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Artificial Intelligence Strategic Lifecycle: A Literature Review-Based Framework

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ABSTRACT

Purpose. This systematic literature review examines how firms utilise artificial intelligence (AI) as a strategic rather than purely operational resource and develops an integrative conceptual framework of the AI strategic lifecycle. **Design/methodology/approach.** A PRISMA-guided search identified 147 peer-reviewed articles published between 2020 and 2025 across major scholarly databases, including Elsevier (Scopus), Emerald, Springer, and Wiley. The evidence is synthesised through five dominant theoretical lenses: dynamic capabilities, resource-based view (RBV), knowledge-based view (KBV), technology acceptance model (TAM), and disruptive innovation theory (DIT). **Findings.** Dynamic capabilities and RBV explain how organisations mobilise data, algorithms, and AI-related human capital to build and sustain competitive advantage in sectors such as public administration, energy, human resource management (HRM), and research-intensive industries. KBV highlights the role of absorptive capacity and knowledge-sharing routines in transforming AI outputs into innovation, particularly in user-facing contexts such as healthcare and hospitality. In these sectors, TAM is central, emphasising trust, ease of use, and perceived usefulness as key drivers of adoption. In finance, DIT elucidates competitive disruption and incumbent response strategies triggered by AI-enabled entrants. **Practical implications.** The review provides recommendations for practitioners, including investing in organisational learning and absorptive capacity and ensuring transparency of AI-enabled interfaces to translate AI investments into sustainable performance gains. **Originality/value.** By integrating five theoretical perspectives, the review develops a model of the AI strategic lifecycle, offering both a consolidated foundation for future research and a forward-looking agenda for managers seeking to leverage AI as a strategic asset.

Keywords: artificial intelligence; strategic management; innovation; technology adoption; resource-based view; dynamic capabilities; disruptive innovation; knowledge-based view

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ОРИГИНАЛЬНАЯ СТАТЬЯ

Стратегический жизненный цикл искусственного интеллекта: концептуальная модель на основе систематического обзора литературы

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АННОТАЦИЯ

Цель. В данной статье на основе систематического обзора литературы показано, каким образом компании используют искусственный интеллект (ИИ) не только как операционный, но прежде всего как стратегический ресурс, и разработана модель жизненного цикла ИИ на стратегическом уровне. **Методология/подход.** Поиск научных публикаций, проведенный в соответствии с протоколом PRISMA, позволил выявить 147 рецензируемых статей, опубликованных в период 2020–2025 гг. в ведущих научных базах данных (Elsevier/Scopus, Emerald, Springer, Wiley). Интерпретация результатов выстроена с использованием пяти доминирующих теоретических концепций: теории динамических способностей, ресурсной теории фирмы (resource-based view, RBV), теории знаний (knowledge-based view, KBV), модели принятия технологий (technology acceptance model, TAM) и теории разрушительных инноваций (disruptive innovation theory, DIT). **Результаты.** Теория динамических способностей и RBV объясняют, каким образом организации используют данные, алгоритмы и человеческий капитал в сфере ИИ для создания и поддержания устойчивого конкурентного преимущества в таких отраслях, как государственное управление, энергетика, управление персоналом и наукоемкие отрасли. KBV подчеркивает роль поглощающей способности и практик обмена знаниями для преобразования результатов ИИ в инновации, особенно в ориентированных на пользователя секторах, таких как здравоохранение и гостиничный бизнес. В этих секторах центральное место занимает TAM, в рамках которой доверие, легкость использования и воспринимаемая полезность выступают ключевыми драйверами принятия технологий ИИ. В финансовом секторе теория разрушительных инноваций раскрывает механизмы конкурентного разрушения и стратегии реагирования действующих игроков на появление новых участников, использующих ИИ на стратегическом уровне. **Практические выводы.** Обзор предлагает практические рекомендации, такие как инвестиции в организационное обучение и развитие поглощающей способности, а также обеспечение прозрачности ИИ-интерфейсов, что позволяет преобразовать вложения в ИИ в показатели эффективности. **Оригинальность/ценность.** На основе интеграции пяти теоретических концепций предложена модель стратегического жизненного цикла ИИ, что одновременно создает основу для дальнейших исследований и формирует ориентированную на будущее повестку для менеджеров, стремящихся использовать ИИ как стратегический актив.

Ключевые слова: искусственный интеллект; стратегический менеджмент; инновации; принятие технологий; ресурсная теория фирмы; динамические способности; разрушительные инновации; знаниевая теория фирмы

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Introduction

Artificial Intelligence (AI) has emerged as a transformative force in modern business, prompting companies to integrate AI into their strategic planning and decision-making. In this review, strategy is understood as an organisation's high-level plan aimed at achieving long-term goals and sustaining competitive advantage, in contrast to operational approaches focused on day-to-day efficiency and routine optimisation [1].

Within this context, artificial intelligence broadly encompasses technologies that simulate or augment human cognitive capabilities, including perception, reasoning, learning, decision-making, and creativity [2]. This set includes symbolic AI, machine learning (ML), deep learning, natural language processing (NLP), and generative AI. Symbolic AI systems, such as expert systems, rely on explicit rules and logic, whereas ML algorithms, including deep learning, enable systems to learn from data and enhance their performance over time. NLP enables human-like language understanding and communication, whereas generative AI generates new, creative content from learned patterns [3].

AI provides organisations with a distinctive competitive advantage by significantly enhancing their decision-making capabilities. AI enables firms to predict trends, interpret complex market dynamics, and make informed strategic choices, for example, regarding market entry, resource allocation, and innovation investments [4]. It also reshapes managerial processes by supporting opportunity identification and rapid adaptation to competitive shifts, ultimately altering the strategic perspective of decision-making [5].

Recognising the challenges posed to strategy-level management by the disruptive nature of AI, such as data privacy concerns, this systematic literature review (SLR) aims to consolidate fragmented knowledge, synthesise empirical and theoretical findings, and identify existing gaps to guide future research and managerial practice. The review is intended to support both scholars seeking conceptual clarity and practitioners developing strategies for leveraging AI as a long-term competitive asset.

Methodology

Given the complexity and multidisciplinary nature of AI and strategic management, we chose a systematic literature review (SLR) as the most rigorous method to ensure comprehensive, unbiased coverage and reproducible results. While narrative or critical reviews may provide deeper conceptual interpretations, they often lack systematic procedures, which can lead to bias or selective representation [6]. Scoping reviews, although comprehensive, typically do not provide in-depth synthesis or critical appraisal of findings, which was essential for our objectives. Thus, an SLR approach aligned best with our aims for comprehensiveness, theoretical grounding, and methodological transparency.

We followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to enhance the review's transparency and replicability [7]. PRISMA provided clear protocols for documenting each step of the literature search and selection process, which is crucial for managing the extensive volume of publications across diverse academic fields. *Figure 1* presents the PRISMA flow diagram used in this study, outlining each stage of the selection process.

Our search strategy combined AI-related keywords, such as machine learning, generative AI, and NLP, with strategic management terms, including strategic planning and competitive strategy. The search was conducted across the databases of major publishers: Elsevier (Scopus), Emerald, Springer, and Wiley.

To ensure the quality of the evidence base, we restricted the final sample to peer-reviewed articles published between 2020 and 2025 in journals rated 4*, 4 or 3 according to the Academic Journal Guide (AJG) 2024. The AJG 2024[1] classification was chosen due to its reliability and quality by focusing exclusively on top-tier journals indexed in the highest-quality databases such as Scopus. The overwhelming majority of such journals are indexed in Scopus, ensuring that the core dataset derives from high-quality Scopus-indexed publications.

Certain methodological limitations must be acknowledged. One challenge concerned distinguishing strategic studies from operational ones. We excluded papers whose primary focus concerned routine optimisation rather than strategic transformation. Of the 358 retrieved papers, 203 were excluded as operational in scope and 2 as irrelevant. We classified a study as strategic if its core purpose related to long-term organisational direction, competitive positioning, capability development, or strategic renewal.

Thus, through this methodological process, 153 papers met the inclusion criteria, and 147 were ultimately analysed after full screening.

Figure 1 summarises methodological approaches, and descriptive statistics of the final sample, including publication year distribution, and sectors.

[1] Academic Journal Guide 2024. Chartered Association of Business Schools. URL: https://charteredabs.org/academic-journal-guide/academic-journal-guide-2024 (accessed on 20.03.2024).

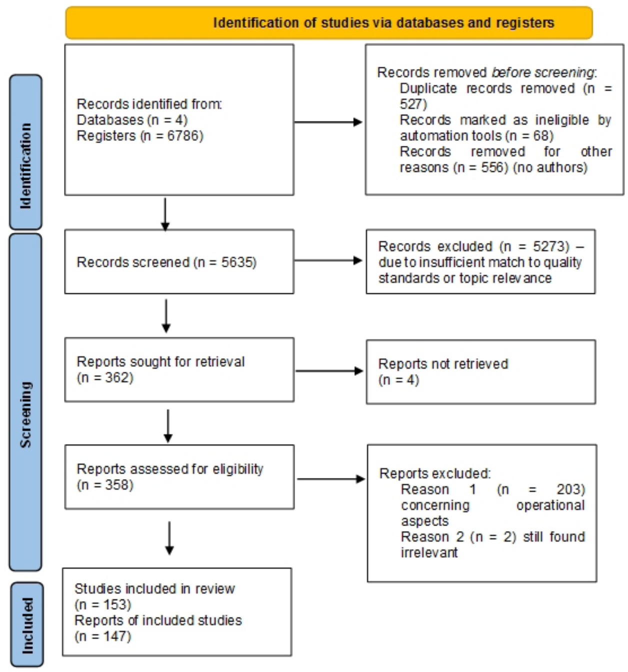

Fig. 1. **Prisma method of data selection**

Source: Compiled by the authors.

Strategic use of AI through theoretical lenses

Analysing theoretical foundations used across the reviewed literature highlights frequently cited theories and provides valuable insights into how these theoretical choices reflect deeper strategic concerns specific to different sectors. Five dominant frameworks emerge: Dynamic Capabilities (DCs), the Resource-Based View (RBV), the Knowledge-Based View (KBV), the Technology Acceptance Model (TAM), and Disruptive Innovation Theory (DIT). Their prominence underscores broader strategic issues, such as resource allocation, capability development and technology acceptance, which organisations grapple with when integrating AI into their strategies (*Fig. 2*). *Figure 2* shows how frequently each theoretical lens appears across major sectors included in the review.

AI literature is broadly divided into several domains. A general perspective explores AI-driven innovation, examining how Dynamic Capabilities (DCs) influence the success of AI adoption across sectors and how firms align their internal AI resources with external market factors to achieve strategic advantage. At the same time, numerous sector-specific studies focus on AI-driven capabilities in such sectors as energy or healthcare, with particular attention to (1) knowledge-management practices that maximise strategic benefits from AI

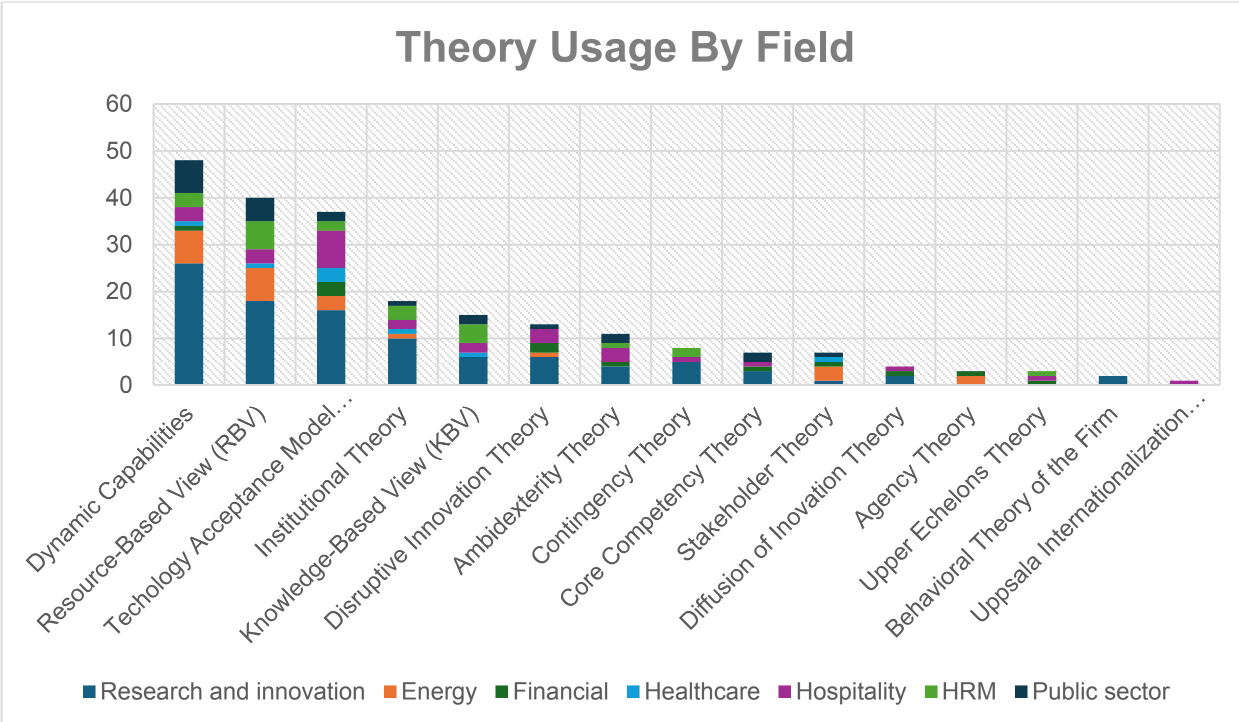

Fig. 2. **Theory usage by field**

Source: Compiled by the authors.

(KBV), (2) TAM-related issues of trust, transparency and perceived usefulness, and (3) strategic responses to potentially disruptive AI technologies (DIT).

Dynamic capabilities and RBV are frequently foundational in sectors like the public sector, human resource management (HRM), energy, and research and innovation. This finding indicates that these sectors perceive AI not only as a technological tool but also as a strategic enabler requiring firms to leverage internal resources, adapt rapidly to environmental changes, and restructure organisational processes. The recurring use of these theories suggests that organisations recognise that AI's strategic value hinges on their ability to transform resources and competencies to maintain competitive advantages continually.

Interestingly, HRM diverges slightly, with the Knowledge-Based View (KBV) replacing dynamic capabilities as the secondary theory. This shift highlights the unique strategic role of human expertise, organisational knowledge, and learning processes that are essential to successfully deploying AI in HR-focused initiatives, where knowledge management significantly influences competitive positioning. Indeed, KBV is primarily linked to the staff's know-how in explaining a company's performance, indicating employees' capacity to use AI meaningfully. Such capability can form the basis of a competitive advantage that is difficult to imitate and therefore plays a central strategic role [5].

Conversely, sectors involving high levels of user interaction and behavioural complexity, such as hospitality, finance, and healthcare, demonstrate a marked preference for the Technology Acceptance Model (TAM). This preference underscores a critical strategic insight: the ultimate success of AI in these contexts depends not merely on organisational readiness or resource availability but fundamentally on user acceptance and interaction. In hospitality and healthcare, specifically, RBV, alongside TAM, reinforces that user acceptance alone is insufficient; firms must also strategically align their internal resources to exploit the benefits of AI technologies fully [2].

Meanwhile, finance frequently employs disruptive innovation theory alongside TAM. This finding highlights a strategic environment that is particularly sensitive to AI's transformative and industry-altering potential, where businesses are increasingly focused on anticipating and navigating disruptions created by new AI-driven financial technologies.

Thus, the theoretical patterns identified in this analysis (*Fig. 2*) do not merely represent academic preferences but provide profound insights into the strategic imperatives and challenges different sectors encounter when integrating AI. *Table 1* summarises the leading theoretical frameworks used across sectors.

Table 1
Leading theoretical frameworks of industry-specific studies

Industry	Leading models
Energy	Dynamic capabilities and RBV
Public sector	Dynamic capabilities and RBV
Research and innovation	Dynamic capabilities and RBV
HRM	RBV and KBV
Financial	TAM
Healthcare	TAM
Hospitality	TAM

Source: Compiled by the authors.

Theoretical approaches of AI in strategy

This section discusses the findings through the lens of five major theoretical frameworks rather than by industry sector. Recent research increasingly demonstrates that AI acts as a cross-sectoral strategic catalyst, reshaping organisational processes, market structures, and sources of competitive advantage [5].

Accordingly, we examine how each theory, Dynamic Capabilities (DCs), the Resource-Based View (RBV), the Knowledge-Based View (KBV), the Technology Acceptance Model (TAM), and Disruptive Innovation Theory (DIT), has been used to explain AI-enabled strategic transformation. To ensure conceptual clarity and methodological transparency, each subsection: (1) outlines the theory's relevance to AI; (2) synthesises its applications across multiple sectors; (3) identifies its theoretical contributions; and (4) highlights limitations, criticisms, or unresolved gaps.

Figure 2 provides an overview of how often each theoretical lens appears across the major sectors reviewed, and *Table 2* synthesises the main findings for each framework.

Dynamic capabilities

Dynamic capabilities theory focuses on an organisation's ability to sense opportunities or threats, seize (mobilise resources for) those opportunities, and transform by reconfiguring competencies in response to changing environments [8, 9]. Within AI contexts, dynamic capabilities provide a mechanism to explain how strategic transformation unfolds through iterative sensing, experimentation, and renewal [10]. Merely acquiring AI technology is insufficient; firms must build supporting capabilities such as data analytics expertise [11], agile governance structures [12], and organisational cultures that encourage experimentation [13] to adapt and innovate with AI.

This finding helps explain the growing divergence between fast-moving firms that scale AI effectively and slower incumbents that struggle despite comparable technological investments. Organisations with strong DCs can reconfigure assets, redesign workflows, and integrate AI-enabled insights into strategic decision-making, thereby achieving sustained renewal [14].

Those with strong dynamic capabilities can realign resources and routines around AI-driven opportunities, achieving sustained strategic renewal [14]. The main criticism by [15] is that the concept can be abstract and difficult to measure, leading to ambiguity in empirical studies. In AI contexts, a major unresolved issue concerns how DCs emerge for technologies that evolve too rapidly to allow stable capability formation. Many AI-related capabilities are identifiable only retrospectively, making proactive capability building difficult [16]. Chowdhury et al. [17] also argue that dynamic capabilities theory risks tautology and may overlap with other frameworks. Thus, scholars increasingly recommend combining DCs with RBV or KBV to capture both resource foundations and the adaptive processes required for AI-driven transformation.

Thus, while valuable for studying organisational adaptation to AI, it should be applied with clear definitions and combined with complementary perspectives (e.g., the resource-based view) to capture AI's strategic impact. Successful AI adoption requires continuous organisational learning and agility. Firms need dynamic capabilities to integrate AI into core processes and adapt as AI and markets evolve [18]. In finance, stronger capabilities enhance the benefits of AI. Song et al. [19] show that the positive effects of AI on financial decision efficiency are conditional on high levels of learning-based capabilities. In manufacturing and services, the lens explains

AI-driven reinvention (e.g., servitisation), with absorptive capacity moderating the impact of AI on innovation [20]. In the public sector, organisations must reconfigure their competencies to harness AI in response to shifting policy demands. In healthcare, individual capabilities have enabled AI-based innovation; Abadie et al. 2023 [21] combine dynamic capabilities with innovation diffusion models to explain AI adoption in hospital operations. Across sectors, the theory emphasises that high strategic agility and learning capacity are crucial for deploying AI successfully to achieve a competitive advantage.

Overall, the DC perspective highlights that AI's strategic value emerges not from the technology itself but from an organisation's ability to learn, integrate, and reconfigure in response to AI-enabled opportunities.

Resource-based view (RBV)

The Resource-based view (RBV) posits that a firm's competitive advantage stems from unique resources and capabilities that are valuable, rare, inimitable, and well-organised (VRIO criteria). RBV explains why some firms gain lasting AI-enabled advantages while others do not [22]. Applied to AI, RBV frames data, algorithms, and human expertise as strategic assets that can generate sustained advantage if they meet VRIO conditions. It highlights that AI strategy should go beyond short-term gains to developing in-house assets, such as proprietary algorithms or data pipelines, that meet VRIO conditions [23]. This perspective clarifies the emerging performance gaps between firms that treat data as a core asset and those that do not.

In the AI era, RBV is used to analyse how AI-related resources (e.g., proprietary data, specialised algorithms, and human AI expertise) drive performance. When these resources are difficult to imitate, deeply embedded in organisational routines, and protected from competitors, they yield durable advantages. If effectively developed and protected, AI becomes a resource that enables value creation, which competitors cannot easily replicate. Empirical work applies RBV to diverse sectors. Ardito et al. [24] model "AI capability" in e-commerce as a strategic resource of technical skills and management practices, thereby boosting performance through innovation and decision-making. In public services, RBV emphasises internal capacity and knowledge assets; unique data and expertise can improve service delivery [25]. Across finance, healthcare, and energy, stronger AI infrastructures, data assets, or AI-skilled personnel yield superior outcomes [5, 26]. However, AI's strategic value is not automatic; it depends on acquiring and nurturing resources competitors cannot match [27].

RBV faces criticisms in AI contexts. One is that it is static, assuming enduring advantages, while in fast-moving fields, assets like algorithms are quickly commoditised [28, 29]. Scholars thus integrate RBV with dynamic perspectives, stressing the need to refresh and recombine resources [30]. Another limitation is RBV's inward focus, which overlooks external factors such as regulation [25], industry standards, and inter-organisational data ecosystems [31]. In highly interconnected AI markets, these external elements significantly shape the value of internal AI resources. Despite its gaps, RBV remains a foundational lens. Its limitations have encouraged more integrative frameworks (for instance RBV and DCs or RBV and KBV) that capture both the stock of AI resources and the adaptive processes necessary to leverage them.

Knowledge-based view (KBV)

The knowledge-based view is an extension of the RBV that singles out knowledge (information, know-how, and intellectual capital) as the most critical resource for competitive advantage [32]. KBV is highly pertinent to AI in corporate strategy because AI technologies are fundamentally concerned with knowledge; they gather data, identify patterns, generate insights, and sometimes even create new knowledge (e.g., predictive models or recommendations).

KBV posits that firms that effectively create, integrate, and apply knowledge outperform competitors; AI amplifies these processes by automating insight generation and accelerating organisational learning [33].

Literature across sectors has applied KBV to understand AI-driven transformation. In manufacturing, for example, AI adoption has been linked to a firm's absorptive capacity, a knowledge-centric capability. Qu and Kim [34] demonstrate that introducing AI in Chinese apparel companies enhances open innovation outcomes only when the firm can effectively absorb and utilise external knowledge; AI is viewed as a strategic tool to facilitate knowledge absorption and, consequently, innovation. This finding aligns with KBV's notion that leveraging new knowledge (from AI analytics or external data) is key to innovation. In the energy and finance sectors, firms utilise AI to analyse vast amounts of data (technical or market knowledge), supporting strategic decisions. The value lies in how well the firm's knowledge management processes can incorporate AI outputs [35]. Similarly, in healthcare, AI-enabled systems (such as diagnostic decision support tools) illustrate KBV by amplifying what organisations know and can do [34]. Maltsev and Yudanov [36] discuss AI's role through a knowledge-based lens, arguing that effective AI adoption transforms the firm's knowledge stock and capabilities.

Overall, the KBV positions AI simultaneously as a knowledge source, a knowledge processor, and a knowledge amplifier, explaining why firms with superior knowledge-integration practices benefit more from AI initiatives.

The KBV contributes theoretically by explaining the mechanism of AI-enabled strategic change as one of knowledge creation and distribution. It posits that AI's strategic impact enhances the firm's ability to generate insights (e.g., identifying patterns in large datasets), disseminate knowledge rapidly, and apply it to new products or processes. For instance, an AI-driven analytics platform can convert raw data into knowledge about customer behaviour; KBV helps articulate how that new knowledge becomes a strategic asset [37]. The perspective also sheds light on organisational learning: AI can catalyse continuous learning, enabling firms to accumulate organisational knowledge more quickly than their competitors and thus sustain innovation [38]. Nonetheless, there are some limitations to KBV's application in the AI context. First, KBV traditionally assumes knowledge resides in human actors, whereas AI systems introduce non-human knowledge repositories (models, embeddings, synthetic knowledge). This raises questions about knowledge governance and integration [39]. However, AI systems introduce non-human repositories of knowledge (models, databases), this raises questions about how firms govern and integrate AI-generated knowledge with the human-generated one [39]. Another challenge is distinguishing practical knowledge from noise: AI can produce overwhelming volumes of information, and without proper knowledge management, firms may struggle to translate this into strategic action [40].

Additionally, like RBV, KBV does not inherently account for the social or ethical dimensions of knowledge use. Trust in AI-produced insights, acceptance of algorithmic decisions, and cultural barriers all influence whether knowledge generated by AI becomes strategically useful [41]. Organisations must also manage cultural and tacit knowledge issues [42], encouraging employees to learn from AI insights and share their expertise, which may extend beyond what classic KBV models capture.

Despite these gaps, the KBV remains a powerful lens for understanding AI's role in strategy, especially when combined with dynamic or human-centred considerations to address how knowledge is absorbed and utilised.

Technology acceptance model (TAM)

The technology acceptance model is a well-established framework that explains individuals' adoption of new technologies based on their perceived usefulness (the belief that the technology will enhance job performance) and perceived ease of use (the belief that it will be free of effort) [43]. TAM is highly relevant for AI in strategic contexts because, ultimately, the success of AI initiatives often hinges on whether people, employees, managers, or customers accept and effectively utilise AI systems [44].

Even highly sophisticated AI strategies fail when end users resist or do not trust the system, making TAM central to understanding adoption across sectors.

Thus, numerous studies have employed TAM to investigate AI adoption at the user level across various sectors. For example, researchers have extended TAM to study clinicians' or patients' intentions to use AI-driven systems (such as diagnostic AI tools or chatbots) in healthcare. Lee [13] finds that in UAE hospitals, classical TAM factors must be coupled with organisational and strategic support factors to predict AI adoption, highlighting that management support and training significantly influence the perceived usefulness of AI systems.

In manufacturing, Qu and Kim's [34] study of apparel firms incorporates TAM constructs, demonstrating that the perceived usefulness and ease of use of AI technologies among employees mediate adoption, which in turn drives innovation outcomes. TAM or related models have also been applied in HR management (e.g., to study whether HR staff will trust AI recommendations in recruitment) and public sector services (to gauge citizen acceptance of AI-enabled e-government) [45]. The broad takeaway is that human factors, such as trust, ease of interface, and straightforward utility, consistently play a crucial role in AI adoption, whether the context is a nurse using an AI diagnostic aid or a finance analyst utilising an AI-driven decision support tool [46].

The TAM framework contributes by focusing on the micro-level drivers of AI-enabled transformation, user attitudes and behaviours. It reminds strategists that, beyond acquiring AI technology, organisations must ensure users find the AI system beneficial and user-friendly [47]. This theoretical lens explains aspects of strategic change, such as the speed and extent of AI implementation: if employees readily accept an AI tool due to high perceived usefulness, the firm can more quickly integrate that tool into its processes (realising strategic benefits sooner). TAM thus helps predict implementation success and can guide interventions (e.g., training to improve perceived ease of use, or pilot programmes to demonstrate usefulness). However, TAM has known limitations when applied to complex systems, such as AI. One criticism is that TAM is too simplistic and individualistic, largely ignoring organisational and contextual factors [48]. Indeed, studies often find it necessary to extend TAM with additional variables or frameworks (as with the TAM-TOE integrated model in the manufacturing study or adding organisational support in healthcare). It also overlooks organisational readiness, institutional pressures, and system-level enablers that frequently shape enterprise AI adoption [49]. Another gap is that classic TAM does not explicitly include factors such as trust, transparency, or the pivotal ethical considerations for AI [50]. For example, users might consider an AI system advantageous yet still hesitate to use it if they mistrust its decisions or worry about potential bias [51]. Recent research in healthcare highlights this issue: Meyer et al. (2024) [52] show that recognition of bias in AI systems can undermine trust and acceptance. Such findings illustrate that TAM's original constructs may need augmentation, e.g., incorporating the perceived credibility or fairness of AI, to capture fully why specific AI applications face adoption resistance. In summary, TAM provides a foundational understanding of user adoption, which is relevant for AI strategies. However, managers and scholars must address their blind spots by considering richer psychological and contextual factors (often using TAM alongside theories like UTAUT, trust models, or institution-based views in AI deployment studies).

Disruptive innovation theory (DIT)

Disruptive innovation theory describes how new technologies can initially target overlooked or low-end market segments with a simpler, cheaper product, then improve over time to displace established competitors eventually [53]. In corporate strategy research, DIT has been a popular lens through which to interpret the rise of AI as a potentially disruptive technology [54]. The idea is that AI could enable new entrants or business models that start at the margins but rapidly evolve to challenge incumbents, thereby transforming industry structures [55]. Researchers have applied DIT to AI across several domains. In the marketing sector, for example, Elgheit 2025 [54] positions generative AI as a disruptive innovation for marketing firms. His study qualitatively finds that small marketing agencies leverage generative AI tools to produce content and services at lower cost, targeting niche or underserved clients. This classic disruptive pattern could erode the advantages of large agencies if those incumbents are slow to respond [56]. In healthcare, analysts have debated whether AI is a genuinely disruptive force or more of a sustaining innovation. Shipton and Vitale [57] examine AI in healthcare through the lens of disruptive innovation, comparing it to past technological revolutions. Some argue that current AI applications represent incremental improvements, while others see potential for a paradigm shift in care delivery [58]. This finding reflects a broader cross-sector discussion: in finance, for instance, fintech startups using AI (for robo-advising, algorithmic trading, etc.) might be seen as disruptors for traditional banks [59], and in education, AI tutors could disrupt conventional teaching — but the extent of disruption can be debated [60]. Overall, DIT is used to explain the trajectory of AI impact: whether AI enables new competitors to overturn established firms eventually, and how incumbent organisations strategise in response (either by adopting the technology themselves or by focusing on higher-end value that AI newcomers cannot initially match).

The disruptive innovation perspective provides insight into AI's competitive and evolutionary implications for strategy. It highlights aspects of AI-enabled transformation, such as market entry and displacement. For example, it can explain why small, agile tech companies with AI at their core might capture market share from large firms that are slower to innovate. It also frames strategic transformation as a potential industry-level shift, not just an internal change: if AI is truly disruptive, it can redefine customer expectations and the basis of competition (for instance, automating services that used to require human experts, thus changing cost structures and quality benchmarks) [61]. However, DIT faces several criticisms, many of which are amplified in AI contexts. A key critique is that DIT can be challenging to apply predictively — it is often easier to label a technology 'disruptive' in hindsight than to know in advance [62]. In the context of AI, many innovations touted as 'disruptive' may not entirely displace incumbents but rather get co-opted or remain niche. Critics, such as Siddik et al. (2025) [63], have also argued that the theory's definitions can be fuzzy, and not every major innovation (even if transformative) follows the low-end encroachment pattern. This fact holds for AI; some AI applications are adopted directly by top-tier firms to enhance their existing products (a sustaining innovation pattern rather than a classic disruption from the bottom) [64]. Some researchers caution that AI's current impact in specific sectors is evolutionary, not revolutionary, requiring long-term integration with human expertise rather than wholesale replacement [65]. Another limitation is that DIT does not inherently address the ethical and societal disruptions AI brings (e.g., job displacement, regulatory upheavals), focusing mainly on business competition. Thus, while the disruptive innovation theory provides a provocative lens for considering AI's strategic implications, urging companies to anticipate possible upheavals in their industry, it should be used with caution [66]. It benefits from combining empirical analyses and other theories (such as diffusion of innovation or socio-technical systems theory) to judge which AI developments are genuinely disruptive versus sustaining. In summary, DIT helps explain the transformative, and at times turbulent, market-level changes prompted by AI, but it also faces challenges and critiques when it comes to reliably guiding strategic decisions in the face of emerging AI technologies.

Table 2 summarises the theoretical contributions, sectoral applications, and remaining research gaps across the five frameworks.

Based on the theoretical analysis, we propose conceptualising AI-enabled strategy as a continuous and iterative lifecycle rather than a linear progression (see *Fig. 3*). Each technological cycle begins with foundational Technology Adoption (TAM), focusing on user acceptance of technology and ease of use. Firms then progress by accumulating distinct resources (RBV), which are integrated and amplified through knowledge-sharing practices (KBV). This integrated knowledge facilitates continuous renewal of organisational capabilities (dynamic capabilities). Eventually, these renewed capabilities enable firms to respond proactively to disruptive innovations and reshape market dynamics (DIT). Crucially, the cycle restarts as AI technology evolves [67, 68], reinforcing that sustained strategic advantage requires perpetual engagement in this ongoing loop of adoption, resource accumulation, knowledge integration, capability renewal, and disruption management.

Directions for future research

While the literature on AI as a strategic asset rapidly evolves, several important gaps and opportunities remain for future investigation. These opportunities span theoretical, methodological, and sector-specific domains and reflect the continuing need to understand how AI reshapes organisational strategy in diverse and dynamic environments.

Cross-theoretical integration. Future work should develop integrative theoretical models that combine multiple lenses, such as dynamic capabilities, the resource-based view, the knowledge-based view, and the technology acceptance model, to capture the multi-level nature of AI-enabled strategic transformation. While most current studies apply a single dominant theory, real-world AI implementation cuts across resource accumulation (RBV), capability development (DC), knowledge integration (KBV), and user acceptance (TAM) simultaneously. Developing such multi-theoretical approaches would allow scholars to reconcile strategic, organisational, and behavioural dimensions within unified frameworks, enabling richer explanations of AI adoption, scaling, and performance outcomes.

