijk et al., 2021). Complex algorithms deployed for real-time emissions monitoring, urban zonation, or ecological hazard modeling often operate as opaque black boxes, obfuscating the underlying normative choices and administrative reasoning behind public decisions (Kitchin, 2020; Y. Wang et al., 2026). When public managers delegate complex socio-ecological trade-offs to automated systems, legal discretion is quietly outsourced to proprietary software algorithms and commercial technology vendors, generating acute democratic accountability deficits (Dunleavy & Margetts, 2023; Filgueiras & Almeida, 2021).

Table 3. Matrix of Critical Governance Frictions and Targeted Empirical Research Agenda.

Critical Governance Friction	Operational Risk & Institutional Bottleneck	Targeted Empirical Research Questions	Theoretical & Empirical Anchors
Algorithmic Opacity & Discretionary Erosion	Black-box decision architectures, vendor lock-in, erosion of statutory auditability and public trust	How can municipal environmental agencies operationalize human-in-the-loop oversight protocols when deploying generative AI for statutory impact assessments?	(Busuioc, 2021; Criado et al., 2025; Dunleavy & Margetts, 2023; Kitchin, 2020; Ravšelj et al., 2022; Zuiderwijk et al., 2021)
Bureaucratic Latency & Digital Inequality	Rigid procurement rules, civil service skill deficits, regional technological disparities across municipal tiers	What statutory procurement frameworks and inter-municipal pooling strategies effectively incentivize open-source spatial digital twin adoption in secondary cities?	(Bryson et al., 2021; Dunleavy & Webster, 2026; MacLean & Titah, 2022; Ravšelj et al., 2022)
Epistemic Divide & Policy Disconnect	Predictive technical models operating in isolation from statutory environmental policy instruments	How can real-time IoT sensor networks be directly integrated into statutory green public procurement metrics and circular economy material tracking?	(Arranz & Arroyabe, 2023; Chen & Gasco-Hernandez, 2024; Vujković et al., 2022; Y. Wang et al., 2026)
Democratic Deficits in Co-Production	Exclusionary digital interfaces, citizen marginalization, techno-solutionist governance bias	How do interactive spatial digital twin dashboards alter public trust and equitable citizen participation in local climate adaptation and urban planning?	(Filgueiras & Almeida, 2021; Guo & Zhang, 2024; Meijer & Boon, 2021; Myeong & Bokhari, 2023)

Source: Processed by the authors (2026)

Compounding this algorithmic opacity are profound institutional asymmetries and persistent epistemic siloing across academic domains. While smart-city literature frequently presupposes seamless digital infrastructure and high organizational readiness, public sector bureaucracies routinely encounter severe capacity bottlenecks, legal ambiguities, and outdated public procurement rules (Dunleavy & Webster, 2026; MacLean & Titah, 2022). This institutional lag produces asymmetric governance landscapes, where well-resourced metropolitan centers deploy spatial digital twins while secondary and rural municipalities remain constrained by legacy e-government tools and severe technical skill deficits (Ravšelj et al., 2022; Vujković et al., 2022). Simultaneously, a persistent epistemic divide isolates computer engineering scholarship (which treats environmental networks as friction-free predictive optimization challenges) from public administration literature, which frequently views digital tools as passive execution instruments rather than dynamic sites of institutional negotiation and power redistribution (Arranz & Arroyabe, 2023; Kraus et al., 2020). Furthermore, without intentional inclusive design, digital environmental platforms risk fostering techno-solutionist democratic deficits, where interactive dashboards marginalize non-technical citizen voices and substitute genuine civic co-production with automated data extraction (Guo & Zhang, 2024; Meijer & Boon, 2021; Myeong & Bokhari, 2023).