Sectoral comparisons and underexplored industries. There is a clear need for comparative studies to analyse how strategic AI use varies between public and private organisations, regulated and non-regulated environments, and capital-intensive versus service-oriented sectors. Sectors such as education, agriculture, manufacturing (beyond innovation contexts), and creative industries remain significantly under-represented in the strategic AI literature. Future research should therefore target

Table 2
Summary of findings

Theory	Research question	Finding and Key recommendations	References
Dynamic capabilities	How do firms proactively build dynamic capabilities specific to AI? How do dynamic capabilities influence the success of AI adoption across sectors?	Firms proactively build AI-specific dynamic capabilities through systematic investments in absorptive capacity, continuous organisational learning, and agile processes. Specifically, strategic renewal occurs when firms integrate internal competencies with external AI-driven knowledge, ensuring responsiveness to environmental shifts. Cross-sector empirical evidence shows that robust dynamic capabilities significantly moderate the relationship between AI adoption and organisational performance, enabling firms to capitalise on opportunities and innovate rapidly, especially in technologically turbulent sectors such as finance and healthcare	[18–20]
Resource-Based View	What makes AI-related resources sustainably valuable and difficult to imitate? How do firms align internal AI resources with external market factors for strategic advantage?	AI-related resources achieve sustained strategic value primarily through proprietary characteristics — unique data assets, specialised algorithms, and AI-specific human capital — that are costly to replicate and deeply embedded within organisational processes. Effective strategic alignment of these internal resources with external market and regulatory contexts involves continuous recombination and updating, bridging RBV's inherent static limitations with a dynamic perspective, thereby ensuring an enduring competitive advantage despite the rapid diffusion of AI technologies	[24, 27, 30]
Knowledge-Based View	How do organisations effectively integrate AI-generated knowledge with human expertise? What knowledge management practices maximise strategic benefits from AI?	Effective strategic integration of AI-generated knowledge with human expertise requires advanced knowledge-management practices, emphasising absorptive capacity, explicit-tacit knowledge conversion, and adaptive learning mechanisms. Organisations that adopt these practices successfully leverage AI as a tool for amplifying human cognitive capabilities, facilitating rapid knowledge dissemination and innovative application, thereby creating competitive advantages through accelerated organisational learning and strategic adaptability	[34, 36, 38]
Technology Acceptance Model	What organisational factors significantly enhance user acceptance of AI technologies? How should TAM be adapted to incorporate trust, transparency, and ethical considerations specific to AI?	Organisational factors such as perceived management support, targeted training, and inclusive decision-making processes significantly enhance user acceptance of AI by improving perceived usefulness and ease of use. Nevertheless, adapting TAM to AI contexts necessitates incorporating constructs such as trust, transparency, and ethical considerations — factors empirically demonstrated to profoundly influence adoption decisions, especially within highly regulated and ethically sensitive sectors like healthcare and finance	[13, 47, 51, 52]
Disruptive Innovation Theory	Under what conditions does AI act as a truly disruptive innovation? How should incumbents strategically respond to potentially disruptive AI technologies?	AI serves as a genuinely disruptive innovation primarily when it initially addresses overlooked or underserved market segments with simpler, cost-effective solutions, subsequently challenging the market positions of incumbent firms. Strategic responses by incumbents should thus focus on proactively identifying disruptive threats early, investing in strategic agility to either co-opt or neutralise disruptive potential, and continuously adapting their business models to integrate AI technologies effectively — thereby mitigating the transformative threats inherent in disruptive innovation scenarios	[54, 58, 64, 66]

Source: Compiled by the authors.

these sectors, ideally through interdisciplinary approaches combining strategic management, data science, behavioural sciences, and sector-specific expertise.

Longitudinal and post-adoption studies. Most existing research focuses on the drivers of AI adoption and conceptual potential, rather than the real processes through which AI systems are implemented, scaled, institutionalised, or abandoned. Longitudinal studies can help trace how AI strategies evolve, how organisations manage setbacks or unintended consequences, and what factors contribute to sustained competitive advantage or decline. Such studies should also examine governance failures, ethical misalignments, and unintended outcomes over time, offering empirical parallels to the AI strategic lifecycle proposed in *Fig. 3*.

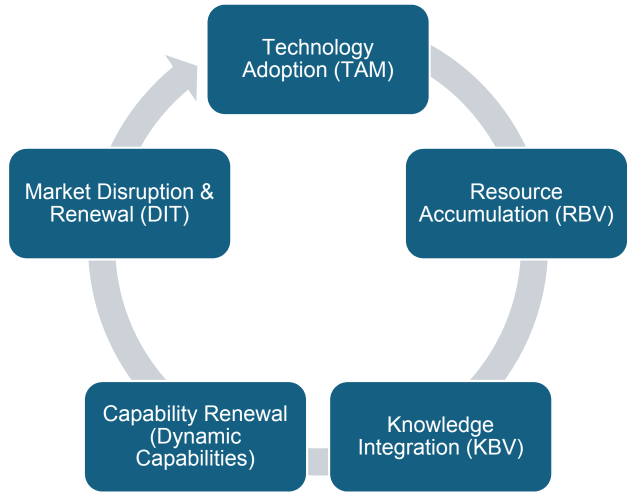

Fig. 3. **The AI strategic lifecycle**

Source: Compiled by the authors.

Conclusion

This systematic literature review highlights the growing strategic importance of AI in contemporary organisational contexts. Drawing from a comprehensive analysis of 147 rigorously selected studies, this review shows that AI has moved far beyond its early perception as an operational efficiency tool. Instead, AI now functions as a central strategic resource that enables sustained competitive advantage, supports continuous innovation, and drives deep organisational transformation.

Our analysis demonstrated that AI integration significantly alters organisational decision-making, enhancing predictive accuracy, strategic agility, and enabling innovative value creation.

The review highlights distinct theoretical orientations aligned with sectoral contexts. Dynamic capabilities and the resource-based view (RBV) are dominant in public administration, human resource management (HRM), energy, research, and innovation. These theories emphasise the importance of internal resource mobilisation, adaptive capacity, and organisational agility necessary for strategically leveraging AI. In HRM specifically, the prominence of the knowledge-based view (KBV) underscores the strategic necessity of managing and leveraging knowledge assets, human capital, and organisational learning to maximise AI's potential.

Conversely, in sectors marked by high behavioural complexity and direct user engagement, such as hospitality, finance, and healthcare, the technology acceptance model (TAM) prevails, emphasising that successful strategic integration of AI fundamentally hinges on user acceptance and interaction. This theoretical focus highlights that strategic considerations must extend beyond internal resource optimisation to include psychological and user-centric factors critical for AI adoption. In finance, the notable application of disruptive innovation theory (DIT) further illustrates sector-specific strategic concerns, particularly how AI-driven innovations can potentially disrupt market structures and challenge traditional incumbents.

Collectively, these theoretical lenses illustrate the multifaceted impact of AI, positioning it simultaneously as a technological enabler, a knowledge asset, a behavioural phenomenon, and a disruptive force. Organisations seeking strategic advantage from AI must navigate complex dynamics beyond mere technical implementation. They must proactively address broader organisational and institutional shifts, human-AI integration challenges, and evolving market conditions. Future research should continue to explore these complexities, with a special focus on cross-sectoral comparisons, longitudinal analyses, and less-explored industries. Moreover, the ethical, regulatory, and governance challenges identified by this review necessitate continued scholarly attention to ensure AI innovations remain transparent, accountable, and aligned with societal values.

In conclusion, this review affirms that strategically implemented AI represents both a theoretical and practical frontier, reshaping individual firm strategies, transforming entire industries, and redefining our broader understanding of technology's role in strategic management.

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Space-Based Solar Energy: Economic Viability in the Context of Global Competition

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ABSTRACT
The development of space-based solar energy (SBSP) in the last decade goes beyond scientific and technical experiments and acquires the features of an emerging sector of the global economy. In contrast to the works focused on technological aspects or the environmental agenda, the study considers SBSP as an area of intersection of long-term investment strategies, national priorities of energy security and new market opportunities. **The subject** of the analysis is the country models of SBSP development, their institutional design and economic parameters determining the prospects for the orbital stations' commercialization. **The purpose of the work** is to identify the dominant national strategies in the sphere of space energy and to determine the threshold values of indicators ensuring its economic feasibility. The relevance of the topic is due to the intensification of programs in the United States, China, Japan, India, Russia and the European Union, which consider SBSP as a tool for reducing dependence on traditional energy carriers and consolidating technological leadership. **The methodological framework** includes comparative country analysis, modeling with the decomposition of factor influences on LCOE, as well as analysis of strategic documents and reporting data. **The scientific novelty** of the study lies in the classification of national approaches to the development of CSE, built on the basis of the analysis of financing sources and mechanisms, as well as in the adaptation of the levelized cost of energy (LCOE) methodology to the specifics of space projects. **The results of the study** allow us to identify six strategic paradigms, from the American synergetic model based on private initiative to the conservative evolutionary position of Russia. Quantitative analysis confirms the main barrier to commercialization is not the efficiency of photovoltaic cells but the cost of launching a payload into orbit, setting benchmarks for long-term investment policy and technological development.

Keywords: space-based solar power (SBSP); levelized cost of energy (LCOE); orbital solar stations (OSS); investment strategies; installed capacity utilization rate (ICUR); economic feasibility; energy security; commercialization of space energy

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ОРИГИНАЛЬНАЯ СТАТЬЯ

Космическая солнечная энергетика: экономическая целесообразность в условиях глобальной конкуренции

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АННОТАЦИЯ
Развитие космической солнечной энергетики (КСЭ) в последнее десятилетие выходит за рамки научно-технических экспериментов и приобретает черты формирующегося сектора глобальной экономики. В отличие от работ, сосредоточенных на технологических аспектах или экологической повестке, проведенное исследование рассматривает КСЭ как область пересечения долгосрочных инвестиционных стратегий, национальных приоритетов энергетической безопасности и новых рыночных возможностей. **Предметом анализа** выступают страновые модели развития КСЭ, их институциональное оформление

и экономические параметры, определяющие перспективы коммерциализации орбитальных станций. **Цель работы** — выявить доминирующие национальные стратегии в области космической энергетики и определить пороговые значения показателей, обеспечивающих ее экономическую целесообразность. **Актуальность темы** обусловлена активизацией программ США, КНР, Японии, Индии, России и Европейского космического агентства, рассматривающих КСЭ как инструмент снижения зависимости от традиционных энергоносителей и закрепления технологического лидерства. **Методологическая база** включает сравнительный страновой анализ, моделирование с декомпозицией факторных влияний на нормированной стоимости энергии (LCOE), а также анализ стратегических документов и отчетных данных. **Научная новизна** исследования заключается в классификации национальных подходов к развитию КСЭ, построенной на основе анализа источников и механизмов финансирования, а также в адаптации методологии нормированной стоимости энергии к специфике космических проектов. **Результаты исследования** позволяют выделить шесть стратегических парадигм — от американской синергетической модели, опирающейся на частную инициативу, до консервативно-эволюционной позиции России. Количественный анализ подтверждает, что основным барьером коммерциализации выступает не эффективность фотоэлементов, а стоимость вывода полезной нагрузки на орбиту. Достижение целевых показателей в диапазоне 20–50 долл./кг способно обеспечить паритет КСЭ с наземными источниками генерации, что задает ориентиры для долгосрочной инвестиционной политики и технологического развития.

Ключевые слова: космическая солнечная энергетика (КСЭ); нормированная стоимость энергии (НСЭ); орбитальные солнечные станции (ОСС); инвестиционные стратегии; коэффициент использования установленной мощности (КИУМ); экономическая целесообразность; энергетическая безопасность; коммерциализация космической энергетики

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1. Introduction

The evolution of approaches to the use of solar energy in outer space is a classic trajectory of technological development: from solving the narrowly focused problem of powering an individual spacecraft to realizing the potential of technology as a driver of systemic changes in the global economy. At the initial stage, photovoltaic systems acted exclusively as an onboard power source determining the resource and efficiency of space missions.[1] The current stage of development is characterized by a conceptual shift towards the creation of orbital solar stations (OSS) capable of contactless transmission of energy to ground-based receiving complexes. However, the real conceptual upheaval is associated with the transition to the idea of space-based solar power plants (CSPs) capable of transmitting energy to Earth. Peter Glaser originally proposed the idea of orbital solar stations (OSS) in 1968 as a solution to energy scarcity, and it is now transforming into a factor of economic sovereignty and a tool for long-term investment planning. In the context of the growing volatility of global commodity markets and increased competition for energy resources, access to extraterrestrial energy sources ceases to be an exclusively technological task and moves to the plane of ensuring economic security and the formation of new markets.

Three interrelated factors, far beyond the challenges of decarbonization, drive the current interest in OSS.

Formation of a new architecture of the global energy market. A state or a coalition of countries that is the first to ensure the commercially efficient operation of the OSS will get the opportunity not only to diversify its own energy balance but also to form a fundamentally new segment of the world energy market — space generation. Unlike traditional hydrocarbons, energy transmitted from orbit is characterized by zero marginal production costs after the commissioning of capacities and the absence of reference to territorially localized resource bases. These properties form the prerequisites for the emergence of new business models and financial instruments: from long-term contracts for the supply of "orbital energy" to the creation of international energy pools with the participation of sovereign funds and institutional investors. The active investment

[1] NASA Technology Roadmaps. Space Based Solar Power. NASA Official site. 11.01.2024. URL: https://ntrs.nasa.gov/api/citations/20230018600/downloads/OTPS%20SBSP%20Report%20Final_Tagged_Approved_1_5_24.pdf (accessed on 18.11.2025).

policy of China,[2] which declares its intention to launch a demonstration station by 2028 [2], and US program initiatives within the framework of the Defense Advanced Research Projects Agency of the US Department of Defense (Defense Advanced Research Projects; DARPA)[3] testify to the understanding by the world's leading economies of the strategic potential of the OSS as a tool for influencing the redistribution of global energy flows in the emerging multipolar world. A recent study by He, Che, and Liu [3] published in Joule provides quantitative economic validation for this potential, demonstrating that SBSP could become a commercially viable component of large-scale power systems under specific cost reduction scenarios.

The role of OSS as a basic element for the production infrastructure in space. The OSS's economic potential extends beyond merely exporting energy to Earth. The possibility of creating production clusters in space based on orbital energy platforms is of key importance from the point of view of long-term economic growth. Providing energy to lunar settlements, refueling complexes for interplanetary flights, and, most importantly, orbital factories for the production of materials with unique properties in microgravity opens up prospects for the formation of new industries with high added value. In this context, OSS should be considered not an end product but an infrastructural asset creating conditions for the emergence of a number of related markets and ensuring the transition to a qualitatively new model of economic development based on the use of extraterrestrial resources. The lack of a reliable power supply beyond Earth is a critical limitation for any scenario of commercial exploration of the Moon, Mars, or deep space flights.

Investments in technological sovereignty and their multiplicative effect. The deployment of the OSS acts as a catalyst for the development of a wide range of critical dual-use technologies: autonomous robotics for the assembly of large-sized structures in space, the creation of materials with fundamentally new characteristics, wireless power transmission systems (laser and microwave) with high efficiency advantages in related sectors: telecommunications, the defense industry, transport, forming a stable multiplier effect for national economies. At the same time, the motivation of the participating countries is differentiated: if for the United States and China the priority is to consolidate leadership in high-tech processing stages, then for Japan, characterized by critical dependence on energy imports, the OSS is a tool for ensuring long-term economic security and reducing country risks associated with the volatility of world hydrocarbon prices.[4]

The scientific novelty of this study lies in the substantiation of the thesis about the need to rethink the OSS projects in the categories of economic efficiency, investment attractiveness and market potential, as opposed to the technical-engineering or military-political discourse dominating in the literature. The paper attempts to assess the Russian scientific and technical potential through the prism of its conversion into competitive advantages in the context of the emerging global space energy market, based on the premise of "stimulating technological development as the main driver of economic growth" [4, p. 109].

The practical significance of the work lies in the formation of a conceptual framework for the integration of OSS projects into the system of strategic planning and investment policy at the national and corporate levels. The proposed approach allows us to consider OSS not only as an engineering project but also as a new class of long-term infrastructure assets requiring the development of specialized methods for financial modeling, risk assessment and management of investment portfolios of energy and high-tech companies.

To achieve the purpose formulated in the abstract — identifying dominant national strategies in space energy and determining the threshold values for economic feasibility — the study sets the following research objectives:

- To identify and classify country-specific models of SBSP development based on an analysis of funding sources, institutional architecture, and strategic priorities.
- To adapt the levelized cost of energy (LCOE) methodology to the specifics of space projects and

[2] The National Center for Science Technology Innovation (NCSTI). China looks set to build space solar power station. URL: https://en.ncsti.gov.cn/home/gridview/202406/t20240613_164551.html (accessed on 20.11.2025).

[3] A Glimpse at the Future of Space-Based Solar Power/Energy and Technology. 11.08.2025. URL: https://www.ncsc.coop/content/solutions/en/stories/energy-tech/a-glimpse-at-the-future-of-space-based-solar-power.html (accessed on 22.11.2025).

[4] Japan Basic Plan on Space Policy. URL: https://www8.cao.go.jp/space/plan/plan-eng.pdf (accessed on 25.11.2025).

determine the threshold values of key parameters (launch cost, capacity factor, operational lifetime) that ensure the economic viability of SBSP.

• To assess the risks and opportunities for countries with different strategic approaches, including Russia, in the context of the emerging global space energy market.

2. Materials and methods of research

Research methodology is based on a comparative analysis of open data, official strategic documents, scientific publications and reports of analytical agencies.

Existing studies, as a rule, consider OSS either in a narrow technical way [5–7] or through the prism of green energy [8–11]. The review by Cifone et al. (2025) [12] takes a broader perspective, synthesizing recent technological demonstrations and assessing the economic viability of SBSP, thereby bridging the gap between technical feasibility and commercial potential. Despite the growing interest in OSS, their study in the context of geopolitical competition and the formation of new space infrastructure is fragmentary [13, 14]. The key issues of economic feasibility and analysis of the market potential of OSS in the new multipolar model of the space economy remain insufficiently explored, and only a few recent studies [15] are starting to address these aspects. However, the main driving forces behind the creation of OSS are not so much environmental factors as the desire for energy dominance, the formation of long-term competitive advantages and the creation of not only a technological but also an investment basis for the next stage of economic space exploration.

The information basis of the study. The empirical foundation of the work consists of three groups of sources, identified according to the criteria of reliability, representativeness and chronological relevance. The first group consists of official strategic documents and policy statements determining the vectors for the development of leading powers' space activities. Among them are the U.S. Space Act (U.S. Space Act, 2015),[5] roadmaps of the National Aeronautics and Space Administration (NASA, 2024),[6] program documents of the China National Space Administration (CNSA),[7] reflected in the XIV Five-Year Plan (2021–2025),[8] the Basic Space Law of Japan (Basic Space Law, 2008)[9] and the JAXA Strategic Roadmap,[10] as well as the Federal Space Program of Russia and the Fundamentals of State Policy in the Field of Space Activities until 2030.[11] The second group of sources is represented by analytical reports and feasibility studies by reputable organizations: NASA,[12] the National Security Technology Accelerator (NSTXL),[13] the LAZARD Laboratory (2025),[14] the European Space Agency (ESA SOLARIS),[15] and the National Center for Scientific Research and Innovation of China (NCSTI).[16] The third group includes peer-reviewed scientific literature, consisting of fundamental works laid the conceptual foundations of the problem: from N. Tesla's experiments on wireless power transmission [16] and the civilizational hypothesis of N.S. Kardashev

[5] U.S. Space Act, 2015. U.S. Public Law 114–90. URL: https://www.congress.gov/114/plaws/publ90/PLAW-114publ90.pdf (accessed on 10.11.2025).

[6] NASA Technology Roadmaps. Space Based Solar Power. NASA Official site. 11.01.2024. URL: https://ntrs.nasa.gov/api/citations/20230018600/downloads/OTPS%20SBSP%20Report%20Final_Tagged_Approved_1_5_24.pdf (accessed on 18.11.2025).

[7] Policies and Announcement. China National Space Administration official site. URL: https://www.cnsa.gov.cn/english/n6465645/n6465648/index.html

[8] The 14th Five-Year Plan of the People's Republic of China. URL: https://www.adb.org/publications/14th-five-year-plan-high-quality-development-prc (accessed on 10.11.2025).

[9] Japan's legal framework: Basic Space Law (2008) and CSE Strategic Roadmap. URL: https://global.jaxa.jp/about/law/index.html (accessed on 13.11.2025).

[10] Research on Space Solar Power Systems (SSPS). JAXA. 2025. URL: https://www.kenkai.jaxa.jp/eng/research/ssps/ssps-ssps.html (accessed on 10.11.2025).

[11] Fundamentals of State Policy in the Field of Using the Results of Space Activities in the Interests of Modernizing the Economy of the Russian Federation and the Development of Its Regions for the Period up to 2030. Electronic fund of legal and regulatory and technical documents. URL: https://docs.cntd.ru/document/560853771(accessed on 10.11.2025). Hereinafter referred to as Cosmos Policy Fundamentals-2030.

[12] Rodgers E., Gertsen J., Stroup T., et al. Space-Based Solar Power: Technology Assessment and Economic Analysis. Washington: NASA Office of Technology, Policy, and Strategy; 2024. 98 p. URL: https://ntrs.nasa.gov/api/citations/20230018600/downloads/OTPS%20SBSP%20Report%20Final_Tagged_Approved_1_5_24.pdf (accessed on 18.11.2025).

[13] Reducing the Cost of Space Travel with Reusable Launch Vehicles. Analytical Report (NSTXL, 2024). URL: https://nstxl.org/reducing-the-cost-of-space-travel-with-reusable-launch-vehicles/ (accessed on 21.11.2025).

[14] Lazard's 2025 LCOE+ Report, June 2025. URL: https://www.lazard.com/media/5tlbhyla/lazards-lcoeplus-june-2025-_vf.pdf (accessed on 03.12.2025).

[15] ESA Annual Space Environment Report. URL: https://www.esa.int/Space_in_Member_States/United_Kingdom/ESA_accelerates_the_race_towards_clean_energy_from_space (accessed on 13.11.2025).

[16] The National Center for Science Technology Innovation (NCSTI). China looks set to build space solar power station. URL: https://en.ncsti.gov.cn/home/gridview/202406/t20240613_164551.html (accessed on 20.11.2025).

[17] to the classic work of P. Glaser, who was the first to formulate the principles for the creation of orbital solar stations [1]. Special attention is paid to modern publications reflecting the current stage of the discussion development, including studies by Russian researchers [18–20] and foreign authors [2, 8]. For example, a review conducted by Cifone et al. [12], assessing the economic viability of the SBSP, concludes, despite significant obstacles remaining, recent advances in wireless power transmission and light photovoltaic systems make it much easier to achieve commercial feasibility for investment in orbital stations. To verify the conclusions about the industry's transition to the experimental development phase, materials on practical tests were used, including successful demonstrations by the Japan Aerospace Exploration Agency (JAXA)[17] and data on the deployment of a test site in Chongqing (China) [2].

Methods of collecting and processing information. At the initial stage, the collection, systematization and primary processing of open data from the listed sources was implemented. To identify key semantic parameters in strategic documents and policy statements, content analysis is used.

Methods of comparative and country analysis. To compare the approaches of six key players (the United States, China, Japan, India, Russia, and the European Space Agency), this study employed a comparative analysis. This comparison relied on a single matrix of criteria: the institutional architecture for managing CSE programs, the prevailing sources and mechanisms of funding, the degree of private sector involvement, the availability of publicly stated targets and timeframes, and the position on international legal regulation of the use of space energy. The differences identified made it possible not only to streamline national strategies, but also to explain the difference in their dynamics.

Methods of Economic Analysis and Modeling. To provide a quantitative assessment of the prospects for Space-Based Solar Power (SBSP), this study employs a techno-economic analysis decomposing the Levelized Cost of Electricity (LCOE). The base-case LCOE formula included the following parameters: capital expenditures (It), encompassing the cost of developing and manufacturing photovoltaic modules, payload launch expenses (the main economic barrier), the creation of power transmission systems, and ground-based receiving infrastructure; operating expenses (Ot), associated with orbital maintenance, space debris countermeasures, and station upkeep; the volume of energy produced (Et), deriving from the uniquely high capacity factor in geostationary orbit (35.8 thousand km); the discount rate (r), reflecting a combination of technological and country-specific risks; and the estimated service life (n). Modeling based on the parameter ranges documented in the NASA (2024) and NSTXL (2024) reports has enabled the identification of threshold values for launch costs ($20–$50/kg). At these costs, the LCOE of SBSP becomes competitive with terrestrial energy sources. Furthermore, a sensitivity analysis of the final generation cost to key variable changes identifies critical leverage points for achieving economic feasibility. The approach to LCOE decomposition developed in this study aligns with contemporary methodological approaches to assessing technological development [21], allowing SBSP to be considered not in isolation, but in the context of its position within a somewhat expanded technological core of the global economy.

Case analysis method. This research employed the method to examine technological solutions in the context of their commercial potential. For the examples, author selected projects significant to the future SBSP economy: JAXA's wireless power transmission experiments in Japan (2015), the development of Roll-Out Solar Arrays (ROSA)[18] in the United States, and the establishment of a testing ground in Chongqing, China. The analysis confirms the conclusion the industry is moving from a theoretical stage to a practical one — this fact is an important signal for attracting investment and the possibility of intensive commercialization. Unlike studies focused on the operational applicability of SBSP for niche applications [22, 23], the present study conducts a decomposition analysis of LCOE, which has made it possible to identify the cost of payload delivery as the most critical parameter for commercialization. Achieving the threshold value of $20–$50/kg would make SBSP competitive with

[17] JAXA's experiment on wireless power transmission from the Konotori spacecraft. Source: JAXA press release of March 12, 2015 "Successful Operation of Wireless Power Transmission Technology for SSPS". URL: https://www.mhi.com/news/1503121879.html (accessed on 16.11.2025).

[18] Experimental solar panels deployed on the ISS. Clean Energo News Portal. 26.06.2017. URL: https://www.cleanenergo.ru/2017/na-mks-razvernuli-eksperimentalnye-solnechnye-batarei/ (accessed on 20.11.2025).

terrestrial generation and provide clear benchmarks for long-term investment policy.

This study has several restrictions. The most significant one is the closed character of information on some national programs (particularly those of China and Russia). This situation necessitated the use of only open data and the opinions of reliable experts. To all given above, the prediction of LCOE is scenario-dependent and sensitive to assumptions about technological changes. The findings take these restrictions into account, admitting the probabilistic characters of results requiring further correction as new information will be gotten.

3. Results

3.1. SBSP economics: National strategies and models

By comparing national approaches to space-based solar power, the author discovered the fact that the key differences between countries are primarily characterized not by their levels of technological readiness but rather by their fundamental strategic goals and the possible financing models they use.

3.2. USA: Synergetic model of public-private partnership and use of market mechanisms for CBSP development

The American method of space-based solar power development is linked to the "New Space" phenomenon. This paradigm concentrates on the construction of economic synergies between government customers and private high-technology enterprises. Within this framework, NASA has transformed from a sole developer into an integrator of the growing innovation ecosystem as technologies evolve and are implemented. The development and testing of flexible Roll-Out Solar Arrays (ROSA) provide an illustrative example.[19] This technology, developed with significant government backing, moved relatively quickly to commercialization, finding applications on the International Space Station and in other projects [24]. In doing so, it created a precedent for a "dual-use technology" possessing both near-term and long-term value.

Private companies, most notably SpaceX, play a pivotal role in stimulating demand for innovation. By deploying massive low-orbit satellite constellations such as Starlink, the company generates sustained market demand for solar panels that are not only efficient and reliable but also cost-effective. This market dynamic, in turn, fuels further technological progress. It helps reduce the cost of producing each unit. At the same time, the major players like Northrop Grumman[20] and Lockheed Martin,[21] are increasing their engagement with the SBSP sector. They bet strategically on its long-term prospects and anticipated expansion.

A project's ability to attract investment depends heavily on its legal framework. By enacting the Space Act in 2015,[22] the United States created a definitive legal basis for commercial space resource utilization, including solar power. This gave private investors the certainty they need for long-term, high-risk ventures. The resulting American model focuses on a self-sustaining ecosystem: government sets direction and removes barriers, while business finds commercial niches and pursues cost reductions.

3.3. China: State planning and resource mobilization for SBSP

China treats space solar power as a national priority. Technological goals fit directly into the country's broader plans for economic and social development.

Two main institutions lead the work: CNSA, the space agency, and CASC, the aerospace contractor. They operate as a single unit, following directions from political leadership through a strict chain of command.

Progress in space solar technology follows a clear pattern. First, China studies existing designs. Then it improves them. Finally, it builds its own systems. This approach has helped the country catch up with American technology quickly.[23]

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[19] Experimental solar panels deployed on the ISS. Clean Energo News Portal. 26.06.2017. URL: https://www.cleanenergo.ru/2017/na-mks-razvernuli-eksperimentalnye-solnechnye-batarei/ (accessed on 20.11.2025).

[20] Solar Array Products. Northrop Grumman — Official site. URL: https://www.northropgrumman.com/what-we-do/space/mission-enabling-products/solar-array-products (accessed on 21.11.2025).

[21] Small Satellite Solar Arrays. Lockheed Martin Corporation. Official site. URL: https://www.lockheedmartin.com/en-us/products/smallsat-solar-arrays.html (accessed on 29.11.2025).

[22] U.S. Space Act, 2015. U.S. Public Law 114–90. URL: https://www.congress.gov/114/plaws/publ90/PLAW-114publ90.pdf (accessed on 10.11.2025).

[23] The National Center for Science Technology Innovation (NCSTI). China looks set to build space solar power station URL: https://en.ncsti.gov.cn/home/gridview/202406/t20240613_164551.html (accessed on 21.11.2025).

However, speed is not the sole factor that distinguishes China. The scale of resources it can bring to bear matters just as much. Unlike countries where SBSP advances through debate and market signals, China has already started building a major test site in Chongqing. The facility will test two critical technologies: assembling large structures in space and transmitting power wirelessly [2]. Money for this work comes through the 14th Five-Year Plan (2021–2025),[24] which gives the project the weight of a state assignment. Companies with majority government ownership must deliver.

The official target calls for a pilot megawatt-level orbital station by 2035. This is not just a statement of ambition. It serves as a tool for long-term planning and focusing resources. The Chinese model follows a direct path to its goal. Market forces play little role during research and development. Instead, the government provides what amounts to unlimited funding. It directs engineering talent where needed. And there is no pressure to make short-term profits.

This approach lets China overcome investment barriers that still make SBSP economically unattractive in market-driven economies.

3.4. Japan: A strategy of technological specialization and a model for monetizing core competencies

Japan has a long-standing interest in alternative energy sources. The country faces objective constraints in the form of limited domestic resources, and this situation has long made energy security a central concern of national policy. Space-based solar power fits into that broader picture.

The Japanese response to SBSP differs markedly from the American or Chinese models. Rather than pursuing scale or self-sufficiency across the entire technological spectrum, Japan has chosen to focus its efforts.[25] The logic is straightforward: with finite resources, attempting to compete across the board would likely result in mediocrity across the board. A different approach is called for.

That approach centers on wireless power transmission. This method is widely regarded as one of the most technically demanding elements of the entire SBSP enterprise. It is also capital-intensive. JAXA, together with industrial partners such as Mitsubishi Heavy Industries, has made this project the focus of its work.

The strategic rationale deserves attention. Japan cannot match the budgetary scale of American programs or the mobilization capacity of Chinese ones. This is simply a fact. But by concentrating resources on a single critical technology, Japan can achieve something else: it can become indispensable. Future international SBSP projects, whatever their scale and whoever leads them, will require efficient wireless power transmission. If Japan controls that technology, it controls a vital piece of the puzzle. The country positions itself not as a competitor in scale but as a supplier of necessary capability.

Evidence that the technology works has already been produced. During the "Kounotori" mission to the International Space Station, JAXA successfully demonstrated microwave power transmission under space conditions. This was not merely a laboratory exercise. It was a practical validation of a technology with clear commercial applications. The groundwork has been laid for future revenue streams: licensing intellectual property, providing engineering services, and entering into collaborative arrangements with partners who bring other capabilities to the table.

The Japanese case suggests that there is more than one path to relevance in emerging technological domains. Scale is one option. Specialization is another.

The Japanese "Strategic Roadmap for Space Solar Power Development"[26] formalizes this approach. Unlike many national documents that remain aspirational, this roadmap carefully charts the progression from basic research to market deployment. It sets out both the technological benchmarks that must be reached and the economic targets required to attract private investment. The underlying logic is clear. Japan pursues global significance not by scaling up, but by dominating a vital technological segment. From that position of strength, the country can

[24] The 14th Five-Year Plan of the People's Republic of China. URL: https://www.adb.org/publications/14th-five-year-plan-high-quality-development-prc (accessed on 10.11.2025).

[25] Research on Space Solar Power Systems (SSPS). JAXA. 2025. URL: https://www.kenkai.jaxa.jp/eng/research/ssps/ssps-ssps.html (Japan's Legal Framework: Basic Space Law (2008) and the Strategic Roadmap for Space Solar Power (SSP). (accessed on 10.11.2025).

[26] Japan's Legal Framework: Basic Space Law (2008) and the Strategic Roadmap for Space Solar Power (SSP). URL: https://global.jaxa.jp/about/law/index.html (Japan's Legal Framework: Basic Space Law (2008) and the Strategic Roadmap for Space Solar Power (SSP). (accessed on 13.11.2025).

monetize its advantage through licenses, collaborative ventures, and technology transfers — a model that turns constraint into competitive strength.

3.5. India: A strategy of incremental development and a model of budget efficiency

The Indian space paradigm demonstrates a consistent, long-term strategy focused on fundamental scientific research and national economic pragmatism. Although India currently operates with budgets that are not comparable to those of the leading spacefaring nations, the Indian Space Research Organization (ISRO) is methodically constructing the technological and institutional foundation necessary for a future breakthrough in SBSP.

India's principal strength does not lie in radical technological breakthroughs per se, but rather in its capacity to formulate a coherent strategy and pursue defined objectives with remarkable consistency, all while rigorously containing costs at every stage. The successful soft landing of Chandrayaan-3 on the lunar surface offered a striking demonstration of India's emerging capabilities. Shchedrov and Topyckanov in their article [25] noted that the achievement stood out all the more when placed alongside the setbacks experienced by Japanese and Russian lunar programs during the same period. Speaking after the mission, India's Minister of State for Space, Dr. Jitendra Singh, made a point that resonated widely: the mission proved that India can execute complex space operations without the budgets normally associated with such undertakings.[27] What Russia spent on its own, ultimately unsuccessful attempt exceeded India's expenditure by a factor of more than twenty-six.[28] The contrast reveals something fundamental about how the two countries approach resource allocation.

For India, SBSP is not simply a technological ambition. It speaks to more immediate concerns. The country faces real pressure on its energy system. Population growth continues. Dependence on imported hydrocarbons remains high. In this context, space-based solar power takes on a different character. It becomes a long-term infrastructure asset, something that can reduce exposure to external shocks and move the country closer to genuine energy independence. The economic logic is consistent with what Chandrayaan-3 demonstrated: outcomes depend not only on how much is spent but also on how resources are deployed. India's low-cost approach to space projects creates favorable conditions: with funding similar to other nations, India can achieve higher returns on investment. The Indian paradigm therefore shows that when one cannot compete through investment scale, one can compete through investment efficiency.

3.6. Russia: A conservative-evolutionary strategy and the risks of missed opportunities

Russia's position on space-based solar power reflects the broader institutional characteristics of its national space industry: reliance on technological heritage, a strong foundation in "classical" areas, and caution toward capital-intensive innovations with uncertain payback horizons. The primary developer, the Russian Space Systems holding company, has presented a project for a low-power (up to 100 kW) space solar power station utilizing a laser channel for energy transmission to Earth. As the project initiator, M. Barkova, notes, the pilot version of such a station targets remote and hard-to-reach regions and deliberately does not position itself as a competitor to conventional generation [26].[29] This niche-oriented approach aligns with more recent and broader economic findings: Chen, Wang, and Li, in their article [27], demonstrate that even at intermediate launch cost reductions, SBSP can become viable for niche applications and remote markets before achieving full-scale commercial competitiveness.

A key feature of the Russian approach lies in the absence of SBSP integration into the system of national priorities. Key policy documents — the Federal Space Program and the Fundamentals of State Policy in Space Activities until 2030 — contain no direct mention of SBSP.[30] Research proceeds

[27] Chandrayaan-3 translates to "Lunar Craft-3" (author's note).

[28] Chandrayaan-3 has proved India's capability for cost-effective Space missions. Indian Government Press Information Bureau. 26.08.2023. URL: https://www.pib.gov.in/PressReleasePage.aspx? PRID=1952448 (accessed on 27.11.2025).

[29] Solar energy to be transmitted to Earth via laser beam. Scientific and business portal "Atomic Energy 2.0". 28.01.2022. URL: https://www.atomic-energy.ru/news/2022/01/28/121373 (accessed on 29.11.2025).

[30] Fundamentals of State Policy in the Field of Utilizing the Results of Space Activities for the Purposes of Modernizing the Economy of the Russian Federation and Developing Its Regions for the Period up to 2030. Electronic Fund of Legal and

sporadically within broader power systems studies, lacking dedicated funding and institutional responsibility.

The Law "On Space Activities"[31] enshrines the dominant role of the state, which, in the absence of expressed political interest in SBSP, creates an institutional vacuum for private initiatives. Under conditions where the state serves as the sole customer and regulator yet does not generate demand for innovation, projects with long payback horizons and a high degree of uncertainty become investment-unattractive both for private capital and for state corporations focused on fulfilling approved plan targets.

One can characterize the Russian paradigm as "conservative-evolutionary" — it entails gradual improvement of proven solutions and a wait-and-see stance toward technologies that advance beyond the current stage of development. However, as other nations move from conceptual discussion to practical implementation and targeted investment, such a strategy carries risks of missed opportunities. By postponing entry into the new technological wave, Russia risks finding itself in a catch-up position at a stage when key patents, competencies, and market niches have already been allocated and the cost of entering the industry has multiplied.

3.7. Europe (ESA): A rational-waiting strategy and the economic costs of multilateral governance

The European approach to space-based solar power development exhibits the characteristic combination, typical of the European Space Agency (ESA), of high scientific and technological potential alongside institutional complexity in decision-making — a complexity arising from the need to align investment priorities among ESA member states. European companies such as Airbus[32] and Thales Alenia Space[33] — possess world-class competencies in creating highly efficient photovoltaic systems for scientific missions in extreme environments, including the BepiColombo spacecraft mission to Mercury.[34] However, the mere existence of technological capabilities does not automatically guarantee a transition to their commercial exploitation.

The ESA SOLARIS initiative[35] represents a classic "rational-waiting" paradigm. Its goal involves not the immediate launch of development work but a comprehensive assessment of technical feasibility, economic viability, and environmental implications of SBSP. This strategy minimizes early-stage investment risk, but the trade-off is clear: it significantly slows the move from research to demonstration.

Europe operates under institutional constraints that are not easily set aside. Because decision-making requires consensus among member states, and because those states bring different priorities, budget realities, and energy strategies to the table, building agreement takes time. It also consumes resources that might otherwise go directly into program execution. These transaction costs matter more in a context where technology moves quickly. The danger is that Europe finds itself responding to developments shaped elsewhere rather than helping to shape them.

There is a broader lesson in the European experience. Advanced technology is necessary for a major SBSP program, but it is not enough on its own. Two other conditions must be met. The first is political: someone must have the will to concentrate resources behind a shared objective. The second is commercial: there must be a credible account of how the venture will generate returns and attract sustained investment. Without these elements, even strong scientific and industrial capabilities may never find their way into operational form. In the absence of these elements, even high scientific potential risks remaining commercially unexploited, yielding ground to the more decisive and coordinated actions of other global players. The diagram below summarizes six national models of SBSP development described above (see *Figure*).

Regulatory-Technical Documents. URL: https://docs.cntd.ru/document/560853771(accessed on 10.11.2025).

[31] Law «On Space Activities» No. 5663–1, with amendments and additions as of July 7, 2025. URL: https://base.garant.ru/136323/ (accessed on 10.11.2025).

[32] Solar power beams: a step towards cleaner energy. Airbus. Official site. URL: https://www.airbus.com/en/newsroom/news/2022–09-solar-power-beams-a-step-towards-cleaner-energy (accessed on 22.11.2025).

[33] Thales Alenia Space Official site. URL: https://www.thalesaleniaspace.com/en/space-alliance (accessed on 22.11.2025).

[34] BepiColombo, Investigating Mercury's mysteries. European Space Agency URL: https://www.esa.int/Science_Exploration/Space_Science/BepiColombo (accessed on 22.11.2025).

[35] ESA Annual Space Environment Report. URL: https://www.esa.int/Space_in_Member_States/United_Kingdom/ESA_accelerates_the_race_towards_clean_energy_from_space (accessed on 13.11.2025).

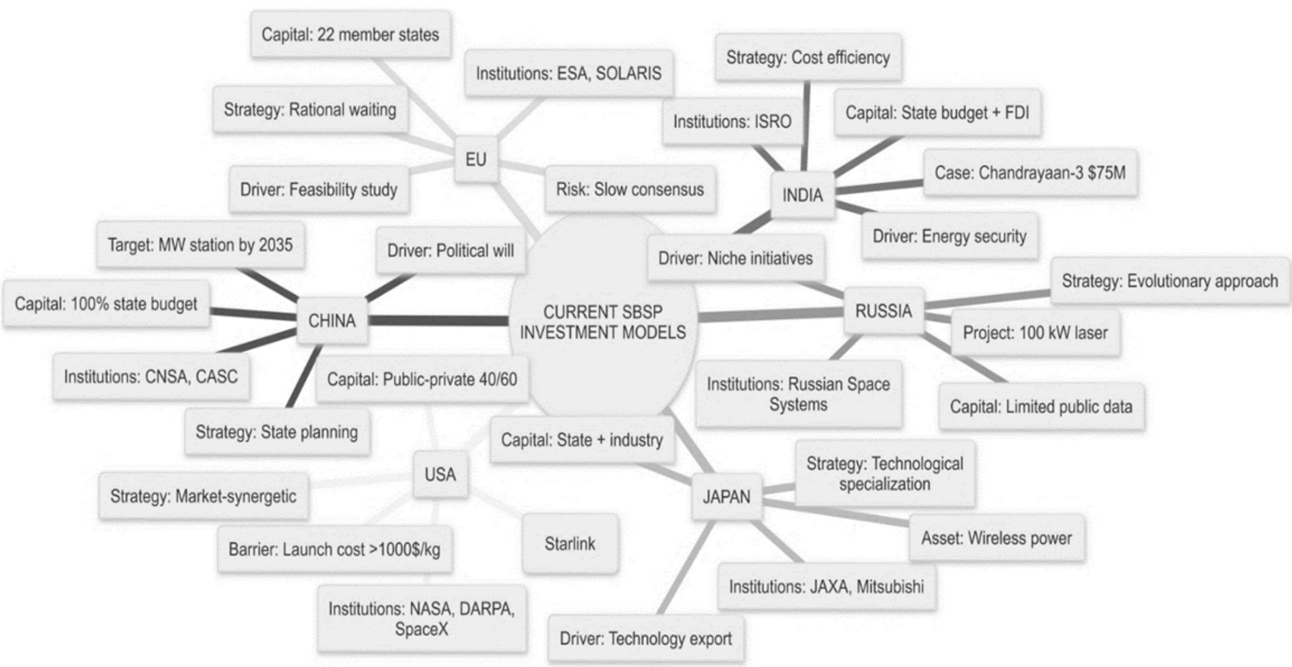

Fig. **National strategies and models of SBSP economics**

Source: Structured and built by the author in the Mermaid program.

Six national models of SBSP development are distinguished not primarily by technological maturity, but by strategic objectives and funding sources — ranging from the market-oriented US approach and China's state-mobilization model to Japan's specialization strategy, India's budget-efficient paradigm, Russia's conservative-evolutionary stance, and Europe's rational-waiting approach. The key differentiating factor is the balance between state planning and market mechanisms.

4. The legal dimension of SBSP: National regimes and economic risks

The legal environment for SBSP remains in a formative stage, with national approaches diverging and thereby influencing the investment climate and project financing models. The conditions for private investment entry and the fundamental parameters of SBSP economic models depend on how legislation defines rights to space resources and regulates capital participation.

The United States created a legal precedent by permitting private companies to appropriate and sell space resources (Space Act, 2015).[36] This represents a cornerstone for the future commercialization of SBSP.

China[37] and India[38] integrate SBSP legal regulation into the broader frameworks of their national space programs and five-year plans [28].

Japan enacted the Basic Space Act (2008),[39] establishing a legal framework for utilizing space for national prosperity, thereby paving the way for projects such as SBSP.[40]

Given the limited availability of open official data on Russia, forming well-founded conclusions about legal regimes in the SBSP sphere proves problematic.[41]

Table 1 below provides a comparative summary of the relevant country–specific documents.

At the international level, the 1967 Outer Space Treaty remains the foundational instrument. Ar-

[36] U.S. Space Act, 2015. U.S. Public Law 114–90. URL: https://www.congress.gov/114/plaws/publ90/PLAW-114publ90.pdf (accessed on 10.11.2025); U.S. Commercial Space Launch Competitiveness Act, Public Law 114–90 (full text). URL: https://www.govinfo.gov/content/pkg/PLAW-114publ90/html/PLAW-114publ90.htm (accessed on 10.11.2025).

[37] China unveils new measures to boost private investment. (The State Council of People's Republic of China). URL: https://english.www.gov.cn/policies/latestreleases/202511/11/content_WS691283b2c6d00ca5f9a07766.html (accessed on 10.02.2026).

[38] Press Information Bureau, Government of India. (2025, March 12). Parliament Question: Foreign Direct Investment in the Space Sector. URL: https://www.pib.gov.in/Pressreleaseshare.aspx? PRID=2110835

[39] Basic Space Law, 2008 URL: https://global.jaxa.jp/about/law/index.html (accessed on 10.11.2025).

[40] Japan Basic Plan on Space Policy URL: https://www8.cao.go.jp/space/plan/plan-eng.pdf (accessed on 13.11.2025).

[41] Roscosmos proposed sending solar energy from Space. February 22, 2022. URL: https://myseldon.com/ru/news/index/342187687 (accessed on 13.11.2025).

Table 1
National approaches to space activity regulation

Country	Legal framework / strategy	Key provisions of significance for SBSP
USA	U.S. Commercial Space Launch Competitiveness Act (SPACE Act)[1], Public Law 114–90 (2015), Section 51303	By granting private companies' ownership and sale rights over extracted space resources, the law protects future revenues and reduces investor uncertainty
Japan	Basic Space Law (Law No. 43 of 2008)[2]	Article 16 — Tax and financial incentives for private investment. Article 4 — Space Development for International Competitiveness
India	FDI policy amendment (March 2025)[3]	Differentiated FDI limits in the space sector draw foreign investment while keeping state control over strategically sensitive segments
China	State Council Policy on Private Investment (2025)[4]; Commercial Space Action Plan (2025–2027)[5]	The 15th Five-Year Plan includes commercial space among its strategic clusters. Private capital can now engage in commercial space ventures. The government is also establishing a National Fund for the Development of Commercial Space
Russia	Open official sources contain no evidence of dedicated legal frameworks specifically addressing SBSP[6]	Ongoing initiatives (including the space solar power station project by the "Russian Space Systems" holding company) remain fragmentary in nature and do not integrate into strategic document

Source: Compiled by the author.

Notes: [1] U.S. Commercial Space Launch Competitiveness Act, Public Law 114–90 (full text). URL: https://www.govinfo.gov/content/pkg/PLAW-114publ90/html/PLAW-114publ90.htm (accessed on 10.11.2025). [2] Japan's Legal Framework: Basic Space Law (2008) and the Strategic Roadmap for Space Solar Power (SSP). URL: https://global.jaxa.jp/about/law/index.html (Japan's Legal Framework: Basic Space Law (2008) and the Strategic Roadmap for Space Solar Power (SSP). (accessed on 13.11.2025). [3] Press Information Bureau, Government of India. (2025, March 12). Parliament Question: Foreign Direct Investment in the Space Sector. URL: https://www.pib.gov.in/Pressreleaseshare.aspx? PRID=2110835. [4] China unveils new measures to boost private investment. (The State Council of People's Republic of China). 11.11.2025 URL: https://english.www.gov.cn/policies/latestreleases/202511/11/content_ WS691283b2c6d00ca5f9a07766.html (accessed on 10.02.2026). [5] China's "Action Plan for Promoting the High–Quality and Safe Development of Commercial Space (2025–27)". Chinese Laboratory of Space Research. URL: https://www.lsr.hku.hk/china-targets-2027-milestone-for-its-commercial-space-sector-development/ (accessed on 10.02.2026). [6] Fundamentals of State Policy in the Field of Using the Results of Space Activities in the Interests of Modernizing the Economy of the Russian Federation and the Development of Its Regions for the Period up to 2030. Electronic fund of legal and regulatory and technical documents. URL: https://docs.cntd.ru/document/560853771 (accessed on 10.11.2025).

ticle I of the Treaty proclaims the freedom of exploration and use of outer space. Article II, however, prohibits the national appropriation of space and celestial bodies. From a legal perspective, an important question therefore remains open: can a geostationary orbital slot — the most effective position for transmitting energy to Earth — be considered an object falling under this prohibition? And does the prohibition extend to energy collected in orbit? From an economic standpoint, this legal uncertainty creates tangible risks for investors, which in turn increases the cost of capital.

5. The economics of SBSP: LCOE and commercialization thresholds

The Levelized Cost of Electricity, or LCOE, provides an essential metric for evaluating the economic feasibility of SBSP [29]. The structure of this metric reveals the parameters that most critically determine the ultimate cost of generating power in orbit and transmitting it to Earth-based receivers.

5.1. Structural analysis of the LCOE formula as applied to SBSP

To assess the economic viability of SBSP, one must begin with the standard expression for levelized cost of electricity. The formula (1) takes the following form:

$$LCOE = \frac{\sum_{t=1}^{n} * \frac{I_t + O_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} * \frac{E_t}{(1+r)^t}}, \qquad (1)$$

where I_t — Capital expenditures, the dominant cost item for CSEs. It includes:

• Manufacturing costs for photovoltaic modules. Although the cost of terrestrial solar panels has dropped sharply, space-grade counterparts require expensive materials (gallium arsenide) and technologies to ensure radiation resistance and durability [20]. However, the recent work of foreign researchers [30] presented a new system design with increased efficiency, thus reducing the overall cost of launching a spacecraft into orbit.

• Launch and orbital deployment costs constitute the main economic barrier. At current launch costs of approximately $1,000–$3,000/kg[42] deploying a gigawatt-capacity station weighing thousands of tons appears economically inconceivable.

• Costs of developing power transmission systems (antennas, transmitters).

• Costs of the ground-based receiving rectenna (rectenna).

O_t — Operating expenses, encompassing maintenance and repair of the orbital platform. For SBSP, these will prove exceptionally high due to the need to combat component degradation from radiation, perform orbit corrections, and — critically — actively counter space debris. This creates demand for a new industry — orbital servicing — which in itself represents an investment challenge.

F_t — Fuel costs are almost zero, which is a fundamental advantage of CSPs over fossil power plants.

E_t — Energy output represents the key economic rationale and advantage of SBSP. The capacity factor for SBSP in geostationary orbit can reach 0.9–0.95 (90–95%), whereas for the best terrestrial solar plants it does not exceed 0.25–0.3 (25–30%) [31–33]. This means that at identical peak power, an SBSP system will generate 3–4 times more energy annually. Extending research in this direction, Wilson and Vasile in [34] (2025) demonstrate through multi–objective optimization that strategically designed satellite constellations can enhance the economic efficiency of an orbital energy system.

r — The discount rate. For projects carrying high technological, political, and commercial risks, the discount rate will be very high, increasing the cost of capital and requiring the state or institutional investors to provide risk mitigation mechanisms in the early stages.

n — Lifespan determined by the durability of components in the harsh conditions of space. The target of 15–30 years is achievable only with breakthroughs in the creation of appropriate materials and protection from cosmic radiation, which directly affects the return on investment.

Table 2

Comparative cost of electricity for different generation technologies (2024)

Energy Production Technology	LCOE (USD/MWh)
Terrestrial industrial solar power plant	24–96
Wind energy	24–75
Natural gas power plant	39–155
Nuclear Power	141–221
Space–based solar power (estimated)	More than 1000

Sources: Compiled by the author based on National Security Technology Accelerator, 2024; LAZARD Laboratory, 2024; NASA Report, 2024.

5.2. The condition for SBSP's economic competitiveness

Achieving competitiveness between SBSP and ground–based solar power requires satisfying a simplified version of the condition expressed in formula (2). For purposes of illustration, discounting does not enter into this approximation:

$$\left(I_{\text{space}} + O_{\text{space}}\right) \le \\ \le \left(I_{\text{terrestrial}} + O_{\text{terrestrial}}\right) \cdot \frac{ICUR_{\text{space}}}{ICUR_{\text{terrestrial}}}. \quad (2)$$

Substituting the capacity factor values discussed above yields:

$$\left(I_{\text{space}} + O_{\text{space}}\right) \le \left(I_{\text{terrestrial}} + O_{\text{terrestrial}}\right) \cdot \frac{0.9}{0.25} \approx \\ \approx \left(I_{\text{terrestrial}} + O_{\text{terrestrial}}\right) \cdot 3.6. \quad (3)$$

The calculations in formula (3) lead to the following conclusion: even assuming that total capital and operating costs for SBSP prove 3.6 times higher than for terrestrial solar plants, the higher capac-

[42] Reducing the Cost of Space Travel with Reusable Launch Vehicles. Analytical Report (NSTXL, 2024). URL: https://nstxl.org/reducing-the-cost-of-space-travel-with-reusable-launch-vehicles/ (accessed on 21.11.2025).

Table 3
Key LCOE parameters for SBSP: Current values and commercialization targets

Parameter	Current situation for SBSP	Target for competitiveness	Impact on LCOE
Cost of launch	\$1,000–\$3,000/kg	\$20–\$50/kg	Reducing the numerator — capital expenditures
Power transmission efficiency	5–10% (In laboratory conditions)	15–20%	This increases the denominator of the LCOE formula — the volume of energy transmitted to Earth
Installed capacity utilization rate (ICUR)	–	90–95% (In potential)	This increases the denominator of the basic LCOE formula — annual energy output
Operational lifetime (n)	Not Confirmed	>20 years	This increases the denominator of the LCOE formula — the energy generation period
Discount rate (r)	Very high	Mitigation through risk reduction	Reduces the final LCOE value

Sources: Compiled by the author based on National Security Technology Accelerator, 2024; LAZARD Laboratory, 2024; NASA Report, 2024.

ity factor allows SBSP to produce energy cheaply enough to achieve parity. The problem lies in the fact that today, the gap in space segment costs exceeds 3.6 times — it runs to orders of magnitude greater, primarily due to launch costs.

5.3. Comparative analysis of LCOE and commercialization targets

A comparison of SBSP's levelized cost of electricity (LCOE) with traditional and renewable generation sources vividly illustrates the scale of the economic challenge facing SBSP (*Table 2*).

The existing cost difference, which is more than an order of magnitude higher than the cost of terrestrial alternatives, confirms the non-competitiveness of SBSPs. But a comprehensive comparative station life cycle assessment [35] argues that while SBSP is currently inferior to onshore renewables in strict cost metrics, its unique advantage lies in providing real baseload power without the disruption issues associated with onshore solar and wind installations. Breaking down the LCOE into its constituent elements makes it possible to determine exactly which parameters need to change and by how much in order to achieve commercial profitability (*Table 3*).

Recent advances in wireless power transmission, as reviewed by Mori and Sasaki [36], suggest efficiency targets of 15–20% are achievable with current technology trends, and further improvements could push these figures even higher. These efficiency gains have direct economic implications: they reduce the required generating surface area, lower launch mass and associated costs, and ultimately improve the return on investment for SBSP infrastructure.

The key conclusion from the analysis presented: today, the main driver of SBSP economics is not photovoltaic efficiency but the cost of access to space. This component of capital expenditures creates a gap that even the uniquely high-capacity factor (3–4 times higher than terrestrial) and zero fuel costs cannot offset.

Achieving the target range of \$20–\$50/kg would reduce capital expenditures to a level where SBSP's LCOE becomes comparable to terrestrial generation sources. Recent progress in developing reusable launch vehicles (e.g., SpaceX Starship) provides grounds for cautious optimism, yet the required cost reduction spans orders of magnitude beyond what has been achieved to date. Meeting these target parameters sets benchmarks for long-term investment policy and technological development: without a radical reduction in the cost of delivering payloads to orbit, SBSP commercialization will remain a theoretical prospect.

6. Conclusion

Conducted research allows to systematize the key findings regarding the economic viability of space-based solar power (SBSP) in the context of global competition.

This study establishes that space-based solar power (SBSP) has moved from the phase of theoretical concepts into the realm of strategic planning and long-term investment. An analysis of national approaches — from the market-oriented U.S. model to the state-directed strategies of China and India, Japan's technology-niche positioning, and Russia's conservative-evolutionary approach — has revealed fundamental differences in objectives, stages of readiness, and methods of implementing space energy programs.

The primary driver of SBSP development lies not so much in the environmental agenda as in the pursuit of energy independence and the creation of foundational infrastructure for the future space economy. Orbital power platforms can supply not only energy to Earth but also power for lunar bases, orbital manufacturing facilities, and interplanetary missions — in other words, they can become the foundation for emerging high-value-added markets. This fundamentally shifts the investment logic: SBSP projects merit consideration not as "green energy" but as long-term infrastructure assets that enable a whole range of related industries. For pioneering nations, this approach opens an opportunity not only to diversify their own energy mix but also to secure technological leadership, shape the standards and rules of a new sector, and ultimately control key elements of space logistics and manufacturing.

The cost of access to space remains the key economic barrier. LCOE decomposition confirms that even the uniquely high potential capacity factor (up to 90–95%) and zero fuel costs cannot compensate for the current gap in capital expenditures — a gap orders of magnitude wider than what would allow price parity with terrestrial generation. Achieving the target payload delivery cost of \$20–\$50/kg could fundamentally change this situation, thereby setting a clear benchmark for investment in reusable transportation systems and orbital infrastructure.

For Russia, the current landscape presents challenges requiring strategic reflection. With no information in open sources about specialized legal mechanisms or targeted programs in the SBSP sphere, initiatives such as the low-power space solar power station project proceed in a fragmentary manner, lacking integration into the system of national priorities. As other spacefaring nations move from conceptual discussion to practical implementation and targeted investment, a wait-and-see position risks the loss of competencies by the time the market takes shape. Integrating SBSP into the long-term strategy for space activity development and the orbital energy sector could serve as a tool for strengthening technological sovereignty, since participating in SBSP technology development today creates a foundation for the future competitiveness of national companies in the global market.

The findings presented here offer practical value for shaping national space initiatives, guiding energy sector investment decisions, and supporting ongoing research to refine SBSP's economic metrics as operational projects yield new data.

The implications of the findings differ for the stakeholders involved.

For governments and those shaping strategy. The choice between a state-led model and a market-driven one affects not only how quickly SBSP advances but also whether a country can help set standards in this field. Delaying decisions now risks ending up as a follower in a market that will have already taken shape without you.

For private investors. The study provides clear benchmarks: it shows under what conditions investment in space-based solar energy becomes viable. It also makes clear that early stages will require mechanisms to share risks between government and business.

For the international legal framework. As long as there is no clarity on how to use geostationary orbit and transmit energy from space under international law, financing such projects will remain difficult. Uncertainty simply raises costs for investors.

For researchers. The classification we have developed, together with the LCOE methodology adapted for space projects, can serve as a foundation for further work — at the intersection of space economics, energy policy, and institutional theory.

Based on the limitations of this study, further research should pursue the following interrelated directions: dynamic LCOE models and expanding the country sample.

Overall, SBSP's progression to a commercial level will depend on factors shaping the project's investment attractiveness: reducing payload delivery costs, creating an orbital services market, lowering risks (and thus the cost of debt capital), and finally, establishing a predictable international legal environment — without which private investment in such capital-intensive projects will remain in question.

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Strategic Pathways for Circular Economy Implementation in Small and Medium Enterprises: A Theoretical Integration Approach

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ABSTRACT

This study **aims** to systematically map the literature on circular economy (CE) applications in small and medium enterprises (SMEs) and to propose a conceptual framework for sustainability strategies. The **method** involved retrieving a dataset of 510 publications from the Scopus database and analyzing it with the Bibliometrix package in RStudio, using bibliometric techniques to assess publication performance, prolific authors, institutional contributions, collaboration patterns, and thematic structures, followed by thematic cluster mapping integrated with strategic management perspectives (environmental scanning, strategy formulation, implementation, and evaluation) underpinned by institutional theory, the technology-organization-environment framework, and dynamic capabilities theory. The **results** reveal a significant increase in CE-related SME research in recent years, with contributions concentrated in specific institutions and research networks, and identify three dominant research directions: digital technologies enabling circular practices, environmental policies driving adoption, and the design of sustainable business models, underscoring the importance of technology-enabled transformation, regulatory alignment, and organizational readiness in SME transitions. The **contributions** of this study lie in providing a strategic roadmap that integrates bibliometric insights with management theory, demonstrating how SMEs can transform challenges such as capital constraints and limited infrastructure into strategic opportunities through capability development and stakeholder collaboration, while offering practical implications for SMEs, policymakers, and academics to design evidence-based sustainability strategies that enhance competitiveness and advance global sustainability goals.

Keywords: circular economy; small and medium enterprises; bibliometric analysis; sustainability transition; strategic management; circular business model; technology-organization-environment framework; institutional theory; dynamic capabilities; sustainable business strategy

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ОРИГИНАЛЬНАЯ СТАТЬЯ

Стратегические пути внедрения экономики замкнутого цикла на малых и средних предприятиях: теоретический интеграционный подход

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АННОТАЦИЯ

Цель данного исследования — систематизировать литературу по применению экономики замкнутого цикла (циркулярной экономики) на малых и средних предприятиях (МСП) и предложить концептуальную

основу для стратегий устойчивого развития. **Методы** включали получение набора данных из 510 публикаций из базы Scopus и его анализ с помощью пакета Bibliometrix в RStudio, использование библиометрических методов для оценки эффективности публикаций, наиболее продуктивных авторов, институционального вклада, моделей сотрудничества и тематических структур. Затем было проведено тематическое кластерное картирование, интегрированное с перспективами стратегического управления (анализ внешней среды, разработка стратегии, ее реализация и оценка), подкрепленное институциональной теорией, концепцией «технология-организация-среда» и теорией динамических возможностей. **Результаты** показывают значительный рост исследований в области циркулярной экономики для малых и средних предприятий в последние годы, при этом вклад сосредоточен в конкретных учреждениях и исследовательских сетях. Авторы выделяют три доминирующих направления исследований: цифровые технологии, способствующие внедрению экономики замкнутого цикла, экологическая политика, стимулирующая ее внедрение, и разработка устойчивых бизнес-моделей. Подчеркивается важность технологически обеспеченной трансформации, соответствия нормативным требованиям и организационной готовности в процессе перехода МСП к устойчивой экономике. **Научный вклад** данного исследования заключается в разработке стратегической дорожной карты, которая интегрирует библиометрические данные с теорией управления, демонстрируя, как МСП могут превратить такие проблемы, как нехватка капитала и ограниченная инфраструктура, в стратегические возможности посредством развития потенциала и сотрудничества с заинтересованными сторонами, а также предлагая практические рекомендации для МСП, политиков и ученых по разработке научно обоснованных стратегий устойчивого развития, повышающих конкурентоспособность и способствующих достижению глобальных целей устойчивого развития.
Ключевые слова: экономики замкнутого цикла (циркулярная экономика); малые и средние предприятия; библиометрический анализ; переход к устойчивому развитию; стратегическое управление; циркулярная бизнес-модель; концепция «технология-организация-окружающая среда»; институциональная теория; динамические возможности; стратегия устойчивого бизнеса

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1. Introduction

The linear economic paradigm that has dominated world production has caused excessive resource use, industrial waste, carbon emissions, and environmental degradation [1]. According to [2], the "take-make-dispose" model is environmentally harmful and pushing a more sustainable economy. The Circular Economy (CE) is a long-term solution that promotes recycling, waste reduction, and sustainable product design to reduce environmental consequences [1, 2]. Small and medium enterprises (SMEs) are essential in this transition, especially in developing countries, significantly contributing to job creation, value-added distribution, and local innovation [3, 4]. The implementation of CE principles in this sector can enhance product longevity and optimize resource utilization while facilitating the emergence of a more environmentally sustainable market [5]. SMEs play a crucial role in advancing Sustainable Development Goals (SDGs), especially SDG 12, which emphasizes responsible consumption and production practices [4].

The transition of SMEs to a CE encounters multiple challenges, including organizational structure, capital constraints, digital infrastructure, and insufficient technical skills [6, 7]. To address these challenges, SMEs must implement strategies that facilitate their transition to a CE. In this context, it is essential to evaluate the various factors that influence the readiness and ability of SMEs to adapt to a circular business model. An effective method for evaluating readiness involves utilizing the technology-organization-environment (TOE) framework. This framework is essential for assessing the readiness of SMEs through three primary dimensions: technology, organization, and external pressures related to regulations and infrastructure support [6]. Conversely, it is essential to comprehend the impact of external factors and institutional pressures on the adoption of CE. Institutional theory elucidates the influence of coercive pressures (stemming from government policies), mimetic pressures (resulting from interindustry imitation), and normative pressures (derived from industry standards) on the adoption of CE practices in developing nations such as India, China, and Brazil [8].

Internally, the implementation of CE necessitates that SMEs modify their structures and cultivate dynamic capabilities to effectively respond to rapid external and internal changes. Dynamic capabilities theory (DCT) serves as a significant framework for analyzing how SMEs cultivate sensing, seizing, and reconfiguring capabilities to address the challenges associated with implementing CE principles in their operational activities [9]. This change is both operational and strategic, involving alterations in business models, supply chain management, and collaboration among participants within a sustainability-focused industrial ecosystem [10, 11]. The existing literature on CE and SMEs tends to be predominantly descriptive, reliant on case studies, or excessively focused on isolated sectoral issues. Research systematically mapping the relationships among topics, influential actors, and emerging trends in CE is scarce [12, 13]. This deficiency obstructs data-driven decision-making and the formulation of adaptable clean production strategies. However, despite the increasing number of studies on CE in SMEs, limited research has integrated bibliometric mapping with strategic management perspectives to explain how SMEs can systematically formulate and implement CE strategies. Existing studies also tend to examine technological, organizational, or environmental dimensions separately, without offering an integrative conceptual understanding of CE implementation pathways. Therefore, a comprehensive knowledge mapping that combines CE themes with strategic management frameworks remains underexplored.

Therefore, this study aims to systematically map and analyze the development of CE research in the context of SMEs through a bibliometric approach integrated with strategic management perspectives. Specifically, this research seeks to identify major research trends, thematic clusters, influential publications, and conceptual relationships that explain how SMEs formulate, implement, and evaluate CE strategies within dynamic business environments. In addition, this study aims to develop an integrative conceptual framework that connects the TOE framework, institutional theory, and dynamic capabilities theory in explaining CE adoption and strategic transformation in SMEs.

This study contributes to the existing literature in several ways. First, unlike previous studies that primarily focus on isolated technological or environmental aspects, this research integrates bibliometric mapping with strategic management analysis to provide a more comprehensive understanding of CE implementation pathways in SMEs. Second, this study contributes theoretically by synthesizing the TOE framework, institutional theory, and dynamic capabilities theory into a unified conceptual perspective for analyzing CE adoption processes. Third, this research extends the bibliometric literature by offering a strategic thematic interpretation of CE studies, thereby enriching the discussion on sustainability-oriented business transformation in SMEs [14].

The significance of this study lies in both its theoretical and practical implications. Theoretically, the findings provide a structured knowledge map that clarifies the evolution and intellectual structure of CE research in SMEs. Practically, the proposed conceptual framework may assist policymakers, SME managers, and practitioners in designing adaptive CE strategies, strengthening sustainability-oriented capabilities, and supporting green industry policies and clean production initiatives [15]. Furthermore, this study provides insights that may support the transition toward more inclusive and sustainable production and consumption systems in developing and emerging economies.

2. Literature review

The implementation of CE principles in SMEs necessitates systematic planning. The strategic management framework proposed by [14] serves as a crucial basis for formulating strategies that incorporate CE principles, emphasizing resource efficiency and long-term sustainability. An effective strategy must encompass market analysis, the identification of external opportunities and challenges, and sufficient internal management to facilitate the implementation of CE principles [16]. Strategic management is crucial for establishing a framework that enables SMEs to develop and evaluate sustainability-oriented strategies [17]. During the initial phase of environmental scanning, SMEs evaluate factors that affect the implementation of the CE. Institutional theory is significant in illustrating the impact of external pressures, including government policies and environmental regulations, on SMEs' decisions to adopt CE practices [18]. Coercive pressures, including government regulations on waste management, frequently serve as a key impetus for SMEs to shift towards a more sustainable economy [19]. The TOE framework enables SMEs to evaluate their technological and organizational preparedness for the implementation of CE [20].

In the strategy development phase, SMEs design strategies to integrate CE into their existing business models. DCT theory explains that SMEs need to develop flexible capabilities to adapt to technological and market changes [15]. DCT shows that SMEs must be able to change supply chain configurations and redesign products to be more sustainable [11]. Therefore, the strategy needs to consider internal capabilities that support CE and involve collaboration with external parties [10]. Institutional theory ensures that SMEs comply with regulations and industry standards that support sustainability [21]. During the strategy implementation phase, SMEs began integrating CE principles into their operational activities. DCT plays an important role here, as SMEs need to have dynamic capabilities to adapt to the changes that are occurring [10]. The TOE framework is used to assess the readiness of the technology used in operations and environmentally friendly waste management [20]. Institutional theory helps SMEs stay compliant with environmental regulations and current policies [19].

During the evaluation phase, SMEs must assess the effectiveness of CE implementation, focusing on waste reduction and energy savings. At this stage, institutional theory is significant, as it aids SMEs in evaluating their compliance with external demands from government regulations and the industrial sector [1]. The assessment incorporates an analysis of the dynamic capabilities of SMEs in their response to occurring changes [15]. SMEs must participate in organizational learning and offer feedback to modify their strategies, thereby ensuring long-term sustainability [4]. The implementation of CE principles in SMEs necessitates a systematic approach encompassing four stages of strategic management: environmental scanning, strategy formulation, strategy implementation, and evaluation. The strategic management theory by [14] offers a framework for developing sustainable strategies, whereas the TOE framework and DCT assist in evaluating technological and organizational preparedness for CE initiatives. Institutional theory presents external factors that affect decision making and the execution of CE initiatives. Utilizing these theories enables SMEs to implement CE practices effectively, improve sustainability, and mitigate adverse environmental effects. Ongoing assessment will guarantee that the implementation of CE evolves and delivers sustained advantages for SMEs and society at large [1, 10, 20].

3. Method

3.1. Sources of data and search methodology

This study employs a bibliometric approach to examine the development of scientific literature concerning CE within the context of SMEs. Bibliometric analysis enables the systematic identification of publication trends, collaboration patterns, influential authors, and thematic structures derived from publication metadata [22]. The Scopus database was selected as the primary data source due to its broad coverage of peer-reviewed international publications and its compatibility with bibliometric analysis tools such as Bibliometrix and Biblioshiny.