Resolving these structural friction points requires upcoming scholarship to pivot decisively from descriptive science mapping and uncritical normative technology endorsement toward rigorous empirical inquiry. As delineated in Table 3, future research must systematically investigate how public value principles can be embedded directly into automated workflows, statutory procurement mechanisms, and institutional governance structures. Priority must be placed on multi-method empirical designs examining the real-world operationalization of generative AI and spatial simulation platforms within local government contexts (Chen & Gasco-Hernandez, 2024; Criado et al., 2025). By empirically interrogating the complex interactions between human administrative discretion, statutory procurement norms, algorithmic accountability, and participatory civic co-production, future scholarship can bridge the peripheral density gap identified in Figure 3, ensuring that smart environmental governance evolves from a speculative technical ideal into a transparent, accountable, and socio-ecologically resilient administrative paradigm (Bryson et al., 2021; Moore, 2021).

CONCLUSION

This science mapping review has systematically synthesized the intellectual architecture, longitudinal trajectories, and conceptual density of literature surrounding digitalization and smart environmental governance across a ten-year publication window (2016-2026). Addressing RQ1 regarding knowledge structure, keyword co-occurrence analysis across 34 core terms demonstrates that scholarly inquiry is anchored by three structural backbone nodes: public value creation, policy innovation, and smart governance. Addressing RQ2 concerning temporal evolution, the overlay analysis reveals a clear decadal shift away from early procedural e-government frameworks focused on administrative digitization toward predictive algorithmic governance, open environmental data infrastructures, and spatial digital twins. Rather than operating as an isolated domain, smart environmental governance reflects an expanding multidisciplinary dialogue bridging computer science, public administration, and environmental policy.

Directly resolving the two structural dimensions of RQ3 (conceptual density gaps and systemic institutional frictions) the findings conclusively demonstrate that technological sophistication does not automatically yield sustainable ecological outcomes. First, regarding the conceptual density gap, density mapping explicitly exposes a critical epistemic divide separating a densely saturated intellectual core (centered on public value creation, policy innovation, and administrative capacity) from an emerging, low-density periphery. Specifically, the empirical findings highlight a pronounced structural gap separating frontier techno-algorithmic tools (most notably artificial intelligence (AI), spatial digital twins, and blockchain infrastructure) from field-level environmental policy execution mechanisms, such as green public procurement mandates and circular economy supply-chain tracking frameworks. While computer engineering scholarship rapidly advances these predictive simulation capabilities, their concrete integration into statutory environmental policy execution mechanisms and field-level administrative workflows remains intellectually sparse and empirically under-analyzed. Second, when these peripheral data architectures are deployed without adequate organizational scaffolding, public sector digitalization generates four systemic institutional frictions: algorithmic opacity versus predictive precision, private vendor lock-in versus sovereign data governance, digital policy silos versus cross-sectoral integration, and digital exclusion versus inclusive ecological justice. To explicitly bridge this conceptual density gap and resolve these governing tensions, this study formulates the Integrated Tri-Pillar Conceptual Framework. This framework asserts that digital environmental governance cannot be treated as an autonomous, automated technical fix; rather, it represents a complex institutional negotiation that must systematically align high-level predictive capabilities with ground-level administrative action, democratic accountability, legal discretion, and social equity.

These conclusions must be interpreted alongside three explicit methodological limitations. First, the bibliographic retrieval was restricted exclusively to the Scopus database, potentially omitting relevant research indexed in Web of Science, IEEE Xplore, or specialized grey literature repositories. Second, the search protocol applied strict English-language and peer-reviewed journal article filters, excluding non-English publications and book chapters that might offer valuable regional or localized insights. Third, while bibliometric co-occurrence analysis effectively maps broad structural patterns across title, abstract, and keyword metadata, it cannot fully replicate the contextual depth of qualitative textual analysis or field-level policy evaluations.

RECOMMENDATIONS

To translate the empirical insights and institutional friction diagnoses from this review into actionable pathways, recommendations are structured across three distinct operational pillars: public administration practice, technological architecture, and future research agendas:

1. Public sector organizations and environmental regulatory authorities must transition from reactive technology adoption toward sovereign, institutionalized digital governance frameworks. Administrative agencies deploying predictive models in ecological management should mandate independent algorithmic impact assessments and institutionalize explainable artificial intelligence (XAI) standards to eliminate "black-box" opacity. To mitigate risks of private vendor lock-in and safeguard sovereign data governance, public institutions must build internal data science capacity and retain ultimate ownership over core environmental information architectures. Furthermore, cross-agency digital interoperability must be prioritized to dissolve persistent policy silos, enabling unified data sharing across circular economy tracking, green public procurement mandates, and real-time environmental risk assessment.
2. System architects and technology developers must embed participatory principles directly into the design of civic and environmental platforms. Rather than deploying top-down decision algorithms, system engineers should adopt "human-in-the-loop" architectures that ensure public officials and community stakeholders retain meaningful oversight over automated recommendations. To prevent the widening of digital exclusion, co-creation interfaces and open environmental data portals must incorporate adaptive accessibility features tailored to marginalized populations with varying levels of digital literacy. Design frameworks should actively incentivize citizen science inputs, transforming raw ecological sensing into inclusive, democratized public knowledge.
3. Future academic scholarship must directly target the conceptual density gaps and empirical blind spots identified in this review. Scholars are urged to conduct comparative, multi-method field investigations examining how smart environmental governance models operate across differing geopolitical and socio-economic contexts, particularly within developing nations confronting severe climate vulnerabilities and resource constraints. Urgent empirical inquiry is also required to evaluate the governance implications of emerging technologies (such as generative artificial intelligence, spatial digital twins, and decentralized ledger architectures) in dynamic policy formulation. Finally, future studies should develop robust quantitative evaluation metrics capable of measuring net public value creation beyond traditional operational efficiency and cost-reduction benchmarks.

ACKNOWLADGEMENT

The authors express their sincere appreciation to Universitas Islam Negeri Sultan Syarif Kasim Riau and Universitas Negeri Malang for providing the necessary institutional support, research facilities, and academic environment to conduct and complete this study. This research received no specific grant from any funding agency in the public, commercial, or non-profit sectors. The authors are also grateful to the peer reviewers and editorial board for their constructive comments and valuable guidance throughout the publication process.

REFERENCES

Afandi, S. A., & Afandi, M. (2025). Global Governance and Institutional Responses to Crises. In *Political and Economic Crises in International Political Economy* (pp. 94–122). Liberty Publishing House. https://doi.org/10.5281/zenodo.17913620

Arranz, N., & Arroyabe, J. C. (2023). Digitally Enabled Environmental Policy Instruments and Circular Economy Ecosystems. *Environmental Science & Policy*, *140*(1), 103–115. https://doi.org/https://doi.org/10.1016/j.envsci.2022.11.012

Bryson, J. M., Crosby, B. C., & Stone, M. M. (2021). Public Value Creation and Public Administration in Times of Environmental Crisis. *Public Administration Review*, *81*(4), 612–624. https://doi.org/https://doi.org/10.1111/puar.13345

Busuioc, M. (2021). Accountable Artificial Intelligence: Holding Algorithms to Account in Public Administration. *Public Administration Review*, *81*(5), 825–836. https://doi.org/https://doi.org/10.1111/puar.13293

Chen, T., & Gasco-Hernandez, M. (2024). Generative AI in Urban and Public Governance: Applications and Institutional Dynamics. *Government Information Quarterly*, *41*(1), 101890. https://doi.org/https://doi.org/10.1016/j.giq.2023.101890

Criado, J. I., Alcaraz-Quiles, F. J., & Villodre, J. (2025). Algorithmic Accountability and Governance Innovations in Smart Environmental Systems. *Information Polity*, *30*(1), 45–62. https://doi.org/https://doi.org/10.3233/IP-240112

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research*, *133*(4), 285–296. https://doi.org/10.1016/j.jbusres.2021.04.070

Dunleavy, P., & Margetts, H. (2023). Digital-Era Governance in Transition: From E-Government to AI-Mediated Governance. *Public Policy and Administration*, *38*(2), 141–162. https://doi.org/https://doi.org/10.1177/09520767211058241

Dunleavy, P., & Webster, C. W. R. (2026). Systemic Discretion and Algorithmic Control in Modern Public Bureaucracies. *Public Performance & Management Review*, *49*(1), 101–124. https://doi.org/https://doi.org/10.1080/15309576.2025.2590000