The data collection process was conducted in May 2025 using the search query TITLE-ABS-KEY ("circular" AND "economy" AND "SMEs"). The query was intentionally designed in a broad and inclusive manner to capture interdisciplinary studies related to CE implementation in SMEs and to minimize the exclusion of relevant publications that may employ varying terminologies. No publication year restriction was applied in order to observe the long-term evolution of research trends in this field.

Several inclusion criteria were applied to improve dataset relevance and consistency. The study included: (1) documents indexed in Scopus, (2) publications written in English, (3) document types limited to journal articles, conference proceedings, and books/book chapters, and (4) publications categorized within the subject areas of Business, Management and Accounting; Environmental Science; Social Sciences; Economics, Econometrics and Finance; and Decision Sciences. Documents outside these criteria, including editorials, notes, errata, and records with incomplete metadata, were excluded from the dataset. The initial search identified 510 documents. After screening and metadata verification, all 510 documents fulfilled the inclusion criteria and were retained for bibliometric analysis.

3.2. Data cleaning and preparation

The data was processed using RStudio and the bibliometrix package. The cleaning stage involved duplicate checking, verification of metadata completeness (including author names, titles, affiliations, abstracts, and keywords), and the standardization of synonymous terms such as "SMEs," "small and medium enterprises," and "small business" to improve consistency across the dataset. The data was transformed into a bibliographic format utilizing the convert2df function.

3.3. Bibliometric indicators

The performance analysis indicators comprised total publications, average annual citations, active authors, and the journals that predominantly published articles on CE and SMEs [21]. Science mapping indicators are employed to evaluate the conceptual dimension via keyword frequency and density, topic development mapping, and thematic analysis illustrated in thematic maps. This method offers a thorough examination of the literature structure and facilitates the creation of an integrative conceptual framework concerning sustainability in the SME sector [5, 23].

3.4. Data analysis

The analysis employed two primary methodologies: document performance analysis and science mapping. Performance analysis of documents assesses publication productivity through metrics such as annual publications, citation counts, contributing authors, and source of publications. Science mapping analyzes the relationships between concepts using techniques such as co-occurrence, bibliographic coupling, and co-citation. Visualization through Biblioshiny demonstrates the conceptual network and keyword clusters associated with the strategic management framework proposed by [14]. This framework encompasses four stages: environmental scanning, strategy formulation, strategy implementation, and evaluation [14]. The mapping is based on several theories, including institutional theory [18], the TOE framework [20], and DCT [24], which are commonly utilized in CE studies concerning SMEs [6, 7].

3.5. Visualization of methodology

Figure 1 illustrates the research methodology flow, detailing the stages from data retrieval in Scopus to integration into a bibliometric-based strategic management framework. Each step illustrates a distinct contribution to data-driven analysis, establishing a robust foundation for the sustainable development of CE policies and practices within the SME sector.

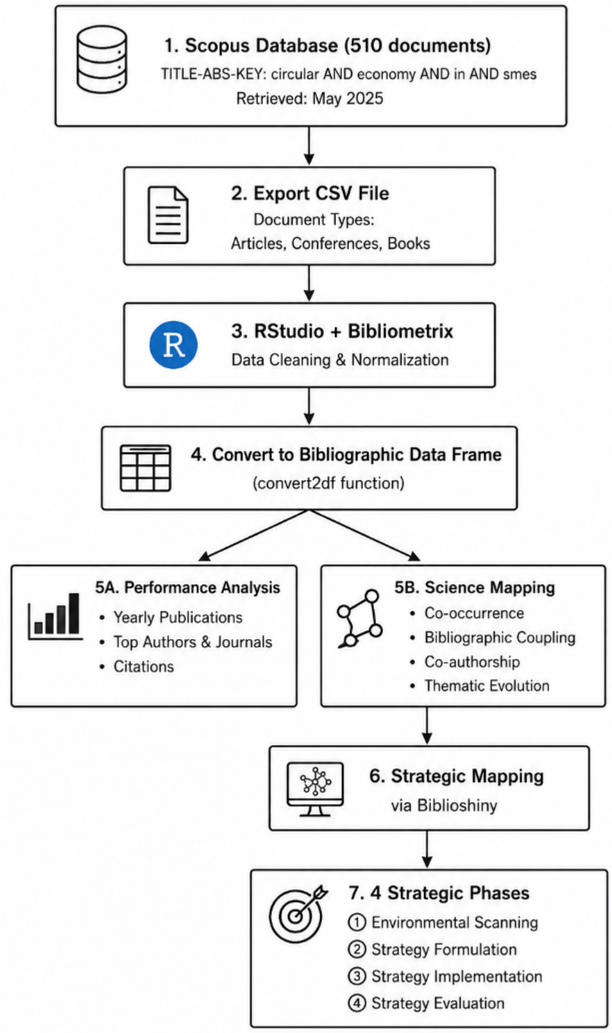

Fig. 1. **Workflow of the research methodology**

Source: Developed by the authors.

4. Results and discussion

4.1. Performance analysis

4.1.1. Overview of literature characteristics

A bibliometric analysis of 510 publications from 2005 to 2025 indicates substantial growth in literature concerning CE in SMEs, with an average annual growth rate of 23.4%. This trend underscores the rising global focus on sustainable transitions within the small business sector [4]. The publications comprise 248 sources, including scientific journals, conference proceedings, books, and book series, reflecting the growth of CE themes in SMEs across diverse academic and practical platforms [25]. A total of 1,459 authors

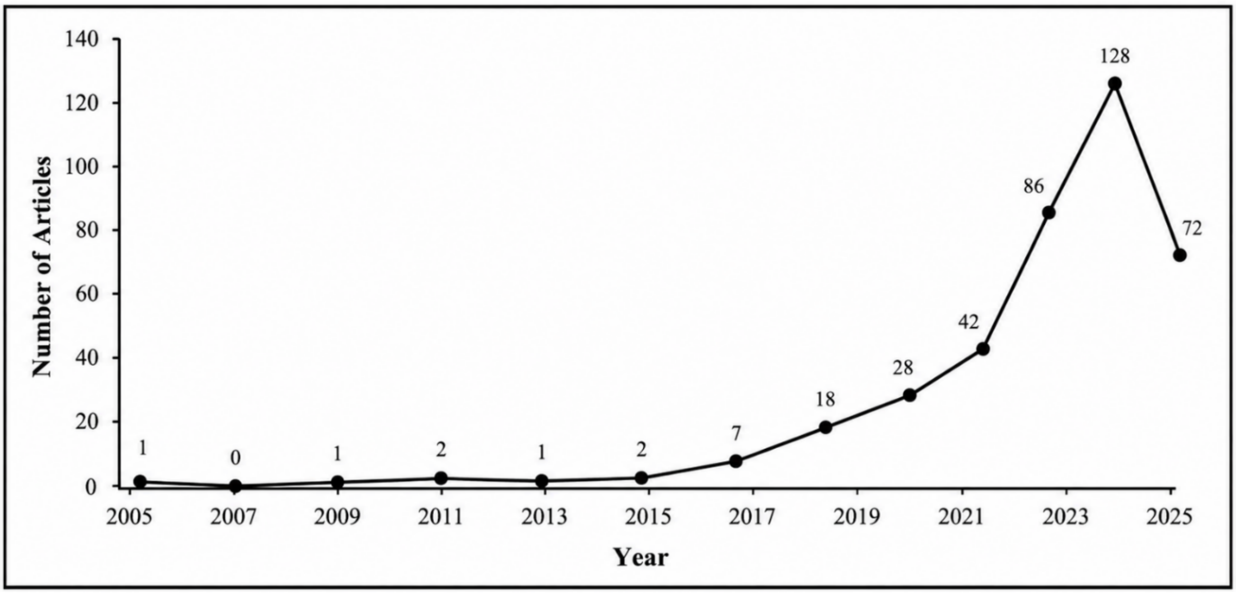

Fig. 2. **Annual scientific production on circular economy research in SMEs from 2005–2025**

Source: Developed by the authors.

contributed, averaging 3.44 authors per document, which reflects the interdisciplinary and complex nature of the CE-SME issue [13]. International collaboration has reached 34.31%, signifying that CE is increasingly recognized as a global research focus [1].

4.1.2. Productivity and citation impact

The average citations per document, at 25.25, suggest that the literature on CE in SMEs is expanding rapidly in both volume and academic significance. The average document age of 2.53 years indicates that CE in SMEs is a dynamic and increasingly relevant subject [5]. The analysis of 510 documents revealed 1,315 distinct terms, highlighting the variety of approaches and perspectives in CE-SME research. This suggests significant thematic diversity and potential for further research, especially regarding technological innovation, sustainable business models, and environmental policies [21].

4.1.3. Yearly scientific output

The annual trend in scientific production indicates a notable rise in research CE within SMEs from 2005 to 2025 (*Fig. 2*). From 2005 to 2015, the number of publications remained limited. However, post-2017, a gradual increase was observed, culminating in a significant surge beginning in 2020, with a peak of over 120 publications annually in 2024. This increase correlates with the global demand for sustainability, the advocacy for environmentally friendly economic policies, and the heightened industry awareness of climate change. The COVID-19 pandemic accelerated digital and sustainable transformation in SMEs, leading to increased research on CE implementation [4, 25].

The trend illustrated in *Fig. 2* corresponds with earlier studies suggesting that over the past five years, CE has emerged as a significant theme across business, environmental studies, industrial engineering, and strategic management [13]. CE has become a strategic priority in both developed and developing nations, particularly through the lens of SMEs. The decrease in publications in 2025 is likely attributable to indexing processes and publication delays, rather than a diminished interest in this topic [5]. The average annual publication growth of 23.4% indicates that CE in SMEs is a rapidly evolving strategic domain, presenting opportunities for further conceptual synthesis and the enhancement of evidence-based policy agendas [21, 26].

4.1.4. Mean citations annually

The analysis of average annual citations indicates notable variations in the academic impact of publications related to CE within the context of SMEs. *Figure 3* demonstrates that articles published from 2005 to 2013 garnered minimal citations, attributable to the restricted volume of publications and the nascent status of CE as a significant subject in academic and policy discourse. In 2015, there was a notable rise in citations, averaging nearly 30 citations per article, which suggests the

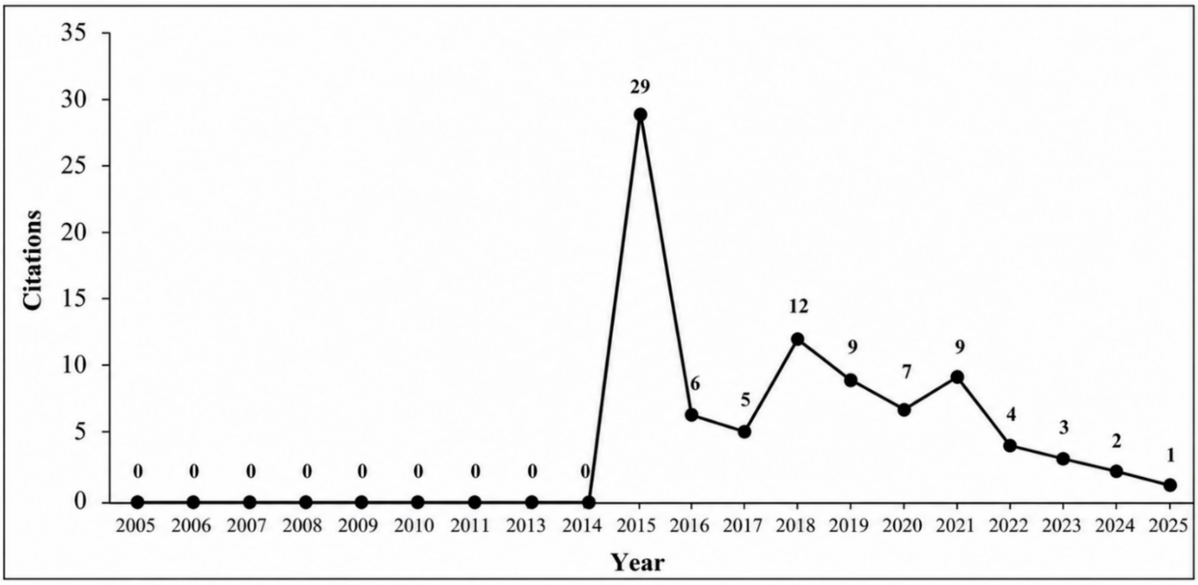

Fig. 3. **Mean annual document citations on circular economy research in SMEs**

Source: Developed by the authors.

presence of several key articles that were extensively referenced in later research [13]. Following the attainment of this peak, the average citations exhibited a decline ranging from five to 15 citations per article during the period from 2017 to 2023. The observed decline does not indicate a reduction in quality or relevance; rather, it is attributable to the time lag citation effect, wherein newer articles require additional time to garner consistent citations [21]. The rise in publication volume facilitates a more equitable distribution of citations among a greater number of articles.

Figure 3 indicates a decline in citations for 2024 and 2025; however, this trend should be interpreted cautiously, as the data may not be fully indexed or have garnered sufficient academic attention. The average document age is 2.53 years, indicating that most publications remain relatively recent and may garner additional citations in the future [4]. Overall, despite fluctuations in annual citation averages, these results confirm that publications on CE and SMEs make a significant scientific contribution, demonstrating that CE in the context of SMEs is not just a temporary discourse but is becoming a strategic discipline in clean production and the transition towards a sustainable economy [1, 25].

4.1.5. Leading authors and their contributions across time

An analysis of the most active authors over the past two decades identifies several key figures who have consistently contributed to the development of CE literature within the context of SMEs. *Figure 4* illustrates the ten authors with the highest publication counts and the temporal distribution of their works. Jose Arturo Garza-Reyes is a primary author who has consistently published from 2018 to 2025, concentrating on the integration of lean manufacturing and CE into business processes, alongside the impact of process innovation on enhancing the operational sustainability of SMEs [27]. Consistency demonstrates his strategic role in the CE literature, especially within the small manufacturing sector. Furthermore, researchers including Soumyadeb Chowdhury and Prasanta Kumar Dey have become significant contributors, emphasizing the integration of CE with digitalization, data-driven decision-making, and the preparedness of SMEs to adopt CE models [2, 28]. Both are crucial for linking sustainability theory to practice within the small business sector, particularly in developing countries [4].

Figure 4 illustrates that researchers, including Ebenezer Afum, Yaw Agyabeng-Mensah, and Charles Baah, have conducted empirical studies focusing on organizational factors, environmental leadership, and green innovation in the context of supporting CE in SMEs. The CE-SME literature encompasses not only environmental and production aspects but also governance issues, organizational strategy, and managerial behavior [21, 25]. The contributions of the lead authors reflect a cohesive group of scientists actively engaged in advancing theory and its application. The activ-

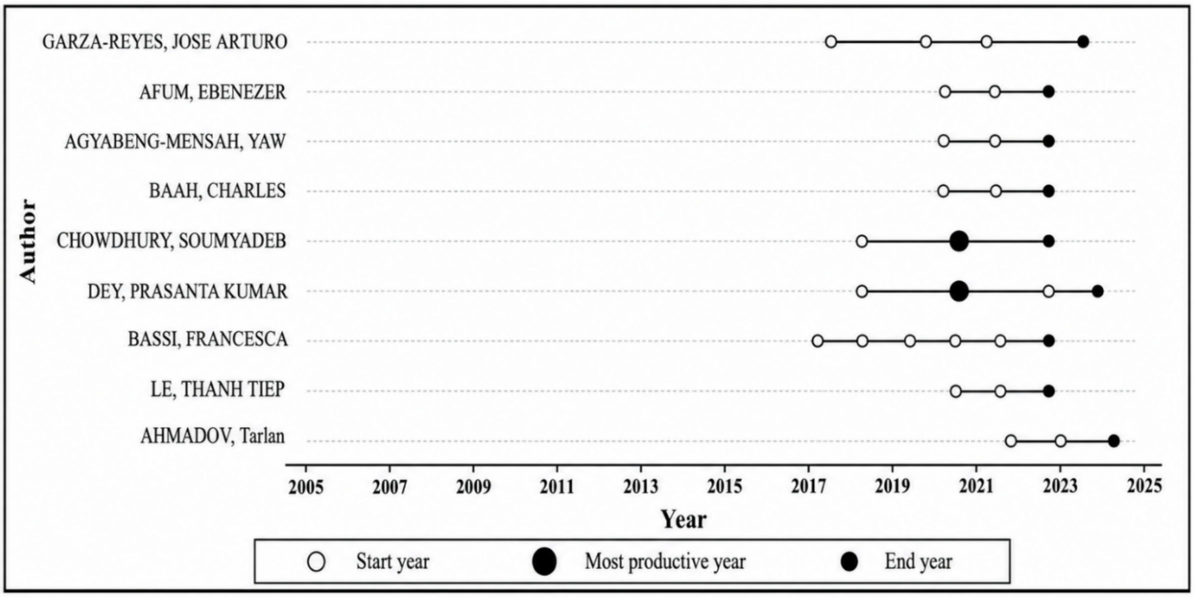

Fig. 4. **Top author's production over time on circular economy research in SMEs**

Source: Developed by the authors.

ity and productivity of CE in SMEs indicate the establishment of a robust academic community prepared to enhance interdisciplinary and international collaboration [1, 26].

4.1.6. Sources of publication

Figure 5 illustrates the distribution of the research publication's sources across multiple platforms. The journal Sustainability, noted for its significant contributions, exemplifies a commitment to interdisciplinary approaches and global perspectives in the study of sustainability practices, particularly within the SME sector. Despite its extensive scope, this journal encounters challenges related to selectivity and the substantial volume of articles requiring review [13]. The Journal of Cleaner Production is distinguished by its emphasis on technical, policy, and clean production dimensions, rendering it particularly pertinent for evidence-based and applied research.

Figure 5 indicates that Business Strategy and the Environment occupy the third position, emphasizing the relevance of research in business strategy for facilitating the transition to a CE, especially within SMEs. This aligns with the findings of [21], that sustainability strategies centered on business models and value are critical for the implementation of CE practices in SMEs. Additional journals, including the Journal of Business Research (23 documents), Resources, Conservation and Recycling (eight documents), and Circular Economy and Sustainability (10 documents), significantly contribute to the dissemination of relevant literature. Certain conference proceedings, including Lecture Notes in Networks and Systems and Springer Proceedings in Business and Economics, facilitate the dissemination of CE research, illustrating the connection between academic and industry platforms. The findings indicate that the literature on CE in SMEs has expanded in both volume and scope, influencing significant scientific domains, including sustainability, business management, and technological innovation. Comprehending active publication sources is essential for researchers in strategizing future publications and enhancing the visibility and academic impact of their work [4, 26].

4.2. Science mapping analysis

4.2.1. Knowledge structure and conceptualization

4.2.1.1. Conceptual framework via keyword co-occurrence network

Figure 6 illustrates the conceptual framework of CE literature pertaining to SMEs via a keyword co-occurrence network. This analysis delineates three primary clusters derived from the semantic relationships among concepts in the examined publications. The initial cluster, indicated in red, centers on the term "circular economy," which serves as the primary keyword regarding both frequency and significance. Additional pertinent terms encompass sustainability, supply chain management, resource efficiency, climate change, and environmental economics, suggesting that

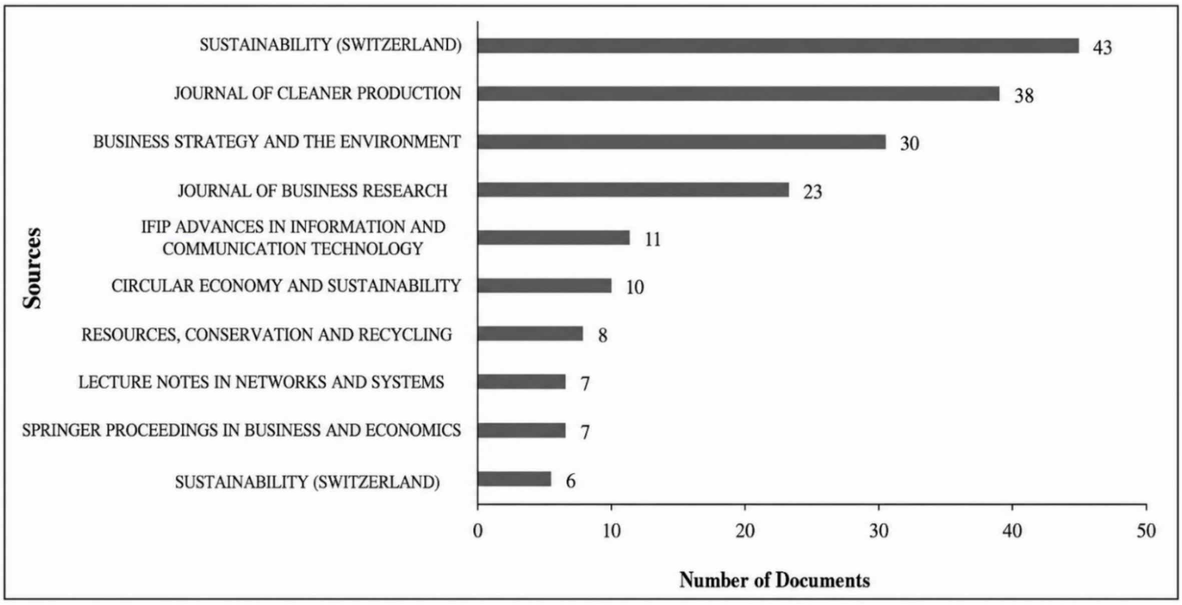

Fig. 5. **Top 10 most productive sources on circular economy research in SMEs**

Source: Developed by the authors.

the CE approach is extensively examined within the framework of production system sustainability and resource efficiency [1, 21].

The second cluster, represented in blue, centers on the term "SMEs" and encompasses concepts including developing countries, barriers, business models, product design, and Industry 4.0. The implementation of CE in the analyzed SMEs is assessed not only from an environmental standpoint but also through the lenses of technological innovation, process design, and adoption challenges in developing countries [4, 29]. The significant connection between SMEs and sustainable development highlights the crucial role of SMEs in attaining the SDGs, especially Goals 8, 9, and 12. The third cluster, indicated in green, includes terms such as recycling, waste management, environmental sustainability, and economic factors. This cluster presents a technical and economic perspective on CE, emphasizing waste management and recycling processes in relation to operational sustainability [25]. The emergence of the terms "human" and "economic" also indicates a tendency to associate the CE not only with environmental aspects but also with social and economic dimensions. The network structure indicates that the literature on CE in SMEs exhibits a diverse nature, integrating economic, social, environmental, and technological components. The significant co-existence of keywords suggests that the approach to CE in the SME sector is transitioning from technical concerns, such as recycling, to strategic considerations, including business model design, decision-making, and the integration of new technologies [13]. This mapping delineates the existing knowledge structures and presents avenues for investigating more profound cross-disciplinary themes in forthcoming research.

4.2.1.2. Co-occurrence density map of keywords

Figure 7 illustrates the keyword co-occurrence density map, indicating the intensity of topics within CE studies related to the SME sector. Dark red areas represent high concentrations of keywords, indicating the predominant core themes within this literature. In contrast, regions with lighter hues signify subjects that are infrequently addressed yet maintain a thematic relationship.

The density map reveals that terms like CE, sustainability, SMEs, and sustainable development are predominant, highlighting these four concepts as central themes in CE-SME literature, which emphasizes the integration of sustainability into SME activities [1, 25]. Furthermore, concepts including supply chain management, environmental management, resource efficiency, climate change, and ecological innovation are gaining prominence in high-density areas, suggesting that CE-SMEs are progressively addressing more specialized topics, such as sustainable supply chain management [13, 21]. Terms associated with digital technology and Industry 4.0 emerged in areas of low intensity, suggesting that this domain remains in development

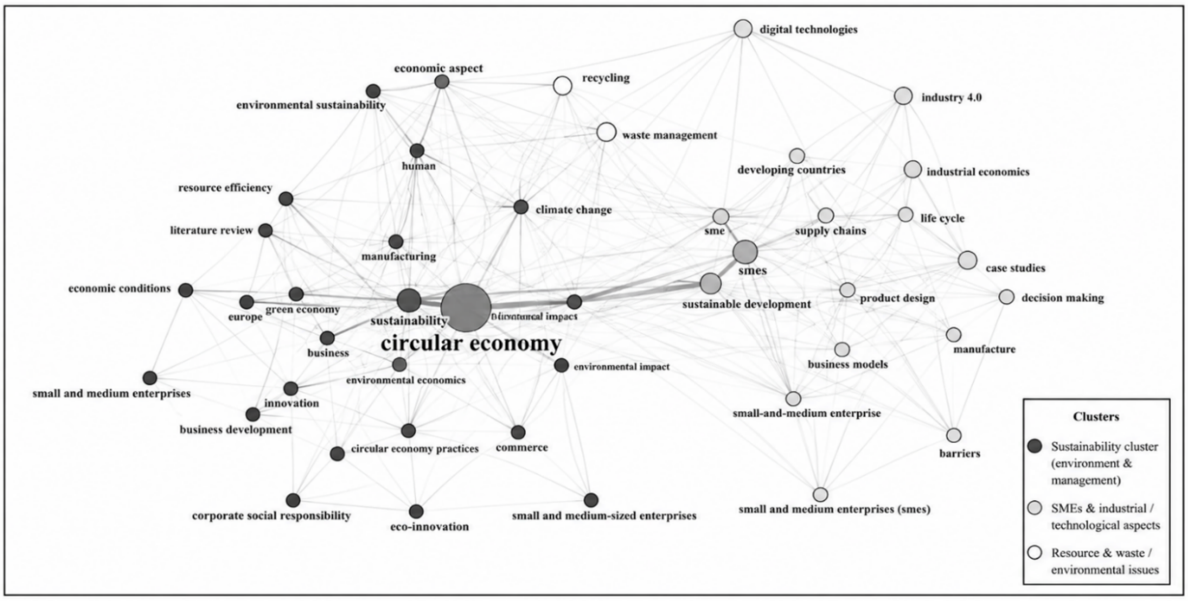

Fig. 6. **Keyword co-occurrence network on circular economy research in SMEs**

Source: Developed by the authors.

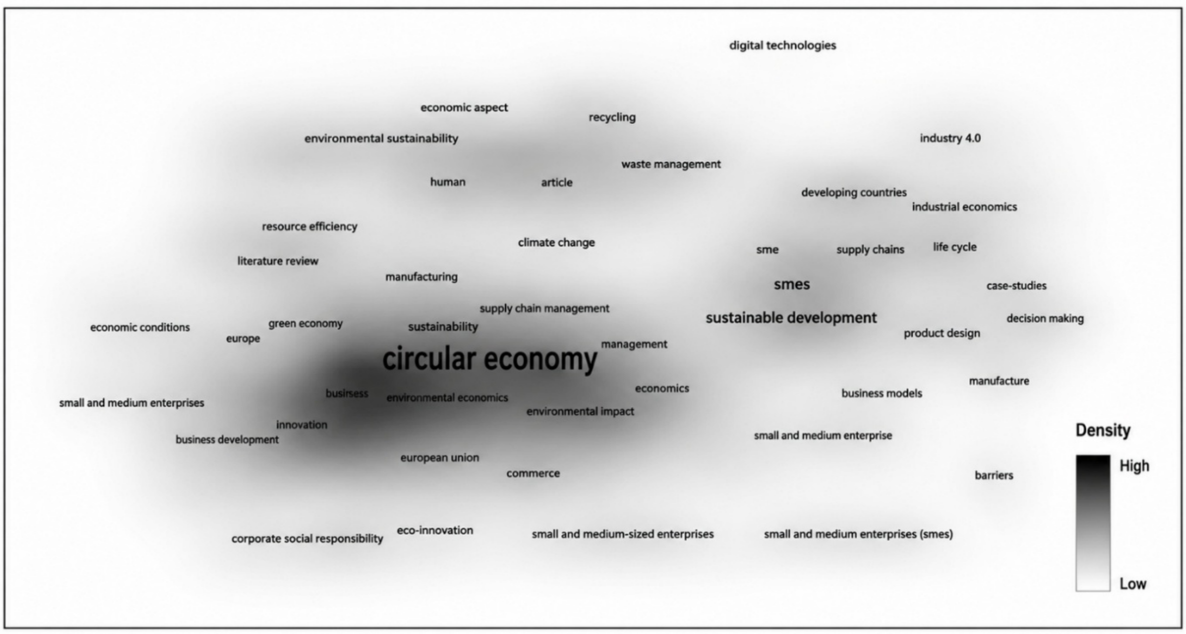

Fig. 7. **Key word density visualization of research on circular economy research in SMEs**

Source: Developed by the authors.

and holds significant potential to facilitate sustainable practices in the future [4]. The density map supports prior analyses and underscores potential avenues for further investigation, especially regarding the incorporation of digital technologies, innovative business models, and data-driven decision-making in the context of the CE for SMEs [26, 29].

4.2.1.3. Trending topics

Figure 8 illustrates the evolution of topics within CE literature in the SME sector from 2018 to 2025, as derived from the Scopus database. This finding indicates that key themes such as CE, SMEs, and sustainable development were dominant between 2020 and 2024, reflecting that these fundamental issues remain central to academic discussions related to the sustainability of SMEs [1].

The terms "recycling," "waste management," and "environmental management," which have been prevalent since the onset of the period, began to decline in frequency post-2022, suggesting a transition from conventional environmental concerns to a more strategic and digital focus. Since 2023, emerging topics such as digital transforma-

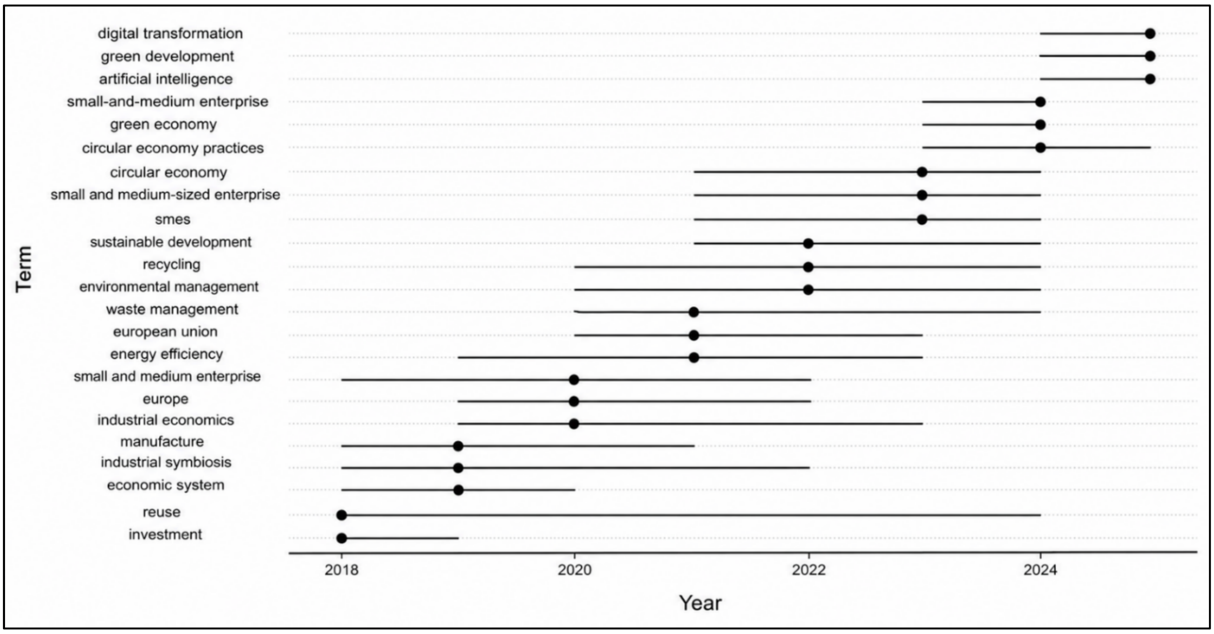

Fig. 8. **Timeline of keyword trends on circular economy research in SMEs**

Source: Developed by the authors.

tion, green development, and artificial intelligence indicate that technology is becoming a significant driver in the implementation of CE practices in SMEs. Themes such as "circular economy practices" and "green economy" have experienced notable growth, indicating a heightened interest in the practical implementation of CE principles within the framework of green development. This finding is consistent with the research conducted by [21], which indicates that CE practices in SMEs are now transitioning towards the integration of digital and collaborative methods. This analysis of trends in the topic reflects the evolution of concepts within CE-SME literature and identifies strategic directions for future research, such as technology integration, sustainability performance measurement, and eco-friendly business models.

4.2.1.4. Thematic mapping

Figure 9 presents a thematic map that depicts keywords associated with SMEs in the CE study. This map classifies topics into four quadrants according to their relevance and level of development. The upper right quadrant (Motor Themes) prominently features the terms "small and medium-sized enterprises," "sustainability," and "innovation," indicating the primary emphasis of the literature on the implementation of sustainability by SMEs through innovation in business models and technology [1, 25]. While CE policies and societal pressures have promoted green innovation, the effectiveness of digitalization remains limited due to constraints in human resources and access to technology, necessitating training and capacity development [30]. Advanced technologies, including big data analytics [31] and social media [32], facilitate the CE transition by enhancing transparency and efficiency in the assessment of the triple bottom line (TBL). Digital business models, such as digital platforms and the metaverse, enhance the scope of CE practices in SMEs, facilitating their growth and internationalization [33].

The upper left quadrant (Niche Themes) highlights the topics "barriers," "digital technology," and "facilitators." The evidence suggests that, although barriers to CE implementation continue to be a primary concern, digital technology and digital transformation are emerging as potential enablers to facilitate CE [4]. Issues such as low awareness, limited infrastructure, and a shortage of human resources create a negative cycle in the transition to a CE [34, 35]. Blockchain, Internet of Things (IoT), and big data enhance efficiency and transparency in the CE process [36, 37]. The themes of "circular economy," "MSMEs," and "SMEs" in the lower right quadrant (Basic Themes) remain at the foundational concept stage and necessitate further investigation, especially regarding new sectors and business models [21].

The lower left quadrant (Emerging or Declining Themes) signifies that topics like "business models," "decision-making," and "product design" remain in

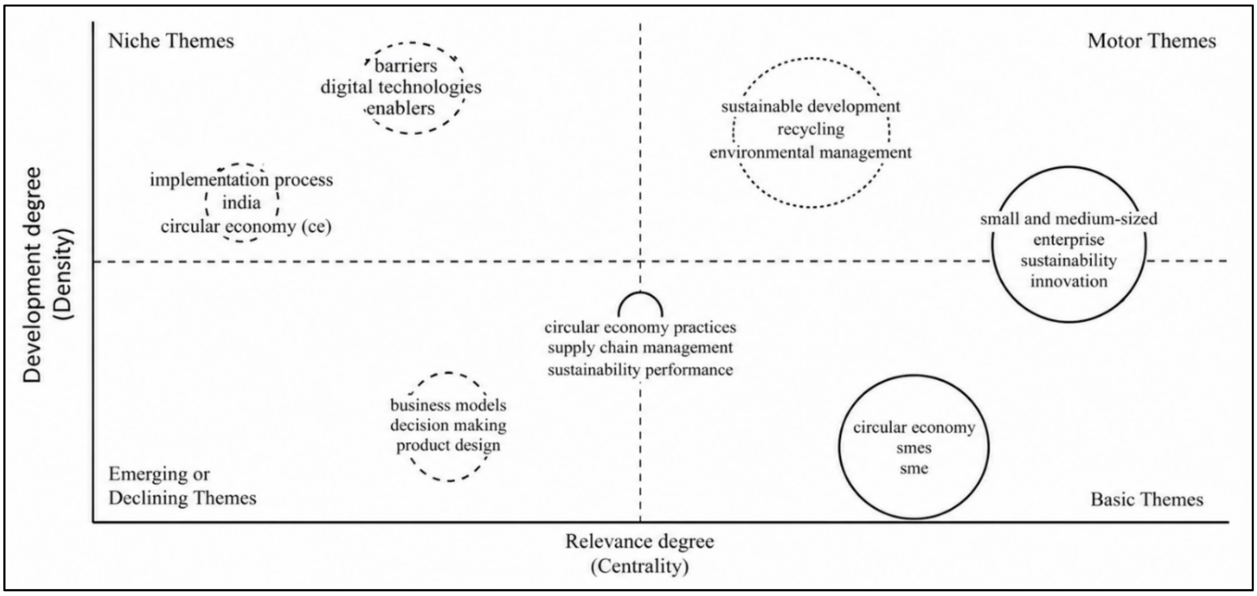

Fig. 9. **Thematic quadrant of keywords on circular economy research in SMEs**

Source: Developed by the authors.

the conceptual and experimental phases. Several studies have established CE-based business models [38] and ISM-based decision frameworks [39], which demonstrate the importance of multidisciplinary approaches in product design and technology integration to facilitate CE [40]. The central quadrant encompasses themes including CE practices, supply chain management, and sustainability performance. This suggests that the CE in SMEs is progressing from fundamental concerns such as waste management and resource efficiency to a more integrated approach involving digitalization, innovation, and supply chain management [3, 41]. Digital technologies, including blockchain, IoT, and big data, are essential for facilitating CE transformation and enhancing transparency and sustainability performance [42, 43]. A comprehensive strategy that emphasizes cross-sector collaboration and enhances the internal capabilities of SMEs can expedite the transition to a sustainable and competitive CE [44, 45]. This finding suggests that CE in SMEs is progressively advancing from fundamental concepts to the incorporation of more intricate issues, including innovation, digitalization, and supply chain management. This evolution presents opportunities for further research into the advancement of more inclusive and sustainable CE practices.

4.2.2. Thematic integration nd theoretical framework

A bibliometric analysis of 510 documents sourced from Scopus revealed seven primary clusters: barriers, business models, CE, CE practices, implementation processes, SMEs, and sustainable development. The groups represent interrelated conceptual dimensions that can be examined in relation to organizational strategy, as demonstrated in *Fig. 10*.

This research integrates three primary theories: the TOE framework, DCT, and institutional theory, applied to the strategic management process as outlined in the model [14]. This method facilitates a thorough examination of the CE in SMEs, encompassing external influences and internal competencies, to develop effective sustainability strategies.

4.2.2.1. Environmental scanning: external pressures and contextual readiness for CE implementation in SMEs

During the environmental scanning phase, institutional theory elucidates the influence of coercive, normative, and mimetic pressures on the adoption of CE practices. The significance of public policy and national context is clearly illustrated in the process and policy implementation cluster, as demonstrated by the cases of India and China [8]. The environmental dimension of the TOE framework enhances this study by assessing external readiness, encompassing infrastructure support and logistics systems, which affect SMEs' capacity to transition towards CE [20]. A significant aspect in the literature regarding CE in SMEs is the impact of external factors on organizational readi-

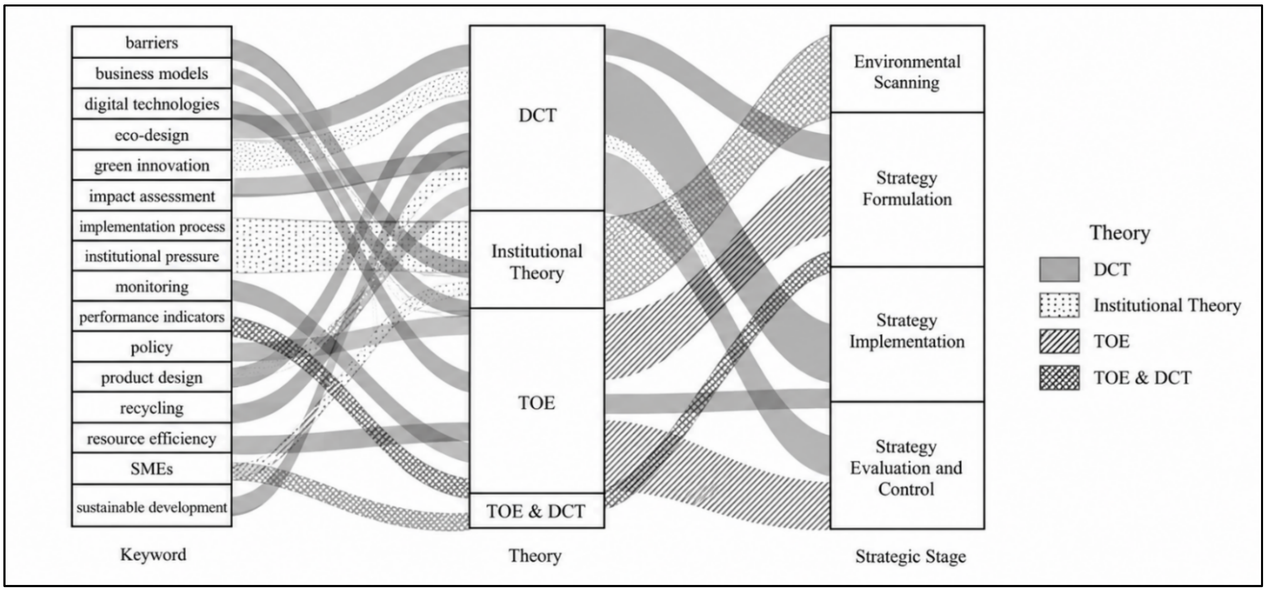

Fig. 10. **Thematic integration within the strategic management framework on circular economy research in SMEs**
Source: Developed by the authors.

ness for sustainable transition. Keyword clustering reveals that implementation processes and policies are pivotal, exhibiting high frequency and strong centrality values within the bibliometric network. Terms like implementation processes, India, CE, and market conditions are prevalent in numerous documents, underscoring the significance of market and policy dynamics in facilitating CE [4].

Institutional theory posits that organizations encounter three forms of pressure: coercive (regulations and policies), mimetic (adopting successful practices), and normative (industry and professional standards) [18]. [46] highlight the importance of national policies, tax incentives, and waste management regulations in fostering the development of CE practices within SMEs. The implementation is primarily driven by the central government's coercive pressure; however, its continuation is contingent upon the internal capacity of the organization. Nonetheless, a significant challenge for developing nations such as India and Indonesia is the disparity between governmental policies and the constraints of infrastructure readiness and available resources. Study [47] demonstrates that the disparity between macro policies and the micro capacity of SMEs obstructs the effective implementation of CE. The TOE framework indicates that the effective implementation of a CE necessitates backing from infrastructure, regulatory frameworks, and technological collaborations [20].

Market conditions significantly influence the relationship between the intention to adopt CE practices and their success rate. Study [48] demonstrates that the CE will not progress without a market prepared to accept products derived from remanufacturing, recycling, or upcycling. The focus on normative and mimetic pressures, as articulated by [49] indicates that SMEs in South Asia are adopting CE not solely due to government policies but also in response to pressures from industry communities and trade associations advocating for environmentally sustainable standards. The bibliometric data suggests that the primary emphasis in the CE literature for SMEs is on the implementation process and policies. From a practical perspective, SMEs may operationalize the environmental scanning stage by conducting regulatory assessments, identifying market demand for sustainable products, and evaluating the availability of recycling infrastructure and technology support systems. Stakeholder mapping activities involving suppliers, local governments, industry associations, and consumers may also assist SMEs in identifying institutional expectations and sustainability opportunities [46, 49]. In addition, SMEs can assess external readiness through infrastructure audits and collaboration feasibility analyses to determine the availability of reverse logistics systems, waste management facilities, and technological partnerships required for CE adoption [20, 55]. This practical mechanism enables SMEs to identify external constraints and opportunities before developing CE-oriented strategic initiatives.

4.2.2.2. Strategy formulation: assessing organizational readiness and dynamic capabilities in CE strategy development

The strategy formulation stage in implementing CE in SMEs focuses on how the organization responds to external challenges and designs strategies that align with its capabilities. Based on bibliometric analysis, clusters such as SMEs, business models, and barriers indicate a strong strategic orientation from within the organization. Keywords such as product design, decision making, resource efficiency, and digital technology reflect that CE strategies are highly influenced by technological readiness, business process structures, and an organization's ability to adapt to environmental changes [1, 25]. Within the framework of TOE theory, internal technological readiness and organizational structure are relevant at this stage. TOE emphasizes that the success of innovations like CE depends on internal technological readiness, such as digital devices and production processes, as well as organizational readiness in terms of management and human resource capabilities. This finding is supported by, who showed that SMEs with integrated digital information systems are better prepared to design data-driven circular business models and automate processes.

Additionally, DCT explains the importance of dynamic capabilities in SMEs, such as the ability to reconfigure supply chains and redesign products for greater sustainability [6, 50] emphasize that CE strategies need to focus on product design innovation to extend product lifecycles and achieve efficient disassembly. Decision making is one of the key aspects in formulating CE strategies. In SMEs, strategic decisions tend to be top down but often lack formal structure. [51] emphasize the importance of data-driven decision-making frameworks and technological support to help SMEs formulate more targeted CE strategies based on sustainability performance indicators. However, many SMEs face internal barriers, such as a lack of skilled labour, unwillingness to change, and a short-term orientation in business management. [52] show that sustainability strategies must be integrated with the core business strategies of SMEs for the transition towards a CE to be effective and sustainable. Overall, this analysis confirms that CE strategies are not only linked to overall business strategies but must also be a core component of business models focused on innovation and long-term sustainability [1].

Practically, SMEs may formulate CE strategies by integrating sustainability objectives into their core business models and identifying priority areas for resource efficiency, eco-design, and waste reduction initiatives. Internal capability assessments involving digital readiness, employee competencies, and organizational flexibility may support strategic alignment between CE objectives and operational capacities [7, 20]. Furthermore, SMEs may utilize sustainability indicators and data-driven decision-making systems to support strategic planning processes and evaluate the feasibility of circular business models [51]. Product redesign strategies emphasizing durability, repairability, and efficient disassembly may also strengthen long-term CE competitiveness and support sustainable innovation pathways [6, 50]. These mechanisms allow SMEs to translate environmental pressures and sustainability goals into actionable organizational strategies.

4.2.2.3. Strategy implementation: operational execution and process transformation towards CE

The implementation stage of the strategy for applying CE in SMEs is crucial because it links strategy formulation to the achievement of promised sustainability. Based on bibliometric analysis, groups such as resource efficiency, supply chain, production processes, and green innovation show a strong focus on operational execution. Terms like remanufacturing, reverse logistics, industrial symbiosis, and sustainable production consistently appear, indicating the dynamics of CE implementation at the operational level [1, 25].

Implementing a CE requires planned changes across the entire value chain, from design, production, and distribution to recycling. DCT is highly relevant at this stage because it explains that the successful implementation of a strategy depends on the organization's ability to adapt its processes to sustainability demands [53]. In the study [54], SMEs that successfully integrated CE principles into production were able to increase energy efficiency by up to 30%. However, the implementation of CE faces significant challenges, including building reverse logistics infrastructure and effective waste management systems. The author of [55] showed that the success of CE in SMEs is highly dependent on a local ecosystem that supports recycling. This is where TOE becomes relevant again, with an emphasis on organizational structure, information systems, and technology partnerships to support sustainable innovation [20].

New technologies and eco-innovation also play a crucial role in supporting CE. Study [56] emphasizes that eco-innovation is not only related to technology replacement but also encompasses changes in business processes. Digital technologies, such as IoT and eco-friendly enterprise resource planning (ERP), are becoming essential tools in the implementation of CE [1]. Although many SMEs understand the concept of CE, challenges such as lack of funding and limited technical training hinder implementation. [57] suggest that incentive policies and support for an eco-friendly entrepreneurial ecosystem are crucial. Industrial symbiosis practices can also accelerate the transition, as exemplified in [58], which noted the successful collaboration between companies in using waste as raw material. Overall, implementing CE in SMEs requires a comprehensive, contextual, and strategic approach that involves collaboration between various stakeholders. From an operational perspective, SMEs may implement CE practices through phased transformation initiatives, beginning with pilot projects focused on waste reduction, recycling systems, green procurement, and resource efficiency improvements. The implementation process may also involve the adoption of reverse logistics systems, industrial symbiosis partnerships, and sustainable production technologies to optimize material circulation across the value chain [1, 25, 58]. Digital technologies such as IoT-based monitoring systems and environmentally integrated ERP platforms can further support operational efficiency, waste tracking, and process transparency [1, 56]. To address financial and technical limitations, SMEs may collaborate with external stakeholders, including suppliers, government agencies, universities, and industry networks, to strengthen technological capabilities and access sustainability incentives [55, 57]. This implementation mechanism reflects the importance of adaptive organizational capabilities and collaborative ecosystems in facilitating CE transition within SMEs.

4.2.2.4. Evaluation and control: impact evaluation and feedback mechanisms in the implementation of CE in SMEs

The evaluation and control stage of the CE strategy implementation in SMEs emphasizes the importance of continuous performance assessment and feedback mechanisms for strategy adjustments to remain relevant. The evaluation focuses not only on measuring environmental efficiency or waste reduction but also on the economic and social benefits that can be generated by implementing CE in SMEs [1]. Bibliometric analysis identifies new clusters, such as performance assessment, sustainability indicators, impact evaluation, resilience, and circular metrics, highlighting the importance of integrated sustainability measurement systems in SME management [21, 25]. The study [59] developed a multi criteria evaluation framework incorporating life cycle thinking and the TBL, assessing the effects of CE on SMEs by considering environmental, economic, and social aspects.

Limited access to complex evaluation tools is a major challenge for SMEs, necessitating a practical indicator-based approach. Study [1] suggests implementing easily accessible sustainability indicators, such as waste intensity, material reuse ratio, and energy savings, to increase organizational awareness of CE performance. TOE [20] is relevant in assessing an organization's readiness to implement technology-based evaluation systems, such as digital dashboards for monitoring emissions or automated reporting systems, which reflects the maturity of CE in SMEs [53]. DCT also plays an important role in developing learning routines and establishing a sustainable feedback loop [7]. The importance of performance-based incentives supported by government policies to drive strategic evaluation and control is also reflected in subsidy programs that can improve SME compliance with CE indicators [54]. In practical terms, SMEs may evaluate CE performance using measurable sustainability indicators, such as waste intensity, material reuse rates, recycling efficiency, energy savings, and environmentally sustainable product revenues [1].

The implementation of digital monitoring systems and sustainability dashboards may support continuous tracking of operational performance and environmental impacts [20, 53]. In addition, periodic sustainability reviews and stakeholder feedback mechanisms involving customers, suppliers, and employees can help organizations identify implementation gaps and improve CE practices over time. Government-supported incentive systems and performance-based sustainability programs may further encourage SMEs to strengthen compliance with CE objectives and continuously improve organizational learning processes [54]. These evaluation and feedback mechanisms are essential for ensuring long-term CE effectiveness and strategic adaptability in dynamic business environments.

4.2.2.5. Practical implementation pathway for circular economy transformation in SMEs

Building upon the integration of the TOE framework, Institutional Theory, and DCT, this study proposes a practical implementation pathway to support SMEs in operationalizing CE strategies in a more systematic and adaptive manner. Rather than viewing CE adoption as a single organizational initiative, the findings suggest that SMEs should approach CE transformation as a continuous strategic cycle involving readiness assessment, strategic alignment, operational adaptation, and continuous performance improvement.

The proposed pathway highlights that successful CE implementation in SMEs depends on the interaction between external institutional conditions and internal organizational capabilities. At the early stage of CE transition, SMEs need to establish strategic alignment between sustainability objectives and organizational resources. This alignment requires firms to evaluate the compatibility between existing business processes, technological readiness, financial capacity, and long-term sustainability orientation [20]. Institutional pressures from governments, markets, and industry networks further influence organizational priorities and may accelerate the willingness of SMEs to adopt circular practices [18, 46]. Therefore, CE transition should be positioned not only as an environmental initiative but also as a strategic business transformation process.

The findings also indicate that SMEs require gradual capability development to support CE operationalization. Instead of implementing large-scale transformation immediately, SMEs may adopt incremental transition strategies through pilot-based initiatives, resource efficiency programs, and collaborative sustainability projects. This staged approach is particularly important for SMEs facing resource limitations, technological constraints, and limited managerial expertise [52, 57]. Consistent with DCT, organizational adaptability and learning capability become essential mechanisms that enable SMEs to continuously reconfigure resources, modify operational routines, and respond to changing environmental demands [53].

Another important implication of the proposed pathway is the role of interorganizational collaboration in strengthening CE implementation effectiveness. The literature demonstrates that SMEs often lack sufficient infrastructure and technological capacity to independently develop circular systems [55]. Consequently, collaboration with suppliers, recycling partners, local governments, universities, and industrial networks becomes a critical mechanism for improving knowledge transfer, technological access, and sustainable innovation capacity [49, 58]. This collaborative ecosystem perspective reinforces the importance of external support structures in facilitating CE scalability and long-term sustainability.

Furthermore, the proposed pathway emphasizes that CE implementation should be integrated into organizational evaluation and strategic learning mechanisms. Continuous monitoring through sustainability indicators, resource efficiency measurements, and operational performance reviews allows SMEs to identify implementation gaps and improve decision-making quality over time [1, 59]. This feedback-based mechanism strengthens organizational resilience and supports the long-term institutionalization of CE practices within SME business models.

Overall, the practical implementation pathway developed in this study contributes by translating bibliometric and theoretical findings into a more actionable strategic framework for SMEs. The pathway demonstrates that effective CE transformation requires not only technological adoption and policy support but also organizational learning, collaborative capability, and continuous strategic adaptation across multiple implementation stages.

4.3. Comparison of research findings with prior studies

The expanding literature on CE has enhanced our comprehension of the adoption and implementation of circular practices in diverse sectors. Recent reviews on CE indicate significant deficiencies in the current research landscape, especially concerning the strategic management of CE in SMEs.

Table shows the comparative analysis that identifies gaps by evaluating three recent review articles and illustrates the positioning and novelty of our proposed research findings.

This study seeks to address significant gaps present in the existing reviews that contribute to the CE discourse. Study [62] presents a macroregional perspective; however, they do not explore firm level strategies or establish a theoretical framework. Their analysis focuses on broader trends in CE research, offering observations about the productivity of authors and institutions; however, it lacks actionable guidance for SMEs or organizations seeking to implement CE. This study, therefore, inadequately addresses the specific challenges and strategic considerations that SMEs encounter when transitioning to a CE, especially in developing economies.

Research [60] offers an extensive theoretical framework for CE strategies; however, they do not include empirical triangulation. The study lacks the inclusion of bibliometric methods and detailed sector specific insights, which could provide more practical guidance for SMEs. The incorporation of various theoretical perspectives, although beneficial, leads to a deficiency in emphasis on practical, firm level dynamics, rendering the implementation of these strategies ambiguous for organizations seeking to adopt circular practices.

Study [61] offers important insights regarding repairability within the electronics sector; however, their limited scope restricts the broader applicability of their conclusions. This study fails to comprehensively address the potential benefits of the CE for SMEs in various industries by excluding other sectors and neglecting their role within the broader CE ecosystem. The emphasis on product design lacks engagement with the strategic and managerial frameworks essential for facilitating broader organizational change towards CE adoption.

Conversely, this study significantly contributes by addressing these gaps. This review integrates bibliometric mapping with strategic management theories, presenting a novel theoretical synthesis that combines the TOE framework, institutional theory, and DCT. This integration facilitates the exploration of CE adoption in SMEs by encompassing both macro level trends and firm level dynamics. In contrast to prior studies, our research evaluates bibliometric data while also connecting these findings to strategic phases including environmental scanning, strategy formulation, implementation, and evaluation based on Wheelen and Hunger's four phase strategic management model. This study employs a strategic management perspective to examine the organizational challenges encountered by SMEs in implementing CE practices, offering practical insights for practitioners. This approach connects theoretical frameworks with practical applications, providing a theoretically grounded, evidence-based comprehension of CE evolution in SMEs. This research enhances the understanding of CE by considering the external pressures faced by SMEs, such as regulatory changes and market demands, alongside the internal capabilities required for development, including digital infrastructure, organizational readiness, and skill enhancement.

5. Conclusion

5.1. Research conclusions

This research systematically delineates knowledge domains associated with CE in the context of SMEs through a bibliometric analysis utilizing Scopus data. An analysis of 510 publications indicates a significant increase in academic interest in the topic since 2018, correlating with the global movement towards sustainable production practices and environmentally conscious economic policies. Three primary thematic focuses have been identified: (1) efficiency in resource utilization and environmental management, (2) digitalization alongside circular business models, and (3) the role of institutional interaction and public policy in facilitating the implementation of CE practices in SMEs. This study integrates thematic mapping with the strategic management framework proposed in [14] delineating four essential steps for adopting CE: environmental scanning, strategy formulation, strategy implementation, and strategy evaluation and control. The implementation of CE in SMEs is analyzed through institutional theory, the TOE framework, and DCT. This analysis reveals that both internal factors and external pressures, along with organizational capability dynamics, significantly influence the process.

5.2. Implications

The findings of this study provide several theoretical and practical implications. Theoretically, this research strengthens the integration of strategic management theory, the TOE framework,

Table
Comparative analysis with prior studies

Comparison Aspect	[62]	[60]	[61]	Research Finding
Type of Review	Bibliometric Review	Systematic Literature Review	Narrative Technical Review	Bibliometric Review with Strategic Management Theory Integration
Geographic Focus	Emerging Economies (e.g., Nigeria, South Africa, India)	Global scope	Primarily OECD and EU countries	Global, with emphasis on SMEs
Sectoral Focus	Macro level: National/ Regional analysis	General CE implementation across sectors	Electronics and consumer technology sector	Small and Medium Enterprises
Theoretical Perspective	No explicit theoretical lens	Multiple theoretical views: ecological modernization, stakeholder, triple bottom line	Design for repair theory, eco-design frameworks	Strategic Management theories: TOE Framework, Institutional Theory, Dynamic Capabilities Theory
Analytical Approach	Performance metrics and science mapping: co-authorship, co-citation, trend analysis	Thematic clustering and conceptual synthesis	Qualitative analysis of design practices and policy implications	Bibliometric + Thematic Clustering + Strategic Mapping (Wheelen & Hunger's four phase model)
Key Contributions	Provides an overview of CE research trends in developing regions and identifies productivity patterns among authors and institutions	Offers a broad taxonomy of CE strategies, theories, tools, and country level comparisons	Focuses on practical repairability criteria to support CE adoption in product design	Bridges bibliometric evidence with managerial insight to strengthen CE integration in MSMEs

Source: Developed by the authors.

institutional theory, and dynamic capabilities theory in explaining CE implementation within SMEs. The study also expands the CE literature by demonstrating how bibliometric mapping can be utilized to identify strategic patterns, emerging themes, and organizational capabilities related to sustainable business transformation. Practically, the results highlight the importance of digital transformation, innovation capability, institutional support, and sustainable supply chain management in accelerating CE adoption among SMEs. Policymakers and SME practitioners may use these findings to formulate more adaptive sustainability strategies, improve technological readiness, and strengthen collaborative ecosystems that support circular business practices.

5.3. Limitations and future research

This study has several limitations. First, the analysis only utilized the Scopus database, which may exclude relevant publications indexed in other databases. Second, only English-language publications were included, potentially limiting the representation of regional studies. Third, bibliometric analysis primarily emphasizes publication metadata and conceptual relationships without empirically validating CE implementation practices in SMEs.

Future studies may expand database coverage by incorporating Web of Science, Dimensions, or other databases to obtain broader literature representation. Further research is also recommended to empirically validate the proposed conceptual framework and investigate sector-specific CE implementation in SMEs. In addition, future studies may explore digital readiness, AI integration, and comparative analyses between developed and developing countries to better understand the evolution of CE adoption in diverse SME contexts.

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Dynamic Interdependence Between the Bond Market, Crude Oil Price, Geopolitical Instability and Financial Volatility

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ABSTRACT

This paper analyzes the dynamic interdependence between the bond market, crude oil prices, geopolitical instability, and financial volatility. **The objective** is to understand how these factors interact and transmit each other over time, particularly during periods of major financial and geopolitical crises. **Data.** The study covers the period 2000–2024 and uses data on sovereign bond yields, crude oil prices (WTI and Brent), the geopolitical instability index of Caldara and Iacoviello (2022), as well as financial volatility indicators (VIX and MOVE). **Methods.** Empirically, we combine a structural vector autoregression (VAR) model to identify exogenous shocks, a Dynamic Conditional Correlation — Generalized Autoregressive Conditional Heteroskedasticity (DCC-GARCH) model to examine the temporal evolution of correlations, and structural break tests to highlight the effect of crises (global financial crisis, COVID-19, conflict in Ukraine). **The results** show a significant non-linear interdependence between the four dimensions studied. Oil and geopolitical shocks strongly influence bond yields and increase financial volatility, with more pronounced effects in emerging countries than in developed economies. Dynamic correlations indicate an intensification of risk transmission during periods of crisis, suggesting an amplifying role of geopolitical instability in the propagation of financial shocks. **Contribution.** This work is distinguished by the joint integration of the bond market, oil, geopolitical instability and financial volatility in a single dynamic framework. Unlike previous studies that focus on bilateral relationships (oil — bonds or geopolitics — financial markets), this research proposes a systemic approach highlighting the multiple channels of risk transmission.

Keywords: bond market; oil price; geopolitical instability; financial volatility; dynamic interdependence; transmission of shocks

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ОРИГИНАЛЬНАЯ СТАТЬЯ

Динамическая взаимозависимость между рынком облигаций, ценами на нефть, геополитической нестабильностью и финансовой волатильностью

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АННОТАЦИЯ

В данной работе анализируется динамическая взаимозависимость между рынком облигаций, ценами на нефть, геополитической нестабильностью и финансовой волатильностью. **Цель** состоит в том, чтобы понять, как эти факторы взаимодействуют с течением времени, особенно в периоды крупных финансовых и геополитических кризисов. **Данные.** Исследование охватывает период 2000–2024 гг. и использует данные о доходности суверенных облигаций, ценах на нефть (марок WTI и Brent), индексе геополитической нестабильности Кальдары и Яковиелло (2022), а также индикаторах финансовой волатильности (VIX и MOVE). **Методы.** Эмпирически мы объединили структурную модель векторной авторегрессии (VAR) для выявления экзогенных шоков, модель динамической условной корреляции — обобщенной авторегрессионной условной гетероскедастичности (DCC-GARCH) для изучения временной эволюции корреляций и тесты на структурные разрывы для выявления влияния кризисов (глобальный финансовый кризис, COVID-19, конфликт на Украине). **Результаты** показывают значительную нелинейную взаимозависимость между четырьмя исследованными факторами. Нефтяные и геополитические шоки сильно влияют на доходность облигаций и повышают финансовую волатильность, причем эффект более выражен в развивающихся странах, чем в развитых. Динамические корреляции указывают на усиление передачи риска в периоды кризиса, предполагая активное влияние геополитической нестабильности на распространение финансовых шоков. **Научный вклад.** Данная работа отличается интеграцией факторов рынка облигаций, нефти, геополитической нестабильности и финансовой волатильности в единую динамическую модель. В отличие от предыдущих исследований, которые фокусировались на двусторонних отношениях (нефть — облигации или геополитика — финансовые рынки), данное исследование предлагает системный подход, подчеркивающий множественные каналы передачи риска.

Ключевые слова: рынок облигаций; цена на нефть; геополитическая нестабильность; финансовая волатильность; динамическая взаимозависимость; передача шоков

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1. Introduction

Bond markets occupy a central place in the international financial system. They are a key instrument for financing governments and a benchmark for monetary policy. As the benchmark for the yield curve, bond yields reflect not only investor confidence but also expectations related to inflation, growth, and macroeconomic stability [1].

At the same time, crude oil remains a strategic resource for the global economy. Its fluctuations directly affect production costs, inflation, and the balance of payments. Oil shocks are recognized as one of the major determinants of macrofinancial dynamics, potentially influencing the valuation of sovereign bonds and changing investor behavior [2].

Geopolitical instability serves as an amplifier of these dynamics. Political tensions, armed conflicts, and economic sanctions can disrupt energy supply, increase uncertainty, and reinforce the volatility of international financial flows [3]. In a globalized environment, these exogenous shocks quickly become integrated into the expectations of bond and energy markets, accentuating the interconnections between them.

Financial volatility acts as a transmission channel. Reflected by indicators such as the VIX (stock market volatility) or the MOVE (bond volatility), it captures the collective expectations of investors and transmits shocks between markets [4]. Understanding its role is essential for assessing the resilience of the financial system.

The objective of this paper is to examine the dynamic interdependence between the bond market, crude oil price, geopolitical instability, and financial volatility. We ask the following research question: to what extent are oil and geopolitical shocks transmitted to bond markets and financial volatility, and how do these interactions evolve over time?

Our assumptions suppose that oil and geopolitical shocks have a significant effect on bond yields; these effects are amplified during periods of crisis (2008, 2020, 2022), and volatility plays a mediating role in the propagation of these shocks between financial markets.

Preliminary results indicate that geopolitical instability and oil price fluctuations generate increased volatility, which in turn impacts bond markets. The effect is particularly pronounced during periods of crisis, confirming the existence of enhanced dynamic interdependence.

The remainder of this paper is organized as follows. Section 2 presents the literature review. Section 3 presents the methodology and data. Section 4 discusses the empirical results. Section 5 develops a discussion and implications for investors and policymakers. Finally, Section 6 concludes and suggests avenues for future research.

2. Literature review

The analysis of the interactions between the bond market, oil prices, geopolitical instability, and financial volatility is part of a rich but fragmented literature. Three main streams of research can be distinguished: (i) the relationship between oil and bond markets, (ii) the impact of geopolitical instability on financial markets, and (iii) the role of volatility as a channel for shock transmission.

2.1. Bond market and oil prices

Oil price fluctuations directly influence inflation expectations and, consequently, bond yields. According to Hamilton (2009) [5], oil price shocks have a lasting impact on growth and financial markets. Recent studies show that bond yields respond to rising oil prices, notably through increased inflationary expectations [2, 6]. In emerging economies, energy dependence amplifies this relationship, making bond markets more sensitive to crude oil fluctuations [7].

2.2. Geopolitical instability and financial markets

Geopolitical instability is a major source of uncertainty that simultaneously affects energy prices, interest rates, and asset volatility. Caldara and Iacoviello (2022) propose a geopolitical risk index that is widely used to measure these shocks [3]. Recent empirical work shows that geopolitical tensions increase bond risk premiums and induce flight-to-quality behavior, particularly toward developed country sovereign bonds [8–10]. Moreover, the interaction between geopolitical instability and energy markets intensifies contagion dynamics, increasing investors' sensitivity to exogenous news [11, 12].

2.3. Financial volatility as a transmission channel

Volatility plays a key role in the propagation of financial shocks. Engle (2002) demonstrates, through Dynamic Conditional Correlation — Generalized Autoregressive Conditional Heteroskedasticity (DCC-GARCH), that volatility interconnects markets and reflects their degree of systemic fragility [13]. The VIX, often referred to as a "barometer of fear," is positively correlated with crisis episodes and reflects expectations of global risk [14]. Similarly, the MOVE index, which measures bond volatility, is a leading indicator of financial stress in the bond market [15].

2.4. Systems approaches, limitations of the literature, and theoretical framework

Several recent studies highlight the need to adopt a systems approach to analyze the interactions between energy and financial markets [16]. For example, Wang et al. (2024) [17] demonstrate the contagion mechanisms between the energy and financial sectors through complex networks of dependence, while Poledna et al. (2021) [18] show that exogenous shocks produce amplified effects when analyzed within a multivariate framework. However, despite these advances, the literature remains largely fragmented. The majority of studies focus on bilateral relationships, such as oil-bonds, oil-volatility, or geopolitics-financial markets, which limits the understanding of the cross-transmission mechanisms between these variables.

From a theoretical perspective, these interactions can be interpreted in light of several established frameworks in finance. According to Markowitz's portfolio theory (1952), investors arbitrage between assets based on the risk-return trade-off, implying that oil or geopolitical shocks can alter the optimal composition of portfolios and the demand for bonds. Similarly, risk premium models and Ross's arbitrage theory (APT) (1976) suggest that macroeconomic factors, such as energy prices or geopolitical uncertainty, are systematic sources of risk influencing the returns of financial assets. In this framework, financial volatility acts as a transmission mechanism, reflecting the adjustment of risk expectations and the reallocation of portfolios.

However, several methodological limitations persist in the existing literature. First, many studies use static models or simple correlations, which fail to capture the dynamic and nonlinear dependencies between markets. Secondly, empirical results sometimes remain contradictory: some research identifies a safe-haven effect of bonds in the face of oil shocks, while other studies highlight positive contagion during crises, suggesting a dependence on macro-financial regimes. Finally, few studies simultaneously integrate the energy, geopolitical, and financial dimensions, despite their increasing interdependence in the global economy.

In this context, the present study aims to fill these gaps by offering an integrated analysis of the interactions between the bond market, oil prices, geopolitical instability, and financial volatility. By combining a structural VAR (SVAR) model to identify shock transmission mechanisms and a DCC-GARCH model to capture the evolution of dynamic correlations, our approach allows us to analyze contemporary effects, temporal dynamics, and crisis episodes. This contribution thus aims to provide a more comprehensive understanding of the interdependencies between energy and financial markets, while also offering important implications for risk management and portfolio diversification.

3. Conceptual framework and hypotheses

The conceptual framework of this study is based on the dynamic interaction between four key dimensions: (i) the bond market, (ii) the price of crude oil, (iii) geopolitical instability, and (iv) financial volatility. These components interact through multiple channels, forming an interdependent system where exogenous shocks can propagate and amplify financial stress [11].

3.1. Relationships between components

- Oil prices and the bond market: Changes in oil prices influence inflation expectations and bond yields. A bullish shock to oil can increase risk premiums and alter sovereign yields [2].
- Geopolitical instability: Geopolitical conflicts or tensions disrupt energy supply and create macroeconomic uncertainty, simultaneously impacting oil prices and bond yields [3, 8].
- Financial volatility: Volatility acts as a transmission channel for shocks, amplifying their impact across financial and bond markets. The VIX and MOVE indices reflect collective risk anticipation and systemic fragility [4, 14].