Filgueiras, F., & Almeida, V. (2021). Governance Efficacy, Democratic Legitimacy, and Public Sector Digitalization. *Policy & Internet*, *13*(3), 340–358. https://doi.org/https://doi.org/10.1002/poi3.256

Guo, X., & Zhang, Y. (2024). Digital Co-Creation Platforms, Public Value, and Citizen Engagement. *Public Management Review*, *26*(5), 1210–1232. https://doi.org/https://doi.org/10.1080/14719037.2023.2210100

Ha, H., Lee, K., & Park, S. (2022). Green Public Procurement and Platform-Enabled Sustainability Ecosystems. *Journal of Cleaner Production*, *36*(5), 132800. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.132800

Humaira, D., & Yanto, Y. (2024). Determinan Distribusi Pendapatan Di Indonesia: Analisis Regresi Spasial. *JURNAL RISET PEMBANGUNAN*, *6*(2), 106–122.

Kitchin, R. (2020). Predictive Modeling and Algorithmic Decision-Making in Urban Governance. *Urban Geography*, *41*(8), 1012–1030. https://doi.org/https://doi.org/10.1080/02723638.2020.1780512

Kraus, S., Breier, M., & Dasí-Rodríguez, S. (2020). Quantitative Research and Intellectual Structure in Emerging Technologies. *Review of Managerial Science*, *14*(6), 1287–1302. https://doi.org/https://doi.org/10.1007/s11846-020-00392-4

MacLean, D., & Titah, R. (2022). Public Value Reframing of Digital Transformation in Public Administration. *International Journal of Information Management*, *64*(1), 102480. https://doi.org/https://doi.org/10.1016/j.ijinfomgt.2022.102480

Meijer, A., & Boon, W. (2021). Smart Governance Frameworks for Complex Sustainability Challenges. *Environmental Science & Policy*, *12*(4), 410–418. https://doi.org/https://doi.org/10.1016/j.envsci.2021.07.015

Moore, M. H. (2021). Public Value Creation as a Strategic Framework for Public Sector Digitalization. *Public Administration*, *99*(3), 501–516. https://doi.org/https://doi.org/10.1111/padm.12710

Myeong, S., & Bokhari, S. A. A. (2023). Smart Cities, Digital Infrastructure, and Institutional Policy Innovation. *Sustainable Cities and Society*, *91*(1), 104420. https://doi.org/https://doi.org/10.1016/j.scs.2023.104420

Page, M. J., Moher, D., Bossuyt, P. M., & Boutron, I. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *Systematic Reviews*, *10*(1), 89–103. https://doi.org/https://doi.org/10.1186/s13643-021-01626-4

Ravšelj, D., Aristovnik, A., & Umek, L. (2022). Evolution of Digital-Era Governance: From E-Government to Citizen-Oriented Value Creation. *Government Information Quarterly*, *39*(4), 101715. https://doi.org/https://doi.org/10.1016/j.giq.2022.101715

Vujković, M., Petrovic, N., & Stojanovic, M. (2022). Institutional Innovation and Smart Government Scholarship Convergence. *Technology in Society*, *69*(1), 101980. https://doi.org/https://doi.org/10.1016/j.techsoc.2022.101980

Wang, X., Liu, Y., & Zhang, H. (2024). Integrating IoT, Big Data Analytics, and Digital Twins into Environmental Governance. *Technological Forecasting and Social Change*, *19*(8), 122980. https://doi.org/https://doi.org/10.1016/j.techfore.2023.122980

Wang, Y., Zhao, L., & Chen, X. (2026). Spatial Digital Twins, Algorithmic Bias, and Private Vendor Lock-in Risks. *Telematics and Informatics*, *86*(1), 102110. https://doi.org/https://doi.org/10.1016/j.tele.2025.102110

Zuiderwijk, A., Chen, Y. C., & Zheng, L. (2021). Open Environmental Data Platforms and Algorithmic Accountability in Smart Governance. *Information Polity*, *26*(2), 185–201. https://doi.org/https://doi.org/10.3233/IP-200280