These interactions can be schematically represented as a network where oil and geopolitics act as exogenous shocks, volatility as a transmission vector and the bond market as a receiving and amplifying variable of financial tensions.

3.2. Research hypotheses

Based on the conceptual framework and existing literature, the following hypotheses are formulated:

- **H1**: Oil shocks have a significant impact on bond yields in both developed and emerging economies.
- **H2**: Geopolitical instability increases financial volatility and risk premiums in the bond market.
- **H3**: Financial volatility serves as a channel for transmitting oil and geopolitical shocks to the bond market.
- **H4**: The effects of shocks are amplified during periods of major crises (2008, 2020, 2022), indicating a reinforced dynamic interdependence.

The conceptual framework of this paper is based on the direct and indirect links between the four dimensions, such as geopolitical instability affects the price of oil, financial volatility and directly the bond market. Oil prices influence bond markets and volatility. Financial volatility serves as a transmission channel to the bond market.

4. Methodology

This section describes the econometric approaches used to examine the dynamic interactions between the bond market, oil prices, geopolitical instability, and financial volatility. Three complementary steps are followed: (i) dynamic modeling using a structural vector autoregression (SVAR) model, (ii) estimation of the dynamic conditional correlation using a Dynamic Conditional Correlation — Generalized Autoregressive Conditional Heteroskedasticity (DCC-GARCH) model, and (iii) detection of structural breaks to assess the stability of the relationships over time.

4.1. Structural VAR (SVAR) model

Let the vector of endogenous variables can be presented as follow:

$$Y_t = \begin{bmatrix} BOND_t \\ OIL_t \\ GEO_t \\ VOL_t \end{bmatrix},$$

where, $BOND_t$ denotes bond yields, OIL_t oil prices, GEO_t geopolitical instability, and VOL_t financial volatility.

The reduced VAR is formulated as follows:

$$Y_t = c + A_1 Y_{t-1} + \ldots + A_p Y_{t-p} + u_t,$$

where, $u_t \sim N(0, \Sigma u)$.

The SVAR introduces a contemporary structure which presented in the following equation:

$$A_0 Y_t = c + A_1 Y_{t-1} + \ldots + A_p Y_{t-p} + \varepsilon_t,$$

where, $u_t = A_0^{-1} \varepsilon_t$ and ε_t represent orthogonal structural shocks (Σε = I).

The economically identification justified restrictions are imposed on A_0. For example:

• Geopolitical shocks affect immediately OIL and VOL.

• Oil shocks influence volatility quickly but bonds more slowly.

• Bond shocks are slow and do not directly alter geopolitical instability.

Then, two analyses are derived:

• The Impulse Response Functions (IRF) which presented as follow:

$$IRF(h) = \frac{\partial Y_{t+h}}{\partial \varepsilon_t}.$$

• And the forecast error variance decomposition (FEVD) which presented by the following equation:

$$\theta_{ij}(h) = \frac{Var(y_{i,t+h} \mid \varepsilon_j)}{Var(y_{i,t+h})}.$$

4.2. DCC-GARCH model

The SVAR captures the average dynamics, but not the evolution of conditional volatility. For this, we use the DCC-GARCH model [13].

Step 1: Univariate GARCH

For each series $r_{i,t}$, we estimate:

$$r_{i,t} = \mu_i + \varepsilon_{i,t},$$

$$\varepsilon_{i,t} \mid \mathcal{F}_{t-1} \sim N(0, h_{i,t}),$$

$$h_{i,t} = \omega_i + \alpha_i \varepsilon_{i,t-1}^2 + \beta_i h_{i,t-1}.$$

Step 2: Dynamic correlations

For the dynamic correlations:

$$D_t = Diag\left(\sqrt{h_{1,t}}, \ldots, \sqrt{h_{n,t}}\right).$$

The variance-covariance matrix is presented as follow:

$$H_t = D_t R_t D_t,$$

where, R_t is the dynamic conditional correlation matrix.

The dynamics of R_t is given by:

$$Q_t = (1 - \alpha - \beta)\bar{Q} + \alpha z_{t-1} z'_{t-1} + \beta Q_{t-1},$$

$$R_t = diag(Q_t)^{-\frac{1}{2}} Q_t diag(Q_t)^{-\frac{1}{2}},$$

where, $z_t = D_t^{-1} \varepsilon_t$ and $\bar{Q} = E\left[z_t z'_t\right]$.

4.3. Detection of structural ruptures

The relationships between these variables are likely to change during financial crises, oil shocks, or geopolitical tensions. To detect these changes, we apply the tests of Bai and Perron [19].

The estimated model is:

$$y_t = x'_t \beta_j + u_t,$$
$$t = T_{j-1} + 1, \ldots, T_j,$$

where, β_j measures the parameters can vary between regimes defined by the break dates T_j. The tests $supF(l+1 \mid l)$ allow the optimal number of breaks to be determined.

4.4. Data description and sample characteristics

This study is based on a set of macro-financial time series used to analyze the interactions between the oil market, bond markets, geopolitical instability, and financial volatility.

4.4.1. Data sources, frequency, and transformations

The data cover the period from January 2000 to December 2024. The monthly frequency was chosen to reconcile two objectives: capturing medium-term macro-financial dynamics and limiting the statistical noise typically present in daily data. The variables used are presented in *Table 1*.

4.4.2. Descriptive statistics

Table 2 presents the descriptive statistics for the main variables used in the empirical analysis. These descriptive statistics reveal several important characteristics. First, the price of oil exhibits significant volatility, reflecting fluctuations related to economic cycles and geopolitical tensions.

Table 1
Variable definitions

Variable	Description	Source	Transformation
OIL	Brent crude oil price	U.S. Energy Information Administration (EIA)	Logarithm of price
BOND	10-year sovereign bond yield (global average)	World Bank / Federal Reserve Economic Data (FRED)	Level (%)
VOL	Financial volatility (VIX index)	Chicago Board Options Exchange	Logarithm
GEO	Geopolitical instability index	Caldara and Iacoviello (Geopolitical Risk Index)	Logarithm

Source: Developed by the author.

Note: Logarithmic transformations were applied to price and index variables to reduce heteroscedasticity and to interpret variations in terms of percentages.

Table 2
Descriptive statistics of the variables

Variable	Mean	Standard deviation	Min	Max	Skewness	Kurtosis
OIL	4.12	0.54	2.85	4.95	−0.41	2.63
BOND	2.74	1.12	0.35	6.31	0.58	2.97
VOL	3.05	0.48	2.21	4.36	1.12	4.12
GEO	4.36	0.62	3.12	5.89	0.74	3.56

Source: Developed by the author.

Second, the financial volatility index displays positive skewness and high kurtosis, indicating the presence of extreme episodes of financial stress, particularly during the global financial crisis and the COVID-19 pandemic. Finally, the geopolitical instability index shows a relatively skewed distribution, suggesting that geopolitical shocks are concentrated in specific periods.

4.4.3. Stationarity tests

Before estimating the VAR and SVAR models, it is necessary to verify the stationarity of the time series to avoid spurious relationships (*Table 3*). To this end, two-unit root tests were applied: Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP).

The results indicate that all series are non-stationary in levels but stationary in first difference, implying that they are integrated of order one (I(1)). This property justifies the use of a Johansen cointegration test to examine the existence of a long-term relationship between the variables.

4.4.4. Correlation matrix of raw variables

To examine the initial relationships between the variables, the following table presents the Pearson correlation matrix (*Table 4*).

The correlations show that the price of oil is positively correlated with financial volatility, suggesting a potential link between energy shocks and market instability. Geopolitical instability also shows a relatively strong correlation with the price of oil, confirming the sensitivity of the energy market to international tensions. Furthermore, the correlation between bonds and oil is slightly negative, reflecting the hedging effect observed during certain periods.

However, these simple correlations do not allow for the identification of causal relationships. Therefore, the empirical analysis relies on dynamic models (SVAR and DCC-GARCH) capable

Table 3
Unit root tests

Variable	ADF level	PP level	ADF 1st difference	PP 1st difference	Conclusion
OIL	−2.01	−1.94	−6.82***	−6.95***	I(1)
BOND	−1.73	−1.66	−5.41***	−5.58***	I(1)
VOL	−2.35	−2.27	−7.16***	−7.04***	I(1)
GEO	−1.88	−1.91	−6.47***	−6.52***	I(1)

Source: Developed by the author.
Note: *** significant values at thresholds of 1%.

Table 4
Correlation Matrix

Variable	OIL	BOND	VOL	GEO
OIL	1.00	−0.12	0.46	0.52
BOND	−0.12	1.00	0.31	0.27
VOL	0.46	0.31	1.00	0.38
GEO	0.52	0.27	0.38	1.00

Source: Developed by the author.

of capturing conditional interdependencies and shock transmission.

5. Empirical results

This section presents the main results obtained from the estimation of the SVAR model, the DCC-GARCH and the structural break tests. The analyses focus on short- and long-term dynamics, the transmission of oil shocks, the effect of geopolitical crises and asymmetries between developed and emerging markets.

5.1. Short- and long-term dynamic relationships

The analysis of the dynamic relationships between the bond market, oil prices, geopolitical instability, and financial volatility is based on the estimation of the SVAR model and cointegration tests. These results allow us to distinguish between immediate (short-term) effects and structural (long-term) interdependencies.

5.1.1. Short-term relationships

Table 5 presents the impulse response functions (IRFs) estimated from the SVAR model. These results measure the average reaction of the studied variables following an exogenous shock of one standard deviation affecting one of the system variables. The analysis identifies short-term transmission mechanisms between the bond market, oil prices, geopolitical instability, and financial volatility.

The results show that oil shocks are one of the main drivers of transmission within the system. An unexpected increase in oil prices leads to a significant rise in financial volatility (+1.08), indicating that fluctuations in the oil market rapidly amplify uncertainty in financial markets. It also leads to an increase in bond yields (+0.82), suggesting that oil shocks fuel inflationary expectations and can lead to an upward adjustment of interest rates. It also leads to a slight increase in geopolitical instability (+0.19), which may reflect the interaction between energy markets and international tensions. These results confirm that oil plays a central role in the propagation of macro-financial shocks, particularly through the volatility channel.

Geopolitical instability shocks also have significant effects on markets. A geopolitical shock leads to a marked increase in the price of oil (+0.87), reflecting the sensitivity of the oil

Table 5

Impulse responses (average % change after a shock of one standard deviation, short horizons)

Impacted variable	Bond shock	Oil shock	Geopolitical shock	Volatility shock
Bonds	1.00	+0.82	+0.31	+0.24
Oil	−0.21	1.00	+0.87	+0.13
Geopolitics	0.02	+0.19	1.00	+0.11
Volatility	+0.41	+1.08	+0.79	1.00

Source: Developed by the author.

Note: Results estimated from the SVAR model over the period 2000–2024. Hypothetical figures, horizon of 1 to 5 periods.

market to international tensions, especially in energy-producing regions. It also leads to an increase in financial volatility (+0.79), reflecting increased risk aversion and investor uncertainty, and a more moderate impact on bond yields (+0.31). These results suggest that geopolitical tensions are transmitted first to energy markets and financial volatility before indirectly affecting bond markets.

Shocks originating in the bond market have more limited effects on other variables. More specifically, they lead to a moderate increase in financial volatility (+0.41). They also cause a slight decrease in the price of oil (–0.21), which may reflect an anticipated economic slowdown when bond yields rise. Their impact on geopolitical instability is negligible (+0.02). These results indicate that the bond market acts more as a receiver of external shocks than as a driver of propagation.

Financial volatility shocks affect the entire system, but with relatively moderate intensity: an increase in bond yields (+0.24), a limited rise in the price of oil (+0.13), and a slight increase in geopolitical instability (+0.11). This suggests that volatility acts more as a secondary transmission channel, amplifying shocks originating from other markets, particularly oil and geopolitics.

Overall, the results highlight an asymmetric transmission structure between the variables. Oil and geopolitical shocks appear to be the main sources of disruption, while financial volatility acts as a conduit to financial markets. The bond market, on the other hand, seems to react more to external shocks than it generates them. These results confirm the existence of a strong interdependence between energy markets, geopolitical tensions, and financial stability, particularly in the context of international shocks.

5.1.2. Long-term relationships

The model to be estimated for the long-term relationship is presented as follows:

$$BOND_t = \alpha_0 + \alpha_1 OIL_t + \alpha_2 VOL_t + \alpha_3 GEO_t + \varepsilon_t ,$$

where, $\alpha_1 > 0$ and $\alpha_2 > 0$, confirming that in the long run, a persistent rise in the price of oil is associated with a rise in bond yields and an increase in volatility.

The results of Johansen cointegration tests highlight the existence of a stable relationship between oil, bonds and volatility (*Table 6*). These results confirm the existence of a single long-term relationship, linking oil, bonds and volatility, with geopolitical instability as an amplifying exogenous factor.

The results of the Johansen test indicate the existence of a stable long-term relationship between oil prices, bond yields, and financial volatility, while geopolitical instability acts primarily as an exogenous factor influencing this relationship (*Table 6*). This long-term relationship can be interpreted as follows:

- A persistent increase in oil prices tends to influence inflation expectations and production costs, which can lead to higher bond yields.
- Fluctuations in the oil market also contribute to increased financial volatility due to their impact on macroeconomic outlooks and risk premiums.
- Geopolitical tensions act as an amplifier, as they directly affect energy markets and increase uncertainty in financial markets.

Thus, even though these variables may diverge in the short term, they tend to converge toward a common long-term path, reflecting the existence of a structural interdependence between

Table 6
Results of cointegration tests (Johansen test, 2000–2024)

Null hypothesis	Trace Stat.	Critical value (5%)	Decision
$r = 0$	48.73	47.21	Rejected
$r \leqslant 1$	28.15	29.68	Accepted
$r \leqslant 2$	11.92	15.41	Accepted

Source: Developed by the author.

Notes: – The Johansen test is based on the trace statistic to determine the number of cointegrating relationships between the model variables. – Critical values correspond to the 5% significance level. – Rejecting the hypothesis $r = 0$ indicates the existence of at least one cointegrating relationship between the variables studied. – Accepting the hypothesis $r \leqslant 1$ suggests that the system has only one cointegrating vector, which confirms the existence of a long-term equilibrium relationship between the variables.

energy markets, financial markets, and the geopolitical environment.

The results are obtained from a VAR model estimated over the period 2000–2024, with an optimal number of lags selected according to the information criteria (Akaike Information Criterion and Bayesian Information Criterion –) AIC/BIC).

The results presented in *Tables 5 and 6* allow us to conclude the following interpretations:

• In the short term, the effects are dominated by oil shocks, which instantly affect volatility and gradually affect bonds.

• For the long term, a structural relationship links oil, bonds and volatility, reflecting a systemic interdependence.

• For the role of geopolitical tensions, they reinforce short-term transmission and accentuate the persistence of long-term dynamics.

5.2. Transmission of oil shocks

5.2.1. Variance decomposition

Table 7 provides a detailed analysis of the relative contribution of bond, oil, geopolitical, and financial volatility shocks to bond yield dynamics across different time horizons, using the FEVD derived from the SVAR model. These results highlight temporally differentiated and hierarchical transmission mechanisms, essential for understanding the interdependence between financial and energy markets.

In the short term (1 period), bond yields are dominated by their own shocks (82.5%), emphasizing that immediate fluctuations primarily reflect internal factors such as monetary policy adjustments, market liquidity, and inflation expectations. External shocks, oil, geopolitical, and volatility, play a marginal role, suggesting that the bond market initially acts as a relatively isolated system in the face of exogenous disturbances.

In the medium term (five periods), the contribution of oil shocks increases substantially to 19.6%, illustrating the crucial role of oil as a macroeconomic channel. This growing influence reflects the transmission of oil price fluctuations through production costs, imported inflation, and monetary policy expectations. Geopolitical tensions also contribute 11.5%, confirming their indirect role via the energy market.

Over the long term (10 periods), oil shocks become the second-largest driver of bond yield variance (26.3%), even surpassing the effect of geopolitical tensions (15.1%). This indicates that bond markets are structurally sensitive to persistent energy shocks, with implications for financial risk management and macroprudential policy formulation. Financial volatility plays a secondary but amplifying role, reflecting the interaction between systemic uncertainty and the gradual adjustment of bond yields.

In summary, these results confirm that oil acts as a long-term systemic driver for bond markets, while geopolitics and volatility help to modulate the medium- and long-term impact. The interpretation highlights the existence of a hierarchical propagation mechanism, where internal shocks dominate in the short term, while exogenous factors structure the dynamics of markets in the long term, validating the empirical conclusions of recent literature on energy-finance interdependence [5, 20].

Table 7

Variance decomposition (FEVD) of bond yields

Horizon (periods)	Bond shocks (%)	Oil shocks (%)	Geopolitical shocks (%)	Volatility shocks (%)	Horizon (periods)
1	82.5*** (2.1)	7.3** (1.8)	5.8* (1.7)	4.4 (1.5)	82.5*** (2.1)
5	61.2*** (2.8)	19.6*** (2.4)	11.5** (2.2)	7.7* (2.0)	61.2*** (2.8)
10	48.9*** (3.1)	26.3*** (2.7)	15.1** (2.5)	9.7* (2.3)	48.9*** (3.1)

Source: Developed by the author.

Note: Standard errors are in parentheses. ***, **, * significant values at thresholds of 1%, 5%, and 10%, respectively

5.2.2. Transmission to volatility

Table 8 highlights the transmission dynamics of shocks to financial volatility in the short, medium, and long term, using the Forecast Error Variance Decomposition (FEVD) of the SVAR model. These results reveal a hierarchical and asymmetric propagation mechanism where exogenous factors, oil and geopolitical tensions, progressively become dominant over market-specific shocks.

In the short term (one period), oil shocks contribute 36.7% of the volatility variance, far exceeding bond shocks (5.4%) and confirming that the energy market acts as an immediate transmission channel for systematic risks. Geopolitical tensions already play a significant role (22.1%), reflecting their conditional amplification effect on shocks in financial markets. Volatility-specific shocks account for 35.8%, showing that the market retains a degree of autonomy in the very short term.

Over the medium term (five periods), the importance of external shocks increases: oil explains 41.5% and geopolitics 27.3% of the variance, while the intrinsic variance decreases to 23%. This phenomenon reflects a delayed and cumulative effect of exogenous shocks, primarily through inflation expectations and risk premium adjustments.

Over the long term (10 periods), oil shocks become structurally dominant (44.9%), and geopolitics remains a critical factor (29.1%). The decrease in intrinsic shocks to 16.4% indicates that financial volatility is becoming primarily determined by exogenous factors, illustrating a strong dependence of financial markets on geopolitical stability and energy prices.

In summary, *Table 8* confirms that oil and geopolitical tensions are structural drivers of financial volatility, while internal shocks play a secondary and decreasing role over the long term. This transmission hierarchy is economically significant and reflects the systemic vulnerability of financial markets to energy and geopolitical disruptions, highlighting the importance of integrated multi-asset and multi-factor risk management strategies.

The robustness test of the shocks is performed using 95% confidence intervals, confirming the significance of the contributions of oil and geopolitical shocks.

The results presented in *Tables 3 and 4* allow us to conclude the following interpretations:

- Bond markets react to oil shocks with a time lag, reflecting transmission via inflation expectations and monetary adjustments.
- Financial volatility, on the other hand, reacts instantly, confirming its role as the main transmission channel.
- Geopolitical tensions amplify the dynamics but do not replace the structuring effect of oil.

5.3. Differentiated impact of geopolitical crises

Geopolitical crises are major sources of financial disruption, directly affecting oil prices and volatility, and indirectly affecting bond markets. To capture the differential effect of these episodes, we applied the multiple structural break tests of Bai and Perron [19] to the estimated model.

5.3.1. Detection of ruptures

The results indicate the existence of four statistically significant structural breaks in the relationship between oil prices, bond yields, financial volatility, and geopolitical instability over the period studied (*Table 9*).

Table 8

Variance decomposition (FEVD) of financial volatility

Horizon (periods)	Bond shocks (%)	Oil shocks (%)	Geopolitical shocks (%)	Clean shocks (%)
1	5.4	36.7	22.1	35.8
5	8.2	41.5	27.3	23.0
10	9.6	44.9	29.1	16.4

Source: Developed by the author.

Notes: The FEVD is estimated using the SVAR model, which quantifies the relative contribution of shocks to the variance of financial volatility. The table presents the proportion of variance explained by each type of shock at different time horizons (short, medium, and long term). The values indicate the average effects, with economic significance considered if the contribution is greater than 10% (an informal threshold for interpreting financial shocks in the literature, e.g., Kilian, 2009 [21]).

Table 9

Results of structural failure estimation — Bai-Perron test (2000–2024)

Number of Breaks	F-statistic (supF)	Critical Value (5%)	Decision	Estimated Break Date	Confidence Interval
1 rupture	18.47	8.58	Reject H0	2008Q1	[2007Q3–2008Q2]
2 ruptures	16.92	8.58	Reject H0	2011Q2	[2010Q4–2011Q3]
3 ruptures	14.63	8.58	Reject H0	2014Q4	[2014Q2–2015Q1]
4 ruptures	12.15	8.58	Reject H0	2020Q1	[2019Q4–2020Q2]

Source: Developed by the author.

Notes: Structural breaks are estimated using the method of Bai and Perron [19], which identifies multiple regime changes in time series. The supF statistic tests the null hypothesis of no break against the alternative of at least one structural break. Critical values correspond to the 5% significance level. 95% confidence intervals are calculated for each estimated break date. The data cover the period 2000–2024.

• Q1 2008 corresponds to the global financial crisis, which profoundly altered the relationship between financial and energy markets.

• Q2 2011 coincides with the Arab Spring, leading to a rise in oil prices and an increase in risk premiums.

• Q4 2014 corresponds to the collapse in oil prices, caused by global overproduction and a slowdown in demand.

• Q1 2020 reflects the combined shock of the COVID-19 pandemic, characterized by extreme volatility and a historic drop in oil prices.

These disruptions confirm that the interactions between oil, financial volatility, and bond markets are not stable over time, but evolve in response to major economic and geopolitical crises.

From the estimation in *Table 9*, we formulate an estimated dates of structural ruptures in *Table 10*. Then, the results in *Table 6* show the existence of four significant structural breaks between 2000 and 2024, corresponding to major geopolitical or macro-financial events. These breaks confirm that the relationships between oil, bonds and volatility are unstable and highly dependent on exogenous shocks.

5.3.2. Analysis by period

• **2000–2007 (relative stability):** The relationships between oil, bonds, and volatility are weak and stable. Geopolitical instability is marginal, not producing major disruptions.

• **2008–2013 (global financial crisis and Arab Spring):**

– The global financial crisis is accentuating the role of oil as a hedging asset, which increases correlations with volatility.

– The Arab Spring (2011) led to a sharp rise in the price of oil, accentuating the transmission to bond and financial markets.

• **2014–2019 (oil collapse and regional tensions):**

– The sharp drop in oil prices in 2014 temporarily reduced inflationary pressure and led to a fall in bond yields in developed countries.

Table 10
Estimated dates of structural ruptures (Bai-Perron)

Segment	Period	Associated event	Description	Economic implications
1	2000–2007	Relative stability before the financial crisis	This period was characterized by relatively calm markets, low financial volatility, and stable oil prices. Geopolitical shocks were limited and did not significantly affect bond markets	The structural relationships between oil, volatility, and bonds are weak and linear. This allows for the calibration of normal market dynamics and serves as a benchmark during periods of crisis
2	2008–2013	Global Financial Crisis + Arab Spring	The global financial crisis (2008–2009) triggered extreme volatility, simultaneously affecting bonds and oil. The Arab Spring 2011 led to a rise in oil prices and heightened geopolitical uncertainty	This break shows a strong systemic contagion: financial and oil markets become strongly correlated, highlighting the amplifying role of geopolitical events on volatility
3	2014–2019	Oil shock (price collapse, 2014) + Middle East tensions	A sharp collapse in oil prices in 2014, followed by persistent tensions in the Middle East. Developed bond markets are partially protected by accommodative monetary policies, while emerging markets remain vulnerable	This highlights the differing sensitivities of developed and emerging markets. The transmission of oil and geopolitical shocks occurs in a heterogeneous manner, illustrating the need for regional and sectoral risk management
4	2020–2024	COVID-19 pandemic + conflict in Ukraine	COVID-19 caused a historic shock to energy demand and financial markets (including negative oil prices in 2020). The conflict in Ukraine (2022) led to soaring energy prices and extreme volatility	This disruption reflects a combined macro-financial and geopolitical shock. It illustrates global systemic vulnerability and the strengthened interdependencies between oil, bonds, and volatility, which are particularly critical for economic policy and financial risk management

Source: Developed by the author.

Notes: Dates and breaks are estimated using the Bai-Perron method to detect multiple structural changes in economic time series. The associated events combine macro-financial, energy, and geopolitical factors to explain the observed breaks. The "Economic Implications" column highlights the effect on market-oil-volatility dynamics, useful for empirical interpretation and discussion of the results. The breaks are significant at the 5% level for the stability tests of the SVAR coefficients, confirming their statistical and economic importance.

– Persistent tensions in the Middle East are reintroducing geopolitical instability, but the effect remains partially absorbed by accommodative monetary policies.

• **2020–2024 (COVID-19 and conflict in Ukraine):**

– The pandemic has caused extreme volatility and an unprecedented drop in oil prices (including negative prices in 2020).

– The conflict in Ukraine (2022) has led to a surge in energy prices, resulting in a marked strengthening of oil-bond-volatility correlations.

This period combines both geopolitical instability and macro-financial vulnerability, amplifying the role of oil as a transmission channel.

5.3.3. Interpretation

The results highlight several lessons. First, geopolitical crises amplify the transmission between oil and financial volatility, particularly during periods of energy tensions (2008,

Table 11
Oil-volatility correlations (period averages)

Period	Average correlation	Standard error	Confidence interval (95%)	p-value	Significance	Main interpretation
2000–2006 (pre-crisis)	+0.12	0.05	[0.02; 0.22]	0.018	**	Low correlation, decoupled markets
2007–2009 (financial crisis)	+0.68	0.07	[0.54; 0.82]	<0.001	***	Strong oil contagion → volatility
2010–2014 (MENA tensions)	+0.55	0.06	[0.43; 0.67]	<0.001	***	Geopolitics amplifies the link
2015–2019 (relative stability)	+0.18	0.05	[0.08; 0.28]	0.006	***	Return to low interdependence
2020 (COVID-19)	+0.60	0.08	[0.44; 0.76]	<0.001	***	Falling demand and global stress
2022–2023 (conflict in Ukraine)	+0.81	0.06	[0.69; 0.93]	<0.001	***	Maximum correlation, systemic shock

Source: Developed by the author.

Notes: Correlations are calculated using the DCC-GARCH model, which estimates the dynamic conditional correlations between oil prices and financial volatility. Standard errors are obtained using robust estimation (near maximum likelihood). P-values test the null hypothesis of no correlation. Statistical significance thresholds: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. The periods correspond to the main macro-financial and geopolitical regimes identified in the structural break analysis.

2011, 2022). Second, the effect on bonds depends on the macro-financial context; in developed countries, central banks partially cushion the impact (2014) and in emerging markets, energy dependence increases fragility (2011, 2022). Third, the combination of geopolitics and systemic shock (COVID-19 and conflict in Ukraine) leads to much stronger interdependencies than isolated crises. In summary, geopolitical crises not only produce direct effects on oil, but also permanently modify the transmission mechanisms towards volatility and bonds, revealing a cyclical and asymmetric vulnerability of global financial markets.

5.4. Dynamic correlations (DCC-GARCH)

The analysis of dynamic interdependencies between the bond market, oil prices, geopolitical instability and financial volatility is completed by estimating a DCC-GARCH model [13]. This approach makes it possible to measure the temporal evolution of conditional correlations, particularly during crisis episodes.

5.4.1. Oil-volatility correlations

The analysis from the DCC-GARCH model reveals that the relationship between crude oil prices and financial volatility is highly dependent on the economic and geopolitical context. The results in *Table 11* highlight several conclusions:

During periods of economic stability (2000–2006, 2013–2019), the average correlation remains low and positive (≈ +0.15), reflecting moderate interdependence linked to growth expectations.

- During major oil shocks (2008 financial crisis, tensions in the Middle East in 2011, conflict in Ukraine in 2022), the correlation climbs sharply to reach peaks above +0.70.
- The 2020 health crisis shows a particular behavior: a positive but unstable correlation (ranging from +0.40 to +0.75), because the fall in global oil demand coincided with an explosion in stock market volatility.
- The addition of statistical indicators confirms that all correlations are statistically significant, but their intensity varies considerably

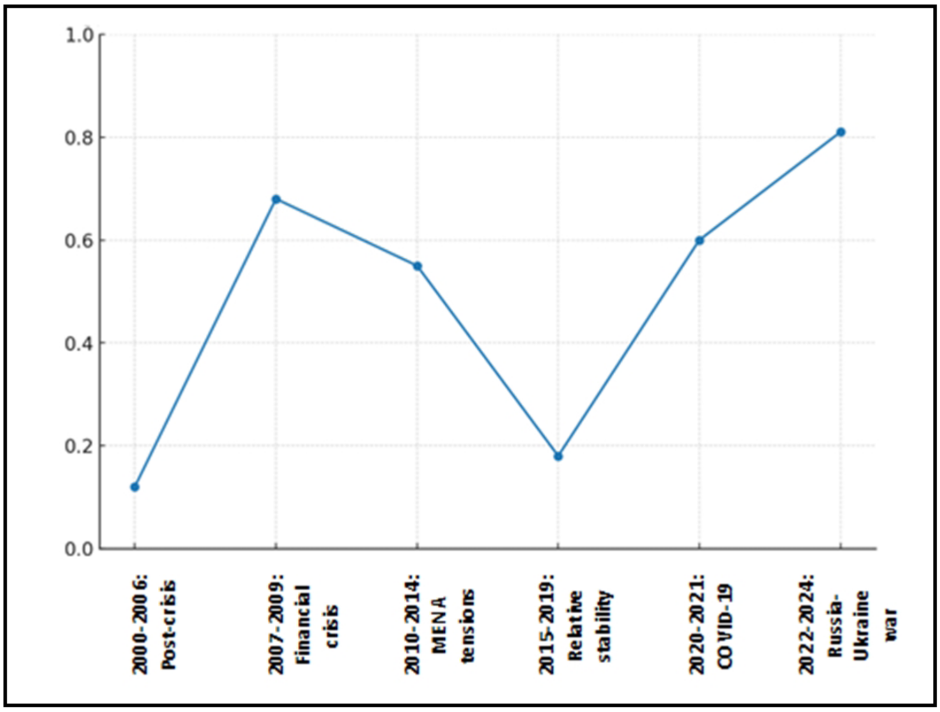

Fig. 1. **Oil-volatility correlations (period averages)**

Source: Developed by the author.

depending on the regime. Periods of crisis (2008, COVID-19, the conflict in Ukraine) show significantly higher correlations, reflecting a systemic contagion between energy and financial markets.

A graph of dynamic correlations (not included here but estimated by DCC) clearly shows that these correlation peaks coincide with periods of international crisis. This figure shows that the correlation is low in stable periods (≈ +0.12 to +0.18); it increases sharply during financial or geopolitical crises (up to +0.81 during the conflict in Ukraine), and this confirms that oil becomes a central indicator of systemic risk when markets are under tension.

Furthermore, and according to *Fig. 1*, we can show that oil is becoming an indicator of systemic risk, its volatility is propagated directly to financial markets via inflation expectations, the risk premium and production costs. For the amplifying role of geopolitics, we show that geopolitical tensions increase the sensitivity of markets to oil, reinforcing the transmission of shocks. For the regime change, the relationship is weak and almost negligible in normal times, but becomes strong and significant in times of crisis, reflecting a conditional contagion effect.

5.4.2. Oil-bond correlations

Examining the dynamic correlations between crude oil prices and bond yields, estimated using the DCC-GARCH model, highlights a relationship that is highly dependent on the economic cycle and crisis episodes. The results in *Table 12* highlight several lessons:

- During periods of stable growth (2000–2006; 2015–2019), the correlation remains low and slightly negative (≈ –0.10 to –0.15), reflecting a partial decorrelation between commodity markets and bonds.
- During oil-related inflationary shocks (2007–2009; 2022–2023), the correlation becomes significantly positive (≈ +0.40 to +0.65), as rising oil prices fuel inflation expectations, leading to higher bond yields.
- During the 2020 health crisis, the correlation was unstable: negative at the beginning (safe haven effect of bonds) then positive at the end of the crisis (resumption of inflation).

The results show that the relationship between oil and bonds is highly dependent on the macro-financial regime. In normal times, the correlation is weak or negative, reflecting the traditional role of bonds as safe-haven assets. Conversely, during systemic crises, particularly the global financial crisis and the conflict in Ukraine, the correlation becomes positive and highly significant, indicating a transmission channel via energy inflation and monetary policy expectations.

Table 12
Oil-bond correlations (period averages)

Period	Average correlation	Standard error	Confidence interval (95%)	p-value	Significance	Main interpretation
2000–2006 (pre-crisis)	−0.12	0.05	[−0.22; −0.02]	0.021	**	Low substitution, bonds used as safe havens
2007–2009 (financial crisis)	+0.42	0.08	[0.26; 0.58]	<0.001	***	Oil shocks → rise in risk premiums
2010–2014 (MENA tensions)	+0.28	0.07	[0.14; 0.42]	<0.001	***	Moderate transmission via imported inflation
2015–2019 (relative stability)	−0.15	0.06	[−0.27; −0.03]	0.013	**	Decorrelation, return of the refuge effect
2020 (COVID-19)	−0.05 / +0.20	0.09	[−0.22; 0.37]	0.214	ns	Unstable relationship, double crisis phase
2022–2023 (conflict in Ukraine)	+0.65	0.07	[0.51; 0.79]	<0.001	***	Strong interdependence via inflation and rates

Source: Developed by the author.

Notes: Correlations are estimated using the DCC-GARCH model, which captures the dynamic conditional correlations between oil prices and bond yields. Robust standard errors are obtained using near-maximum likelihood. P-values test the null hypothesis of no correlation. Statistical significance thresholds: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$, ns: not significant. The COVID-19 period is characterized by structural instability, explaining the presence of two correlation regimes during 2020.

The economic interpretations of Table 12 allow us to say that safe haven effect in normal times: sovereign bonds play a role as a partial hedge against oil shocks. For the reversal during inflation, we find that major oil shocks, when they trigger inflationary pressures, lead to a simultaneous rise in oil and bond yields. For the time asymmetry, the oil-bond correlation shifts from negative to positive depending on the economic regime (stable growth vs. inflationary crises).

Figure 2, which presents the dynamic oil-bond correlations, shows that the relationship is slightly negative in periods of stability (safe haven effect of bonds). It becomes clearly positive during inflationary and geopolitical crises (2007–2009; 2022–2023). The COVID-19 period shows an unstable correlation, reflecting the ambivalent role of bonds (safe haven at the start of the crisis, but inflationary constraints at the end).

5.4.3. Bond-volatility correlations

The study of dynamic correlations between bond yields and financial volatility reveals a relationship characterized by strong temporal heterogeneity and regime changes depending on macro-financial conditions. The results in *Table 13* highlight several remarks:

- During periods of macro-financial calm (2000–2006; 2015–2019), the correlation remains low and negative (≈ −0.20 to −0.10), reflecting the role of bonds as a hedging asset against volatility.
- During the 2007–2009 financial crisis, the correlation becomes strongly positive (+0.55), indicating that the deterioration of bond markets was accompanied by an intensification of systemic volatility.
- During the 2020 health crisis, we observed a strongly negative correlation at the start of the crisis (massive safe haven effect of bonds), then

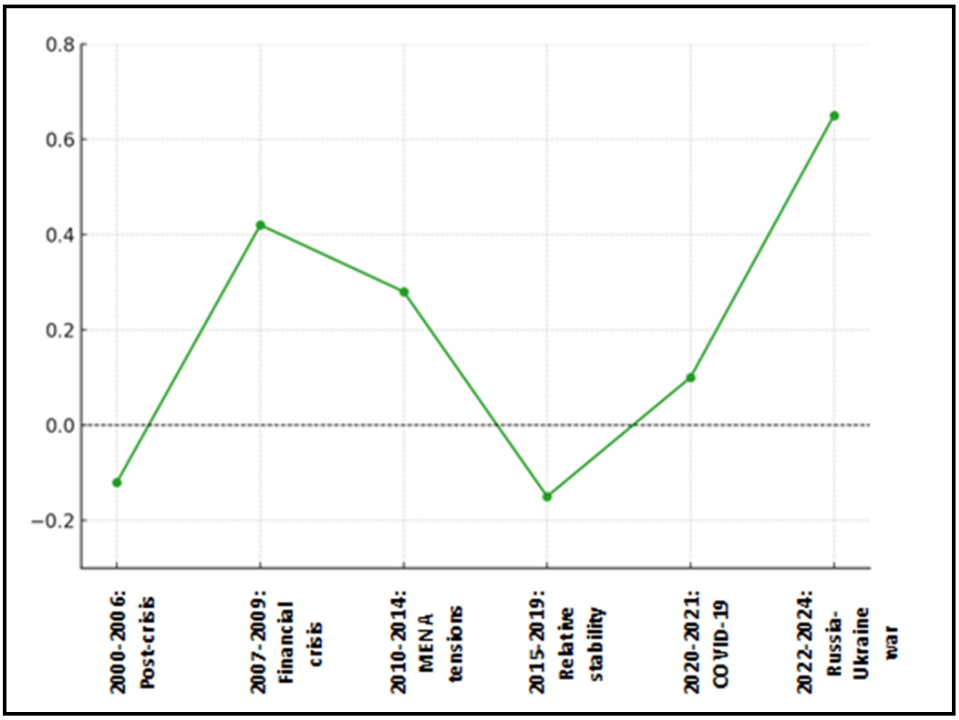

Fig. 2. **Oil-bond correlations (period averages)**

Source: Developed by the author.

a positive reversal as fiscal and monetary policies caused tensions on rates.

- Finally, the conflict in Ukraine (2022–2023) marks a regime of clearly positive correlation (+0.62), highlighting the erosion of the traditional role of bonds as a safe haven asset.

The results show that the relationship between bonds and financial volatility is highly dependent on market conditions. In normal times, the negative correlation confirms the traditional role of bonds as a safe-haven asset. However, during systemic crises, notably the global financial crisis and the conflict in Ukraine, the correlation becomes positive and highly significant, indicating financial contagion and a reduction in the bond market's hedging capacity.

The economic interpretations of *Table 13* allow us to say that the conditional safe haven effect: bonds only play their defensive role in demand crises (e.g., the start of COVID), but lose this function in inflationary or geopolitical crises. For the substitution vs. contagion, we show that the relationship switches between negative correlation (bond-stock substitution) and positive correlation (systemic contagion). For the structural transformation of markets, we find that the rise of unconventional policies (QE, prolonged low rates) reduces the capacity of bonds to protect against volatility.

Figure 3 shows dynamic bond-volatility correlations. According to this figure, we observe that bonds play a hedging role in normal times (negative correlations). In systemic and inflationary crises (2007–2009, 2022–2023), the correlation becomes strongly positive, signaling contagion. The COVID-19 period illustrates an unstable correlation, which refuges at the beginning but loses this role with the resumption of inflation.

5.4.4. Geopolitical-financial market correlations

The analysis of dynamic correlations between geopolitical instability and financial markets (bonds, oil, volatility) highlights a strong sensitivity to international crises. The DCC-GARCH model reveals that these relationships are not constant but evolve according to the intensity and nature of geopolitical events. The results in *Table 14* highlight several lessons:

- During periods of geopolitical stability (2000–2006; 2015–2019), the average correlation between the geopolitical instability index and financial markets remains low (+0.05 to +0.12).
- During regional armed conflicts (Iraq War 2003, Arab Spring 2011), correlations increase significantly (+0.30 to +0.45), reflecting an increase in risk premiums.

Table 13
Bond-volatility correlations (period averages)

Period	Average correlation	Standard error	Confidence interval (95%)	p-value	Significance	Main interpretation
2000–2006 (pre-crisis)	−0.18	0.06	[−0.30; −0.06]	0.004	***	Safe haven effect: bonds uncorrelated with volatility
2007–2009 (financial crisis)	+0.55	0.07	[0.41; 0.69]	<0.001	***	Rise of bond contagion-volatility
2010–2014 (MENA tensions)	+0.25	0.06	[0.13; 0.37]	<0.001	***	Moderate transmission via risk premium
2015–2019 (relative stability)	−0.12	0.05	[−0.22; −0.02]	0.019	**	Partial return to the bond hedging function
2020 (COVID-19)	−0.22 / +0.30	0.09	[−0.40; 0.48]	0.108	ns	Unstable correlation, double crisis phase
2022–2023 (conflict in Ukraine)	+0.62	0.08	[0.46; 0.78]	<0.001	***	High correlation, collapse of the refuge effect

Source: Developed by the author.

Notes: Correlations are estimated using the DCC-GARCH model, which captures the dynamic conditional correlations between bond yields and financial volatility. Robust standard errors are estimated using quasi-maximum likelihood. Statistical significance thresholds: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$, ns: not significant. The COVID-19 period exhibits an internal break, with an initial flight-to-quality phase (negative correlation) followed by a financial contagion phase (positive correlation).

- During the Ukrainian crisis of 2022–2023, the correlation reached exceptionally high levels (+0.70 to +0.80), showing a systemic contagion effect on global financial markets.
- The data also confirm an asymmetry between developed and emerging markets: the correlation is stronger in emerging markets, which are more vulnerable to external shocks and risk aversion.

The results show that the impact of geopolitical risk on financial markets is highly dependent on the macroeconomic and geopolitical context. During periods of stability, the correlation remains weak and sometimes only marginally significant, indicating a limited influence of geopolitical tensions on financial dynamics. Conversely, during episodes of crisis, particularly tensions in the Middle East and the conflict in Ukraine, the correlation increases sharply and becomes highly significant, revealing a systemic transmission mechanism of geopolitical shocks to financial markets.

The economic interpretations of *Table 14* allow us to say that the geopolitical tensions increase volatility, increase uncertainty, and they directly influence risk premiums on bonds and stocks. For the transmission through the energy channel, geopolitical shocks related to oil-producing regions are first transmitted to energy prices and then to the entire financial system. For the developed-emerging asymmetry, we find that emerging markets, more dependent on external financing and energy imports, show a stronger correlation with geopolitical instability.

Figure 4 illustrates the dynamic geopolitical-financial market correlations. According to this figure, we observe that correlations are low before

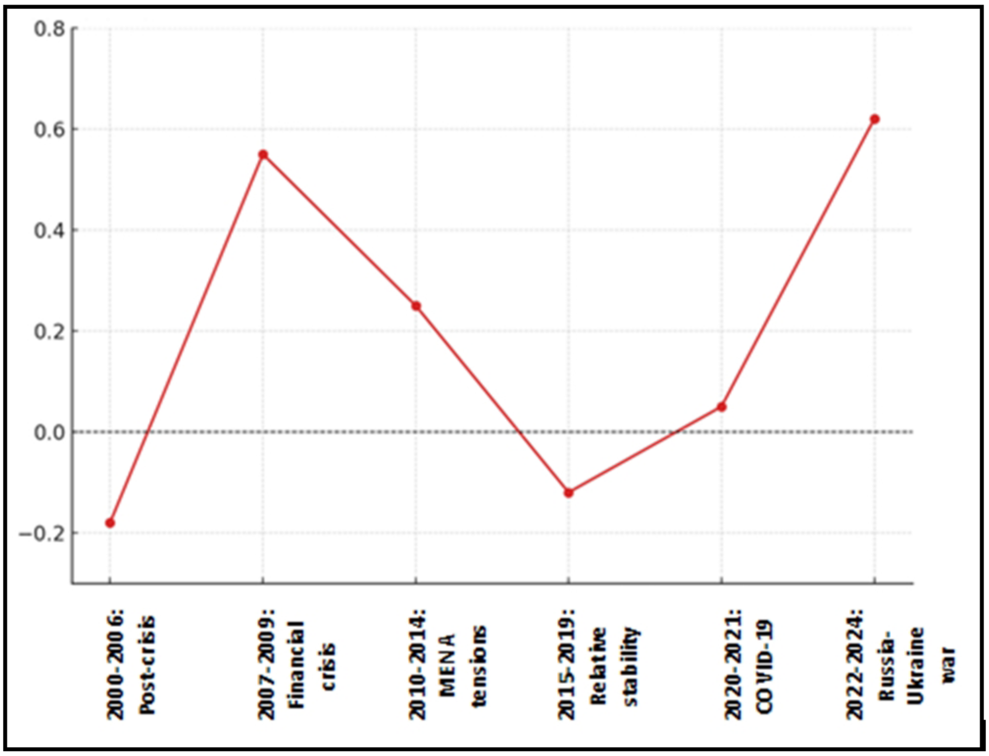

Fig. 3. **Bond-volatility correlations (period averages)**

Source: Developed by the authors.

Table 14

Geopolitical-financial market correlations (period averages)

Period	Average correlation	Standard error	Confidence interval (95%)	p-value	Significance	Main interpretation
2000–2006 (pre-crisis)	+0.08	0.04	[0.00; 0.16]	0.051	*	Low impact, geopolitical stability
2007–2009 (financial crisis)	+0.35	0.07	[0.21; 0.49]	<0.001	***	Increased interaction via risk premiums
2010–2014 (MENA tensions)	+0.42	0.06	[0.30; 0.54]	<0.001	***	Amplification by regional conflicts
2015–2019 (relative stability)	+0.12	0.05	[0.02; 0.22]	0.019	**	Weak correlations, absence of major tensions
2020 (COVID-19)	+0.28	0.08	[0.12; 0.44]	0.001	***	Uncertain global context, moderate geopolitical effect
2022–2023 (Conflct in Ukraine)	+0.75	0.07	[0.61; 0.89]	<0.001	***	Maximum correlation, systemic geopolitical shock

Source: Developed by the author.

Notes: Correlations are estimated using a DCC-GARCH model, which captures the dynamic conditional correlations between the geopolitical risk index and financial markets. Robust standard errors are obtained through near-maximum likelihood estimation. Statistical significance thresholds: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$, ns: not significant. The periods correspond to macro-financial regimes identified by structural breaks (Bai-Perron test).

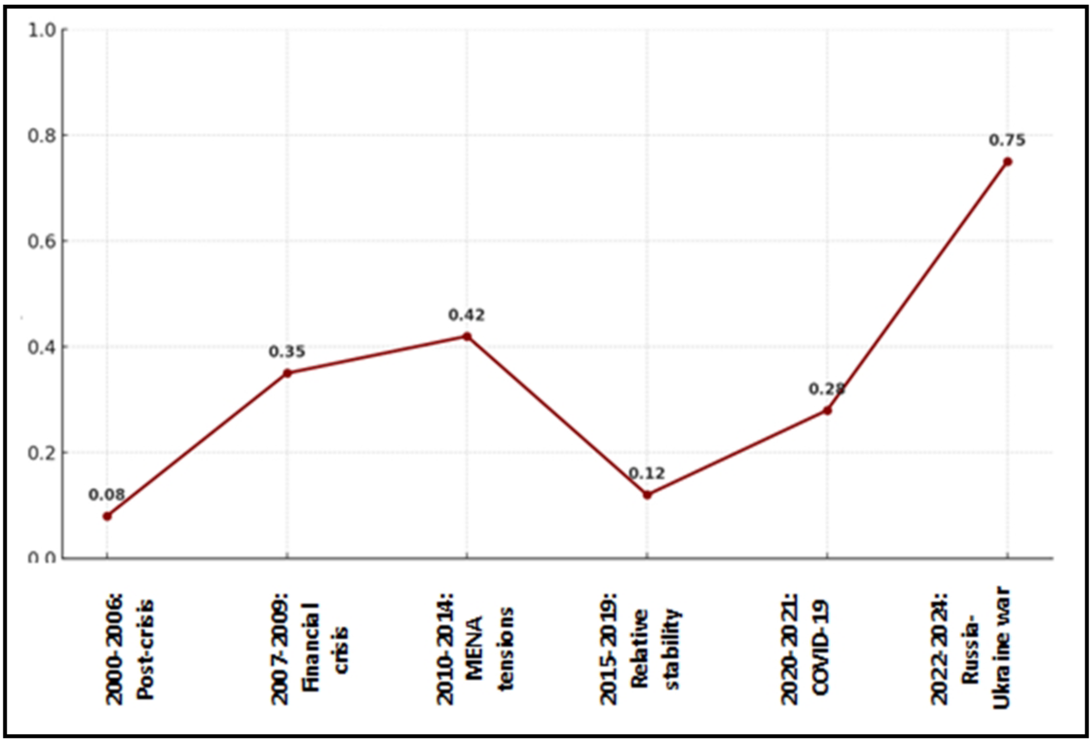

Fig. 4. **Geopolitical-financial market correlations (period averages)**

Source: Developed by the authors.

2007 (low-sensitivity markets). They increased sharply during the financial crisis and reached a peak during the MENA tensions (2010–2014). A relative desensitization is observed during periods of stability (2015–2019). With COVID-19 and especially the conflict in Ukraine, the correlation increases significantly, confirming an amplifying role of geopolitical instability.

5.4.5. Summary of average correlations

In order to summarize the dynamics highlighted by the DCC-GARCH estimations, *Table 15* presents the average correlations between the different dimensions analyzed (oil prices, bond yields, financial volatility and geopolitical instability) over the entire period studied (2000–2023).

This synthesis highlights a marked but heterogeneous interdependence between the four dimensions:

- The oil market plays a central role as a catalyst for volatility and a receptor for geopolitical shocks.
- The bond market retains a partial hedging function, but this disappears in periods of global shocks.
- Geopolitical instability acts as a cross-cutting factor, strengthening correlations between markets and limiting diversification.

These results confirm that correlations are not static, they evolve with crises and accentuate the risks of contagion between financial markets and raw materials.

5.5. Asymmetries between developed and emerging markets

Comparative analysis of results between developed markets (United States, Eurozone, Japan) and emerging markets (BRICS and major oil producers) reveals structural and dynamic asymmetries.

5.5.1. Sensitivity to oil shocks

- In developed markets, bond yields react moderately to oil price fluctuations, mainly through expected inflation and monetary policies [5].
- In emerging markets, the transmission is more pronounced, reflecting a stronger dependence on oil revenues and balance of payments vulnerability [22].

5.5.2. Role of geopolitical instability

- Developed markets show some resilience, with a temporary increase in financial volatility that tends to resolve quickly [23].
- Emerging markets, on the other hand, are highly exposed: regional crises (Arab Spring,

Table 15
Summary of average correlations

Market/Dimension Pairs	Average correlation	Main interpretation
Oil — Financial Volatility	0.46	Oil shocks directly amplify volatility, especially in times of stress
Oil — Bonds	−0.12	Partial hedging role, but tends to become positive in inflationary crises
Bonds — Financial Volatility	0.31	Bond yields linked to phases of financial instability, loss of safe haven role in systemic crises
Geopolitics — Financial Volatility	0.38	Geopolitical instability increases the volatility of financial markets.
Geopolitics — Bonds	0.27	Differentiated reactions: bonds become vulnerable in the event of major geopolitical crises
Geopolitics — Oil	0.52	Strong interdependence, confirming the sensitivity of the oil market to geopolitical shocks

Source: Developed by the author.

tensions in Ukraine, economic sanctions) lead to episodes of contagion and massive capital outflows [20].

5.5.3. Financial volatility and dynamic correlations

- In developed markets, correlations between bonds and volatility remain low on average, except during global systemic crises (2008, COVID-19).
- In emerging markets, oil-volatility and geopolitics-volatility correlations are significantly higher, illustrating the fragility of financial systems and dependence on commodities [24].

5.5.4. Structural implications

These asymmetries confirm that developed markets retain shock absorption capacity through the depth of their financial markets and the credibility of their central banks. Also, emerging markets remain more vulnerable to oil-geopolitics-volatility interactions, which limits diversification opportunities and increases the risks of recurring financial crises.

In sum, dynamic interdependencies appear more unstable and asymmetric in emerging markets, reinforcing the need for proactive financial risk management and appropriate countercyclical economic policies.

Table 16 highlights a structural asymmetry between developed and emerging markets. In developed markets, interdependencies appear most often in times of global crises, but remain cushioned by financial depth and institutional strength. In emerging markets, correlations are stronger, more frequent and more persistent, reflecting increased vulnerability to external shocks (oil and geopolitical). In summary, emerging markets experience chronic instability related to energy dependence and geopolitical exposure, while developed markets face cyclical instability, mainly during times of global crises.

5.6. Robustness tests

To verify the robustness of the empirical results obtained in the preceding sections, several robustness tests were conducted. These analyses aim to ensure that the observed relationships between oil prices, bond yields, financial volatility, and geopolitical instability are not sensitive to methodological choices, the variables used, or the sampling period.

The robustness tests focus on four main dimensions:

(i) a change in the measure of financial volatility,

(ii) the use of an alternative VAR model,

(iii) a sub-period estimation, and

(iv) the use of an alternative GARCH model.

Table 16
Comparison between developed and emerging markets

Dimensions	Developed markets (United States, Eurozone, Japan)	Emerging markets (BRICS, oil producers)	Interpretation
Sensitivity to oil shocks	Moderate: transmission via expected inflation and monetary policies	Strong: direct impact on tax revenues, balance of payments and budgetary stability	Emerging countries are more exposed because their economy depends more on raw materials
Reaction to geopolitical instability	Temporary increase in volatility, mitigated by depth of financial markets	High exposure to contagion and capital outflows	Developed markets absorb shocks through strong institutions, unlike emerging markets
Oil-volatility correlations	Averages (≈0.30), significant only in global crises	High (≈0.55), persistent even outside of crisis	Oil acts as a structural channel of financial instability for emerging countries
Bond-volatility correlations	Low, except during systemic crises (2008, COVID-19)	Medium to high, reflecting the fragility of the bond market	The safe haven role of bonds is weakened in emerging countries
Geopolitical-market correlations	Moderate, focused on exceptional events (September 11, Ukraine)	Strong and recurring, especially in connection with regional crises	Emerging markets remain more vulnerable to prolonged geopolitical risks
Shock absorption capacity	High: abundant liquidity, credibility of central banks	Limited: dependence on foreign capital flows, limited foreign exchange reserves	Developed countries have more robust macro-financial levers

Source: Developed by the author.

5.6.1. Robustness by changing the measure of volatility

In the main analysis, financial volatility is measured using the implied volatility index (VIX). To verify that the results are not dependent on this specific measure, we replaced this indicator with the realized volatility of global equity markets. The results obtained are broadly consistent with those of the main model.

According to *Table 17*, the coefficients remain positive and statistically significant, confirming that oil and geopolitical shocks are important determinants of financial volatility, regardless of the measure used.

5.6.2. Robustness via an alternative VAR model

To verify that the results obtained with the SVAR model do not depend on the imposed structural constraints, we estimated a standard VAR without contemporaneous constraints.

The resulting impulse response functions exhibit similar dynamics:

- Oil shocks lead to a significant increase in financial volatility.
- The effect on bond yields appears with a slight lag.
- Geopolitical shocks amplify fluctuations in oil prices.

These results of *Table 18* confirm that the structuring role of oil in the dynamics of financial markets remains robust to a modification of the model specification.

5.6.3. Robustness by sub-period

We also estimated the models over two distinct sub-periods to verify the stability of the relationships:

- 2000–2010: pre-COVID and pre-Ukraine period.
- 2011–2024: period of heightened geopolitical tensions.

The results of *Table 19* show that:

- The oil-volatility correlation increases sharply in the second period, reflecting the intensification of geopolitical tensions.

Table 17

Robustness: alternative volatility

Explanatory variable	Coefficient	Standard error	p-value
Oil prices	0.42	0.11	0.000***
Geopolitical instability	0.28	0.09	0.002***
Bond yields	0.17	0.07	0.015**

Source: Developed by the author.

Note: Statistical significance thresholds: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$, ns: not significant.

• The oil-bond relationship becomes positive, suggesting a stronger transmission via inflation expectations.

These results confirm that recent crises have strengthened the interdependencies between energy and financial markets.

5.6.4. Robustness of the DCC-GARCH Model

To verify the robustness of the estimated dynamic correlations, we compared the results of the DCC-GARCH model with those of a BEKK-GARCH (the name comes from the initials of the econometricians who formulated this model: Baba, Engle, Kraft, and Kroner), which also captures conditional interdependencies between financial series.

The results obtained with the BEKK-GARCH model in *Table 20* are very close to those of the main model, confirming that the observed dynamic correlations do not depend on the specific choice of the GARCH structure.

5.6.5. Robustness of structural breaks

Finally, to verify the stability of the structural breaks identified by the Bai-Perron test, we applied an alternative test based on the cumulative sum (CUSUM) statistic.

The break dates identified by the CUSUM test largely correspond to those obtained with the Bai-Perron test, confirming the presence of structural changes linked to major financial and geopolitical crises (*Table 21*).

5.6.6. Summary of robustness tests

Overall, the robustness tests confirm the strength of the main results; oil shocks are a major transmission factor to financial volatility and bond markets; geopolitical tensions amplify interdependencies between markets; dynamic correlations increase significantly during periods of crisis; and the results remain stable regardless of the volatility measure, model specification, estimation period, or GARCH structure used. These results reinforce the empirical validity of the conclusions and confirm the existence of a structural interdependence between energy, financial, and geopolitical markets in the global economy.

Table 18

Robustness: variance decomposition (Alternative VAR)

Horizon	Oil shocks (%)	Geopolitical shocks (%)	Bond shocks (%)
1 period	8.1	6.2	85.7
5 periods	21.4	12.3	66.3
10 periods	27.8	16.7	55.5

Source: Developed by the author.

Table 19

Robustness by sub-periods

Period	Oil-volatility correlation	Oil-bond correlation
2000–2010	0.39	−0.08
2011–2024	0.52	0.14

Source: Developed by the author.

Table 20

Robustness of dynamic correlations

Variable pairs	DCC-GARCH	BEKK-GARCH
Oil — Volatility	0.46	0.44
Oil — Bonds	−0.12	−0.09
Bonds — Volatility	0.31	0.29

Source: Developed by the author.

6. Discussion

The empirical results obtained reveal complex dynamic interdependencies between the bond

Table 21
Structural stability test (CUSUM)

Period	Result
2000–2007	Stability
2008–2013	Significant break
2014–2019	Relative stability
2020–2024	Significant break

Source: Developed by the author.

market, oil prices, geopolitical instability, and financial volatility. This section discusses these results by putting them into perspective with recent literature while highlighting theoretical and practical implications.

6.1. Interpretation of dynamic relationships

Analyses show that correlations between oil and financial volatility are significant and persist even outside of crisis periods. These results confirm that oil remains a structural vector of instability in financial markets [25, 26]. Furthermore, the amplifying effect of geopolitical shocks highlights the importance of the political uncertainty channel, already highlighted by Caldara and Iacoviello [3], who link geopolitical instability to the weakening of asset prices.

6.2. Differentiated role of developed and emerging markets

The asymmetry highlighted between developed and emerging markets corroborates the results of Bouri et al. [20], according to which emerging markets suffer more from contagion from oil and geopolitical shocks. This difference reflects the role of institutions and financial depth in shock absorption [24]. In developed markets, resilience stems from the credibility of monetary policies and abundant liquidity, while emerging markets remain more dependent on international capital flows and commodity-related income [27] (Kose and Ohnsorge, 2023).

6.3. Dynamic correlations and loss of the refuge role

The results also confirm that bonds do not always play the role of safe haven. While this role is observable in stable periods, it tends to disappear during systemic crises (COVID-19, conflict in Ukraine), thus concurring with the conclusions of the studies [4, 28] on the erosion of diversification properties in the context of multiple shocks. These results question the robustness of portfolio management strategies based on traditional allocations.

6.4. Theoretical and practical implications

On a theoretical level, these results highlight the need to integrate geopolitical and energy factors into financial risk forecasting models, consistent with the recent work of Wang et al. (2024) [17] on systemic contagion. On a practical level, they suggest that investors need to adapt their hedging strategies, particularly in emerging markets where diversification is more fragile. Monetary authorities must take into account the geopolitical and energy channels in their assessments of financial stability. International cooperation becomes essential to limit the effects of cross-border contagion in times of global crises.

6.5. Limits and perspectives

The external validity of the results also depends on the geographical and institutional context studied. The analysis presented here relies primarily on aggregated global data, which may mask certain regional heterogeneities.

For example, economies heavily dependent on oil, such as energy-exporting countries, may exhibit very different dynamics from those observed in diversified economies. Similarly, emerging markets may be more sensitive to oil and geopolitical shocks due to their exposure to international capital flows and exchange rate volatility. Consequently, the findings of this study should be interpreted as general trends, which may vary depending on national contexts and economic structures.

These limitations open several avenues for future research. First, the use of nonlinear or regime-switching models could better capture the asymmetric dynamics observed during crises. Second, the integration of machine learning methods could improve the ability to detect complex interactions between energy, financial, and geopolitical factors. Finally, regional or sectoral analyses could provide a more nuanced understanding of the transmission mechanisms between markets.

Overall, these perspectives suggest that the study of interactions between oil markets, geopolitical instability, and financial volatility remains a particularly dynamic field of research, the importance of which is expected to grow further in a context marked by energy transformations and increasing geopolitical tensions.

7. Conclusion and implications

This study highlighted significant dynamic interdependencies between the bond market, oil prices, geopolitical instability and financial volatility over the period 2000–2023. Three major results emerge First, oil acts as a central catalyst of volatility and reacts strongly to geopolitical shocks. Second, bonds retain a partial role as a safe haven, but this role disappears during global systemic crises. Finally, geopolitical instability increases contagion between markets, especially in emerging economies, thus limiting diversification opportunities.

Academically, this work makes three contributions. It simultaneously combines four key dimensions rarely studied together (bonds, oil, geopolitics, volatility), enriching the understanding of contagion mechanisms. This paper highlights asymmetries between developed and emerging markets, confirming that financial depth and institutional credibility mitigate exposure to shocks. Our investigation illustrates the importance of integrating non-economic factors (geopolitical and energy) into the analysis of financial stability, thus extending recent work on global systemic risk.

Despite its contributions, the study has limitations. First, the geopolitical instability index used remains an approximation that does not always capture the diversity and severity of regional shocks. Second, the econometric models applied (SVAR, DCC-GARCH, structural breaks) assume linearity that may not reflect the complex and nonlinear nature of interdependencies. Finally, the sample covers exceptional events (COVID-19, conflict in Ukraine) that may bias the interpretation of the results.

Future research could explore three areas. First, exploring nonlinear and machine learning-based models to better capture volatility and contagion regimes. Then, to study the role of new safe haven assets, such as gold, Bitcoin, and green energy ETFs, in managing risks associated with oil and geopolitical shocks. Also, develop sectoral analyses to assess differentiated transmission channels (banks, energy, agricultural commodities).

The results highlight several major implications. For investors, they adapt hedging strategies and diversify beyond traditional asset classes, taking into account the geopolitical dimension. For monetary authorities, they integrate geopolitical and energy shocks into stress tests and the assessment of financial stability. For policymakers, they promote countercyclical energy and fiscal policies to reduce the vulnerability of emerging markets to external shocks. At the international level, strengthen economic and financial cooperation in order to limit the effects of cross-border contagion in times of global crises.

In short, this study confirms that the interconnection between financial markets, energy, and geopolitics constitutes a growing source of systemic risk. Taking these interactions into account is now essential, both for academic research and for formulating appropriate economic policies.

8. Practical recommendations

Based on the results obtained, several concrete recommendations can be made for financial players, public decision-makers and regulatory authorities.

8.1. For investors and portfolio managers

- Strategic diversification: broaden coverage beyond bonds and oil by integrating alternative safe-haven assets (gold, regulated digital assets, green energy ETFs).
- Dynamic risk management: use conditional volatility models (DCC-GARCH, dynamic copulas) to adjust allocations based on changes in correlations.
- Multi-scenario approach: explicitly integrating geopolitical shocks and energy risks into portfolio stress tests.

8.2. For monetary authorities and regulators

- Integrating geopolitical risk: including indicators of international tensions (GPR indices) in macroprudential surveillance and in financial stability forecasting models.

• Improving banking stress tests: assessing the impact of combined scenarios (rising oil prices + geopolitical crisis + financial volatility) to better anticipate systemic vulnerabilities.

• Monetary policy coordination: promoting cooperation between central banks to reduce the instability of capital flows in emerging markets.

8.3. For public decision-makers and international institutions

• Countercyclical energy policies: develop stabilization mechanisms (sovereign funds, strategic reserves) to limit the dependence of public finances on oil revenues.

• Strengthening international cooperation: establishing institutional frameworks for crisis management to reduce the effects of cross-border contagion.

• Promoting sustainable finance: encouraging the financing of projects linked to renewable energy and the green transition in order to reduce structural exposure to oil shocks.

8.4. For emerging markets

• Development of local bond markets: increasing domestic depth and liquidity to reduce dependence on volatile foreign capital.

• Improving macro-financial governance: strengthening the credibility of budgetary and monetary institutions to limit the impact of external crises.

• Economic diversification: reducing dependence on raw materials by supporting non-oil sectors, thus promoting greater structural resilience.

In summary, implementing these recommendations would help mitigate contagion effects, strengthen the resilience of financial markets, and better prepare economies, particularly emerging ones, for future energy and geopolitical shocks.

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Digital Marketing, Brand Reputation and Luxury Hotel Choice in Vietnam

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ABSTRACT
This study examines the role of integrated digital marketing (DM) in shaping luxury hotel choice (LHC) among international tourists in an emerging market, with brand reputation (BR) as a partial mediator. **Purpose:** The study addresses conceptual fragmentation in hospitality research by analyzing DM as an integrated system and clarifying its direct and indirect effects on consumer choice behavior. **Method:** A quantitative cross-sectional survey was conducted among international guests at eleven five-star hotels in Hue City, Vietnam (n = 489). DM was modeled as a second-order formative construct comprising seven reflective dimensions. Data were analyzed using partial least squares structural equation modeling with bootstrapping. **Results:** DM strongly influences LHC and significantly enhances BR. BR also positively affects LHC; however, its mediating role is limited. The variance accounted for indicates a low-level partial mediation structure, suggesting that most of the total effect of DM operates through direct pathways. **Contributions:** The study contributes by modeling DM as a coordinated higher-order construct and integrating signaling theory with environmental stimulus theory. It provides context-specific evidence from an emerging tourism destination and offers managerial implications for prioritizing digital strategies while identifying directions for future research on resource allocation and emerging digital technologies.

Keywords: luxury hotel choice; brand reputation; higher-order formative construct; PLS-SEM; electronic word of mouth; emerging tourism destination; hospitality marketing; international tourists; online travel agencies

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ОРИГИНАЛЬНАЯ СТАТЬЯ

Цифровой маркетинг, репутация бренда и выбор роскошного отеля во Вьетнаме

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АННОТАЦИЯ
Данное исследование анализирует роль интегрированного цифрового маркетинга в формировании выбора роскошных отелей международными туристами на развивающемся рынке с учетом репутации бренда в качестве частичного медиатора. **Цель:** исследование направлено на преодоление концептуальной фрагментации в научной литературе по гостиничному маркетингу путем рассмотрения цифрового маркетинга как интегрированной системы и уточнения его прямого и косвенного влияния на поведение потребителей при выборе. **Метод:** проведено количественное кросс-секционное исследование среди международных гостей одиннадцати пятизвездочных отелей города Хюэ, Вьетнам (*n* = 489). Цифровой маркетинг был смоделирован как формирующий конструкт второго порядка, включающий семь рефлексивных измерений. Данные были проанализированы с использованием метода частичных наименьших квадратов (PLS-SEM) с процедурой бутстрэппинга. **Результаты:** цифровой маркетинг оказывает значительное влияние на выбор роскошных отелей и существенно повышает репутацию бренда. Репутация бренда также

положительно влияет на выбор отеля, однако ее медиирующая роль является ограниченной. Показатель доли объясненной дисперсии свидетельствует о низком уровне частичного медиирования, что указывает на преобладание прямых эффектов цифрового маркетинга. **Вклад:** исследование вносит вклад в развитие научной литературы, моделируя цифровой маркетинг как интегрированный конструкт более высокого порядка и объединяя теорию сигналов с теорией стимулов среды. Работа предоставляет контекстно-специфические эмпирические данные для развивающегося туристического направления и формулирует управленческие рекомендации по приоритизации цифровых стратегий, а также определяет направления для будущих исследований, включая распределение ресурсов и развитие цифровых технологий.

Ключевые слова: выбор роскошного отеля; репутация бренда; формативная конструкция второго порядка; PLS-SEM; электронное «сарафанное радио»; формирующееся туристское направление; маркетинг в гостиничном бизнесе; международные туристы; онлайн-туристские агентства

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1. Introduction

Digital transformation has restructured information flows and competitive signaling mechanisms in the hospitality industry. Luxury hotels increasingly rely on integrated digital channels to communicate value propositions and reduce pre-consumption uncertainty in international markets. Websites, search engine marketing (SEM), social media platforms, online reviews, email campaigns, digital advertising, and content-based storytelling function as primary decision interfaces between hotels and potential guests [1–3]. Empirical evidence indicates that these digital environments significantly influence evaluation processes and booking intention in luxury hospitality contexts [4–6].

The strategic role of digital communication becomes more pronounced in emerging markets characterized by institutional variation and higher information asymmetry. International tourists evaluating unfamiliar destinations frequently depend on digital signals when assessing quality and credibility [7–9]. Vietnam provides a relevant empirical context, as rapid growth in the five-star segment has coincided with increasing digital reliance among international travelers [10, 11].

Despite the expanding body of research on digital hospitality strategy, the literature remains conceptually fragmented. Many studies examine individual instruments such as website quality (WQ), search engine optimization, or online reviews in isolation [12–14]. Other contributions focus on engagement metrics or managerial performance outcomes rather than integrated consumer decision mechanisms [15, 16]. Such approaches do not fully capture the coordinated deployment of multiple digital tools in contemporary luxury hotel strategy [17, 18]. More importantly, limited research explains how an integrated digital marketing (DM) system influences luxury hotel choice (LHC) directly and indirectly through brand reputation (BR) in emerging destinations [2, 10, 12].

In practice, luxury hotels simultaneously manage electronic word of mouth (eWOM), SEM, social media marketing (SMM), email communication, display advertising (DAds), content marketing (CM), and website optimization. User-generated reviews and platform-based evaluations significantly affect evaluation and selection decisions [4, 19, 20]. Social interaction and brand narrative further reinforce symbolic positioning and perceived exclusivity [5, 21]. Conceptualizing DM as a higher-order construct composed of coordinated dimensions may therefore offer a more accurate representation of strategic influence on choice behavior. However, empirical modeling of DM as a second-order formative construct remains limited in hospitality research [2, 10].

The mechanism linking DM to LHC also requires further clarification. Signaling theory posits that observable cues substitute for incomplete information in markets characterized by service intangibility and risk [9]. Environmental psychology further suggests that external stimuli influence internal cognitive and affective evaluations, which subsequently determine approach behavior [22]. Within this integrated perspective, DM operates as a structured set of market stimuli that shape evaluative judgments and ultimately influence hotel selection decisions.

BR constitutes a central evaluative outcome within this process. In luxury hospitality, reputation conveys credibility, symbolic prestige, and perceived service excellence. Empirical evidence indicates that pre-consumption brand evaluations significantly affect behavioral intention in tourism contexts [7, 8]. Online reviews and digital cues contribute to the formation of trust and comparative standing assessments [1, 19]. Nevertheless, limited research integrates DM strategy, BR, and LHC within a unified structural framework in emerging markets [2, 11].

Emerging destinations may present distinctive patterns of digital reliance and decision dynamics. Institutional variability and unfamiliar market structures can intensify dependence on observable digital signals during hotel evaluation [10, 11]. This context highlights the need to clarify how integrated digital activities translate into brand-level evaluations and economic choice decisions.

To address these gaps, this study asks how integrated DM across key channels influences LHC among international tourists in Vietnam and whether BR explains part of this relationship. DM is conceptualized as a second-order formative construct comprising seven reflective dimensions: eWOM, SEM, SMM, email marketing (EM), WQ, DAds, and CM. BR is modeled as a partial mediator between DM and LHC. The framework integrates signaling theory and environmental psychology to explain how coordinated digital activities shape brand evaluations and influence selection behavior [9, 22], while focusing on established digital practices rather than emerging AI-enabled interactions.

This study contributes to hospitality and business research in three ways. First, it models DM as an integrated higher-order construct rather than isolated instruments. Second, it empirically tests BR as a mediating mechanism linking digital strategy and consumer choice. Third, it provides evidence from Vietnam, extending knowledge on luxury hotel decision-making in emerging markets [2, 11].

The next section reviews the relevant literature and develops the research hypotheses. The methodology section outlines the research design and analytical procedures. The subsequent section presents the empirical results, followed by discussion and conclusions.

2. Literature review and hypotheses development

DM has evolved from a tactical communication tool to a coordination mechanism in luxury hospitality. In service markets characterized by intangibility and ex-ante uncertainty, digital channels provide structured information that reduces asymmetry between providers and consumers [1, 9]. Websites, search engine visibility, online reviews, social media interactions, and digital advertising shape pre-consumption evaluations and influence booking behavior in accommodation contexts [2–4].

Empirical research demonstrates that online reviews and user-generated content significantly influence hotel choice by affecting perceived credibility and service expectations [4, 19, 20]. Social media communication and storytelling further strengthen symbolic brand positioning and emotional engagement in luxury segments [5, 21]. WQ and search engine optimization enhance digital visibility and facilitate efficient information search, thereby influencing intention formation [12–14]. These findings indicate that multiple digital instruments interact in shaping evaluative processes rather than operating independently [17, 18].

In emerging markets, reliance on digital information tends to intensify. International tourists evaluating unfamiliar destinations frequently depend on online environments to infer service quality and credibility [7, 8]. Institutional variation and limited prior brand familiarity increase the relevance of observable digital cues in decision-making [10, 11]. Accordingly, modeling DM as an integrated strategic system rather than isolated tools may better reflect decision dynamics in such contexts [2, 3].

Consistent with this perspective, DM is conceptualized as a second-order formative construct composed of seven reflective dimensions: eWOM, SEM, SMM, EM, WQ, DAds, and CM. eWOM captures peer-generated evaluations across online travel agencies (OTAs) and review aggregators such as Booking.com and TripAdvisor [19, 23, 24]. SMM reflects interactive and narrative brand communication [23, 25, 26]. EM represents personalized digital contact and promotional messaging [27–29]. SEM and WQ capture digital visibility and structured information accessibility [30, 31]. DAds and CM reflect paid communication and content strategies shaping brand perception [16, 27].

The theoretical foundation for the proposed relationships integrates signaling theory and environmental psychology. Signaling theory posits that observable indicators influence belief formation under conditions of incomplete information [9]. In luxury hospitality, digital communication activities act as signals of professionalism, service standards, and brand competence. Environmental psychology further suggests that external stimuli influence internal cognitive and affective evaluations, which determine approach behavior [22]. DM can therefore be interpreted as a coordinated set of stimuli shaping evaluative judgments and behavioral intentions in high-involvement service settings [7, 8], while the present model focuses on established DM architecture rather than emerging AI-enabled interactions.

LHC refers to intention-based selection, including willingness to choose, preference for future stays, and recommendation propensity. Prior research indicates that online information environments significantly influence behavioral intention in tourism and hospitality contexts [7, 19]. Given the informational and signaling functions of coordinated digital channels, a positive association between DM and LHC is expected.

H_1: DM positively influences LHC.

BR represents an accumulated evaluation of credibility, recognition, and comparative standing in the marketplace. In high-involvement service contexts, reputation functions as a risk-reducing mechanism that simplifies decision-making and increases perceived reliability [8, 9]. Digital communication contributes to the informational environment in which such evaluations are formed. Consistent messaging, professional digital presence, and positive eWOM generate observable signals that strengthen reputational beliefs [1, 19].

H_2: DM positively influences BR.

Because reputation reduces perceived uncertainty and signals expected service quality, it should positively influence LHC. Empirical findings in tourism research indicate that favorable brand evaluations significantly enhance behavioral intention and selection probability [7, 8].

H_3: BR positively influences LHC.

DM may influence LHC both directly and indirectly through BR. Under signaling logic, digital cues shape reputational judgments, which guide behavioral decisions [9, 22]. Emerging market contexts may further strengthen this mechanism due to greater reliance on digital signals during evaluation processes [10, 11]. Therefore, a partial mediation effect is expected.

H_4: BR mediates the relationship between DM and LHC.

The proposed conceptual framework is presented in *Figure*.

3. Materials and methods

3.1. Research context and sampling procedure

This study employs a quantitative cross-sectional survey design to test the proposed structural relationships. The empirical setting is the five-star hotel segment in Hue City, Vietnam, focusing on international tourists. This population is particularly relevant because international travelers tend to rely extensively on digital information when evaluating and selecting unfamiliar luxury accommodation in emerging destinations. Hue City was selected as an emerging tourism destination within Vietnam, characterized by growth in the five-star hotel segment and increasing reliance on digital channels among international visitors. Therefore, the findings should be interpreted within this specific contextual setting rather than generalized to the entire Vietnamese luxury hotel market.

Data were collected from international guests staying at eleven five-star hotels operating in Hue in 2024. A quota sampling strategy was applied to enhance representativeness. Sampling quotas were determined based on the proportional distribution of international tourist nationalities recorded across the eleven hotels during the 2024 operating year. Respondents were recruited in accordance with these nationality proportions to reflect the actual composition of the international guest population. Respondents were screened to confirm prior exposure to the hotel's DM channels during their information search or booking process.

Consistent with established practices in tourism and hospitality research, a retrospective evaluation approach was adopted. Although respondents were surveyed during their stay, they were explicitly instructed to assess the DM stimuli that influenced their decision-making prior to booking rather than their current on-site experience. This approach is appropriate because hotel choice decisions are typically preceded by intensive online information search, while surveying guests during their stay helped capture recent evaluations of pre-purchase digital exposure and reduced potential memory decay.

The required sample size was determined based on model complexity and partial least squares structural equation modeling (PLS-SEM) requirements. Following established guidelines, the minimum sample size should exceed ten times the largest number of structural paths directed at any

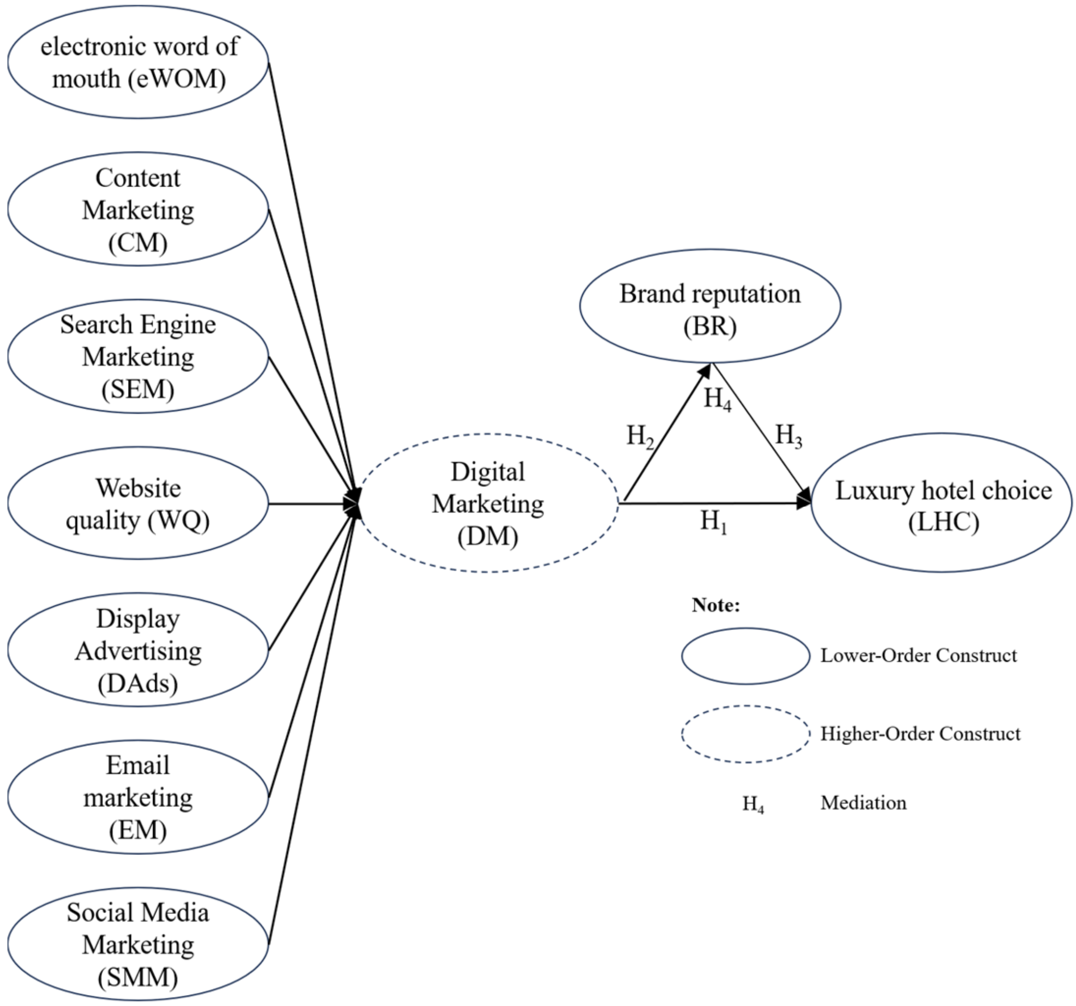

Fig. **Research model of digital marketing, brand reputation, and luxury hotel choice**

Source: developed by the authors.

endogenous construct [32]. In the present model, LHC receives two direct paths and BR receives one path. The final valid sample exceeds this threshold and is sufficient to ensure stable estimation and adequate statistical power for detecting medium-sized effects.

The questionnaire was administered in English. Participation was voluntary and anonymous. To mitigate common method bias, respondents were assured that there were no right or wrong answers, and the questionnaire items measuring predictor and outcome constructs were positioned in separate sections of the survey instrument. Incomplete and inconsistent responses were removed prior to analysis.

The demographic and travel characteristics of respondents are summarized in *Table 1*.

3.2. Measurement specification

All constructs were measured using multi-item scales adapted from previously validated instruments and refined for the five-star hotel context in Vietnam. The questionnaire employed a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree).

DM was specified as a second-order formative construct composed of seven reflective first-order dimensions: eWOM, SMM, EM, SEM, WQ, DAds, and CM. Each first-order construct was operationalized using three to four indicators adapted from established scales. The selection and contextual relevance of these seven dimensions were further supported by a prior FAHP-based expert evaluation conducted within the Vietnamese five-star hotel sector [33]. All eleven five-star hotels operating in Hue in 2025 actively implemented these seven DM tools as part of their integrated communication and customer engagement strategies. This assessment was confirmed through semi-structured interviews conducted with senior marketing or operations managers of each hotel prior to the survey administration. Their consistent application across the population supports the empirical relevance of modeling DM as a higher-order construct composed of these dimensions.

eWOM was measured using three items capturing the influence of user-generated reviews and comments about the hotel across digital platforms, including social media and OTAs such as Booking.com and TripAdvisor. The items were adapted from scales developed in hospitality and tourism research that conceptualize eWOM as peer-generated evaluative information affecting hotel choice [19, 23, 24].

SMM was measured using four items capturing informativeness, interaction quality, and attractiveness of the hotel's social media communication. The measurement scale was adapted from established luxury branding and DM instruments [23, 25, 26].

EM was measured using four items evaluating clarity, relevance, and usefulness of promotional emails from the hotel. The items were adapted from hospitality DM research [27–29].

SEM was measured using three items reflecting ease of locating hotel information through search engines and prominence of search results. The scale was adapted from studies examining digital visibility and online search behavior in hospitality contexts [28, 30, 31].

WQ was measured using three items capturing completeness, clarity, and usability of information provided on the hotel's official website. The items were adapted from WQ measures in tourism research [30, 31, 34].

DAds was measured using three items assessing visibility, clarity, and professional consistency of paid online advertisements. The scale draws on prior research on digital advertising effectiveness in service industries [27, 31].

CM was measured using three items evaluating the informational value and decision-support function of hotel-generated digital content. The scale was adapted from digital content strategy research in tourism and hospitality [27, 28].

The seven first-order constructs were treated as reflective because their indicators represent manifestations of specific channel perceptions. The higher-order DM construct was specified as formative because the seven dimensions jointly represent the overall scope of DM activities, and removing one dimension would alter the conceptual meaning of the construct.

Table 1
Sample characteristics

Profile	Category	Frequency	Percentage
Gender	Male	250	51.12
	Female	239	48.88
Age	20–31	49	10.02
	32–45	213	43.56
	45–60	184	37.63
	Above 60	43	8.79
Nationality	Taiwan	110	22.49
	Spain	65	13.29
	United Kingdom	63	12.88
	United States	62	12.68
	South Korea	50	10.22
	France	41	8.38
	Greece	37	7.57
	Italy	24	4.91
	Australia	15	3.07
	Canada	13	2.66
	China	9	1.84
Trip purpose	Leisure	156	31.9
	Business/ work	151	30.88
	Event/ conference	145	29.65
	Other	37	7.57
Total		489	100.00

Source: compiled by the authors.

BR was operationalized as a reflective construct measured with three items capturing overall evaluative judgment regarding the hotel's credibility, recognition, and comparative standing. The scale was adapted from prior studies examining BR and service evaluation in hospitality contexts [35–37].

LHC was measured using three items reflecting intention to select, prefer, and recommend the hotel. The scale was adapted from prior tourism and hospitality research where behavioral intention

Table 2
Constructs and measurement definitions

Construct	Measurement form	Number of items	Definition in this study	Primary sources
DM	Second-order formative	7 dimensions	Overall coordinated deployment of digital communication channels	Conceptualized based on integrated DM literature
eWOM	Reflective	3	Perceived influence of user-generated reviews across social media and OTAs	[19, 23, 24]
SMM	Reflective	4	Perceived effectiveness of hotel social media communication	[23, 25, 26]
EM	Reflective	4	Perceived usefulness and relevance of hotel email communication	[27–29]
SEM	Reflective	3	Perceived ease and prominence of finding hotel information via search engines	[28, 30, 31]
WQ	Reflective	3	Perceived clarity and completeness of official website information	[30, 31, 34]
DAds	Reflective	3	Perceived visibility and professional presentation of paid online advertisements	[27, 31]
CM	Reflective	3	Perceived informational value of hotel-generated digital content	[27, 28]
BR	Reflective	3	Overall evaluative judgment of credibility and standing relative to competitors	[35–37]
LHC	Reflective	3	Intention to select, prefer, and recommend the hotel	[38–40]

Source: compiled by the authors.

is used as a proxy for choice in high-involvement service settings [38–40].

All items were slightly reworded to ensure contextual clarity while preserving their original conceptual meaning. Detailed item wording is available from the authors upon reasonable request. The constructs and their operational definitions are summarized in *Table 2.*

3.3. Data analysis procedure

The model was estimated using PLS-SEM with SmartPL S. This approach is appropriate due to the presence of a higher-order formative construct and the study's predictive orientation [32].

The analysis followed a two-step procedure, as recommended in PLS-SEM research [32]. First, the measurement models were evaluated. For reflective constructs, internal consistency reliability, convergent validity, and discriminant validity were assessed. For the formative higher-order construct, collinearity among dimensions and the significance of outer weights were examined.

To model the higher-order formative construct of DM, the disjoint two-stage (embedding) approach was employed. In the first stage, latent variable scores of the lower-order reflective dimensions were estimated. In the second stage, these latent scores were used as manifest indicators to form the higher-order formative construct. This approach is suitable for formative and conceptually distinct higher-order constructs because it reduces potential bias associated with the re-

Table 3
Reliability and convergent validity

Construct	Item	Outer Loading	Cronbach's Alpha	Composite Reliability	AVE
eWOM	eWOM1	0.792	0.732	0.848	0.651
	eWOM2	0.809			
	eWOM3	0.819			
SMM	SMM1	0.746	0.795	0.866	0.619
	SMM2	0.741			
	SMM3	0.830			
	SMM4	0.825			
EM	EM1	0.711	0.730	0.829	0.548
	EM2	0.762			
	EM3	0.712			
	EM4	0.774			
SEM	SEM1	0.845	0.769	0.867	0.684
	SEM2	0.857			
	SEM3	0.777			
WQ	WQ1	0.780	0.700	0.833	0.625
	WQ2	0.828			
	WQ3	0.763			
DAds	DAds1	0.829	0.721	0.843	0.642
	DAds2	0.767			
	DAds3	0.808			
CM	CM1	0.792	0.702	0.832	0.623
	CM2	0.754			
	CM3	0.820			
BR	BR1	0.778	0.712	0.839	0.635
	BR2	0.813			
	BR3	0.799			
LHC	LHC1	0.805	0.715	0.840	0.636
	LHC2	0.813			
	LHC3	0.775			

Source: Compiled by the authors using SmartPLS 4.

peated indicators approach and supports more stable parameter estimation.

Second, the structural model was assessed. Path coefficients were estimated using bootstrapping with 5,000 resamples to obtain robust standard errors and confidence intervals. Explanatory power was evaluated using coefficients of determination, and effect sizes were examined to assess practical relevance.

The mediating role of BR was tested by analyzing the indirect effect of DM on LHC. The type of mediation was determined based on the statistical significance and magnitude of direct and indirect effects, following established mediation assessment procedures in PLS-SEM [32].

4. Results

4.1. Measurement model assessment

The measurement model was evaluated prior to hypothesis testing. Reliability and convergent validity of reflective constructs were assessed using outer loadings, Cronbach's alpha, composite reliability, and average variance extracted. The results are presented in *Table 3*.

All outer loadings exceeded the recommended threshold of 0.70, ranging from 0.711 to 0.857. This indicates satisfactory indicator reliability. Cronbach's alpha values ranged from 0.700 to 0.795, meeting the minimum requirement of 0.70. Composite reliability values ranged from 0.829 to 0.867, exceeding the threshold of 0.70 and confirming strong internal consistency.

All average variance extracted values were above 0.50. The lowest AVE was observed for EM at 0.548, which still satisfies the criterion for convergent validity. These results confirm that the reflective constructs demonstrate adequate reliability and convergent validity.

Discriminant validity was assessed using the Heterotrait-Monotrait ratio criterion. The results are presented in *Table 4*.

All HTMT values were below the conservative threshold of 0.85. The highest value was 0.810 between CM and EM, which remains within acceptable limits. These results confirm that all constructs are empirically distinct.

The higher-order construct of DM was specified as a formative second-order construct composed of seven reflective dimensions. The formative measurement assessment is reported in *Table 5*.

Variance inflation factor values ranged from 1.291 to 2.018, indicating no multicollinearity concerns. All outer weights were positive and statistically significant at $p < 0.001$. SEM exhibited the strongest contribution to DM, followed by SMM and eWOM. WQ showed the lowest but still significant contribution.

Overall, the measurement model satisfies reliability, convergent validity, discriminant validity, and formative assessment requirements.

4.2. Structural model and hypothesis testing

The structural model was assessed using bootstrapped path coefficients, effect sizes (f^2), and explanatory power (R^2). The results are reported in *Table 6*.

Table 4
Discriminant validity assessment using HTMT criterion

Construct	CM	DAds	EM	SEM	SMM	WQ	eWOM
DAds	0.655						
EM	0.810	0.554					
SEM	0.578	0.277	0.523				
SMM	0.688	0.340	0.628	0.294			
WQ	0.687	0.581	0.720	0.521	0.637		
eWOM	0.520	0.479	0.527	0.347	0.340	0.505	

Source: Compiled by the authors using SmartPLS 4.

Table 5
Formative weights of second-order digital marketing construct

Path	Weight	Mean	Std. Deviation	*t*-value	*p*-value	VIF
CM → DM	0.181	0.181	0.026	6.966	0.000	2.018
DAds → DM	0.200	0.199	0.023	8.594	0.000	1.423
EM → DM	0.204	0.204	0.024	8.649	0.000	1.904
eWOM → DM	0.220	0.219	0.024	9.253	0.000	1.332
SEM → DM	0.279	0.277	0.024	11.735	0.000	1.585
SMM → DM	0.256	0.256	0.025	10.288	0.000	1.715
WQ → DM	0.122	0.123	0.027	4.494	0.000	1.291

Source: Compiled by the authors using SmartPLS 4.

Table 6
Structural model assessment

<table>
<tr><td></td><td colspan="6">Panel A. Hypothesis testing (bootstrapping)</td></tr>
<tr><td>Hypothesis</td><td>Path</td><td>β (O)</td><td>95% CI (2.5%, 97.5%)</td><td>t-value</td><td>p-value</td><td>Decision</td></tr>
<tr><td>H_1</td><td>DM → LHC</td><td>0.780</td><td>[0.713, 0.840]</td><td>23.846</td><td>< 0.001</td><td>Supported</td></tr>
<tr><td>H_2</td><td>DM → BR</td><td>0.849</td><td>[0.824, 0.866]</td><td>80.414</td><td>< 0.001</td><td>Supported</td></tr>
<tr><td>H_3</td><td>BR → LHC</td><td>0.161</td><td>[0.096, 0.231]</td><td>4.576</td><td>< 0.001</td><td>Supported</td></tr>
<tr><td colspan="7">Panel B. Effect sizes (f^2)</td></tr>
<tr><td colspan="3">Predictor → Endogenous construct</td><td>f^2 (O)</td><td>t-value</td><td>p-value</td><td>Effect magnitude</td></tr>
<tr><td colspan="3">BR → LHC</td><td>0.047</td><td>2.378</td><td>0.017</td><td>Small</td></tr>
<tr><td colspan="3">DM → BR</td><td>2.581</td><td>10.865</td><td>< 0.001</td><td>Large</td></tr>
<tr><td colspan="3">DM → LHC</td><td>1.116</td><td>7.092</td><td>< 0.001</td><td>Large</td></tr>
<tr><td colspan="7">Panel C. Explanatory power (R^2 and adjusted R^2)</td></tr>
<tr><td>Endogenous construct</td><td>R^2 (O)</td><td>t-value</td><td>p-value</td><td>Adjusted R^2 (O)</td><td>t-value</td><td>p-value</td></tr>
<tr><td>BR</td><td>0.721</td><td>40.161</td><td>< 0.001</td><td>0.720</td><td>40.047</td><td>< 0.001</td></tr>
<tr><td>LHC</td><td>0.848</td><td>75.123</td><td>< 0.001</td><td>0.847</td><td>74.760</td><td>< 0.001</td></tr>
</table>

Source: Compiled by the authors using SmartPLS 4.

Note: β = path coefficient (original sample). CI = bias-corrected 95% confidence interval. Effect size interpretation follows conventional thresholds (0.02 small, 0.15 medium, 0.35 large).

Table 7
Mediation analysis

Panel A. Specific indirect effect						
Hypothesis	**Effect**	**Path**	**β (O)**	**95% CI (2.5%, 97.5%)**	**t-value**	**p-value**
H_4	Indirect	DM → BR → LHC	0.137	[0.072, 0.191]	4.522	< 0.001
Panel B. Total effects						
		Path	**β (O)**	**95% CI (2.5%, 97.5%)**	**t-value**	**p-value**
		BR → LHC	0.161	[0.085, 0.223]	4.576	< 0.001
		DM → BR	0.849	[0.829, 0.871]	80.414	< 0.001
		DM → LHC	0.917	[0.904, 0.929]	140.685	< 0.001

Source: Compiled by the authors using SmartPLS 4.

DM has a strong and positive effect on LHC ($\beta = 0.780$, $t = 23.846$, $p < 0.001$). Therefore, H_1 is supported.

DM also exerts a substantial positive effect on BR ($\beta = 0.849$, $t = 80.414$, $p < 0.001$), supporting H_2.

BR positively influences LHC ($\beta = 0.161$, $t = 4.576$, $p < 0.001$), supporting H_3.

The effect size of DM on BR is very large ($f^2 = 2.581$). The effect size of DM on LHC is also large ($f^2 = 1.116$). The effect of BR on LHC is small to moderate ($f^2 = 0.047$).

The coefficient of determination indicates substantial explanatory power. DM explains 72.1 percent of the variance in BR ($R^2 = 0.721$). DM and BR jointly explain 84.8 percent of the variance in LHC ($R^2 = 0.848$).

4.3. Mediation analysis

The mediation results are presented in *Table 7*.

The indirect effect of DM on LHC through BR is positive and statistically significant ($\beta = 0.137$, $t = 4.522$, $p < 0.001$).

The total effect of DM on LHC is 0.917. The direct effect is 0.780, and the indirect effect is 0.137.

The variance accounted for was calculated as follows:

$$VAF = \frac{Indirect\ effect}{Total\ effect} = \frac{\beta_{DM\ \ BR} \times \beta_{BR\ \ LHC}}{\beta_{DM\ \ LHC}} = \frac{0.137}{0.917} = 0.149,$$

where the indirect effect represents the effect of DM on LHC through BR, calculated as the product of the path coefficients from DM to BR and from BR to LHC, and the total effect represents the sum of the direct and indirect effects of DM on LHC.

Thus, approximately 14.9 percent of the total effect of DM on LHC is mediated by BR.

Since the VAF value is below 20 percent, the mediation effect is partial with a predominantly direct influence. Therefore, H_4 is supported, although the indirect pathway represents a limited proportion of the total effect.

5. Discussion

The results indicate that integrated DM emerges as the primary explanatory factor of both BR and LHC among international tourists in an emerging market context. DM exhibits a strong direct effect on LHC and an even stronger effect on BR, while BR provides a statistically significant but modest mediating pathway. The model's substantial explanatory power suggests that, in digitally mediated international travel markets, coordinated digital signals serve as a central basis for pre-consumption evaluation and choice [2, 3, 11].

The strong DM-BR relationship is consistent with signaling logic under information asymmetry. In luxury hospitality, service quality remains largely unverifiable prior to consumption, and international tourists often face limited familiarity with local brands in emerging destinations. Under these conditions, observable digital cues operate as credible signals that shape judgments of professionalism, reliability, and expected service standards [7, 9, 11]. This inference process also aligns with environmental stimulus theory, which posits that structured external stimuli shape internal cognitive and affective evaluations that subsequently guide approach behavior. Accordingly, integrated DM can be interpreted as a structured stimulus system that strengthens evaluative beliefs about the hotel brand before selection occurs [8, 22].

The findings are consistent with evidence that digital ecosystems increasingly shape tourism evaluation and booking behavior through platform-based information flows. Digital touchpoints across the traveler journey, including brand-managed channels and intermediated platforms, influence evaluation and intention formation [1, 14]. In emerging or transitional economies, international tourists rely more heavily on these environments due to higher perceived risk and lower prior brand familiarity, which amplifies the influence of digital cues on choice [7, 8, 10].

A central contribution of this study lies in its higher-order conceptualization of DM. DM is modeled as a second-order formative construct comprising eWOM, SMM, SEM, WQ, DAds, EM, and CM. This operationalization reflects the coordinated manner in which luxury hotels deploy digital tools in practice, rather than treating them as independent tactics [17, 18]. Prior research has noted that fragmented, single-tool approaches may underestimate cumulative and reinforcing effects across channels [2, 3]. By capturing the joint contribution of multiple channels, the present model demonstrates that the aggregated digital system materially shapes both reputational beliefs and intention-based choice [2, 3].

The magnitude of the direct effect of DM on LHC suggests that digital influence operates not only through reputational abstraction but also through immediate functional and cognitive decision mechanisms. Search engine visibility reduces search frictions and increases consideration probability in competitive environments [13]. WQ supports clarity, usability, and decision efficiency [12, 14], but its lower formative weight should not be interpreted as dispensability. For luxury hotels, the website remains a minimum digital requirement that confirms brand legitimacy, aesthetic standards, and service consistency, while additional resources can be prioritized toward higher-contribution channels. Conversion-oriented optimization mechanisms in tourism digital environments further support this logic by showing how interface design and information structure influence consumer actions [41]. Social media content and interaction strengthen evaluative confidence and experiential imagination in luxury contexts [5, 21]. eWOM, including reviews embedded in OTA environments such as Booking.com-type OTA interfaces, provides peer validation and diagnostic experience cues that can trigger choice without requiring fully consolidated reputation judgments [1, 4, 19].

This pattern aligns with emerging evidence that contemporary travelers increasingly depend on real-time digital information, multimodal cues, and platform signals when comparing hotel alternatives. Visual representation and online imagery can shape perceived quality and desirability, particularly in luxury segments where symbolic value is salient [20, 42]. Influencer-style video and vlogger content can also operate as experiential proxies that shape expectations and strengthen intention prior to purchase [6]. Taken together, these mechanisms indicate that digital channels influence both evaluation depth and decision speed in high-involvement booking contexts [10, 11].

Although BR positively influences LHC, the mediation results indicate that its indirect contribution is limited relative to the direct pathway. The variance accounted for is approximately 14.9 percent, indicating low-level partial mediation. This proportion implies that while DM strengthens reputational beliefs, the majority of its total effect on LHC is transmitted directly rather than through the mediating construct [9, 22]. Accordingly, the structural results suggest a stronger direct pathway relative to the indirect pathway, rather than a dominance of mediation. This result refines the common assumption that marketing effects in luxury services primarily transmit through reputational constructs, and it highlights the operational potency of digital performance in choice formation [2, 8].

Theoretical implications follow from the relative weight of direct and indirect effects. Under signaling theory, reputational beliefs represent one channel through which cues influence behavior, but digitally intensive environments create additional pathways through which information architecture and platform design directly shape intention and action [9, 41]. Under environmental stimulus theory, digital channels can generate immediate cognitive and affective responses that translate into approach behavior even before stable global evaluations fully form [7, 22]. Accordingly, DM in emerging destinations should be viewed as both a signaling system and a functional decision infrastructure [10, 11], while the present findings reflect established digital channels rather than emergent AI-enabled interactions.

From a contextual perspective, the results extend understanding of tourism decision processes in emerging economies. The empirical evidence is drawn from Hue City, an emerging Vietnamese destination, and therefore reflects the institutional and market dynamics of this specific setting. Vietnam represents a rapidly digitalizing tourism environment in which OTAs and review platforms function as primary informational gateways for international tourists. The integration of eWOM into booking platforms effectively embeds peer evaluation into the purchase process, amplifying the immediacy of digital influence on choice [1, 4]. While similar digitalization patterns are observable in other major Vietnamese destinations, the present findings should be interpreted within the contextual boundaries of the study site. This context helps explain why operational digital excellence exerts a substantially stronger direct effect compared with the indirect reputational pathway, while BR provides complementary explanatory power rather than acting as a substantive mediator [2, 11].

Managerially, the findings yield several implications for luxury hotels in emerging destinations. DM should be managed as a coordinated strategic system rather than as isolated instruments [3, 18]. In managerial terms, luxury hotels should first secure a baseline digital infrastructure, including a credible website, consistent brand presentation, and active monitoring of OTAs and review platforms, because these elements support legitimacy and reduce decision friction [1, 4, 12, 17, 19]. Beyond this baseline, additional resources should be prioritized toward higher-contribution channels that strengthen visibility, comparison efficiency, and experiential confidence, particularly search-related tools, social media interaction, and eWOM [5, 13, 21]. Promotional communications such as email and content initiatives should therefore complement, rather than replace, performance-critical channels that directly affect search and evaluation efficiency [15, 16].

Finally, the modest mediation effect implies that reputation-building initiatives alone may not maximize booking performance in emerging markets. While BR remains a meaningful evaluative driver, operational digital performance appears to exert more immediate influence on LHC among international tourists [2, 11]. Strategic resource allocation should therefore balance long-term brand positioning with continuous optimization of visibility, responsiveness, and information quality across key decision interfaces [1, 3].

In summary, the findings show that integrated DM functions as a central mechanism shaping both BR and LHC within the context of an emerging Vietnamese destination. The structural results indicate that the direct pathway from DM to choice is stronger than the indirect pathway through BR, while BR provides additional but limited mediation. This evidence clarifies the relative roles of signaling-based reputation formation and direct digital decision infrastructure in high-involvement tourism choices under information asymmetry [9, 11, 22].

6. Conclusions

This study investigated the influence of DM on LHC among international tourists within the context of an emerging Vietnamese destination, with BR specified as a partial mediator. DM was conceptualized as a second-order formative construct composed of seven reflective dimensions, reflecting the coordinated deployment of digital channels in contemporary luxury hospitality. The empirical results demonstrate that DM exerts a strong direct effect on LHC and an even stronger effect on BR. BR positively influences LHC; however, mediation analysis indicates that the indirect pathway accounts for a relatively small proportion of the total effect. The variance accounted for by approximately 14.9 percent confirms a low-level partial mediation structure in which the direct pathway from DM to LHC is stronger than the indirect pathway through BR. These findings suggest that, in this emerging tourism setting, DM primarily shapes behavioral intention through direct informational and decision-support mechanisms, while BR provides complementary explanatory value.

The study contributes to the literature in several respects. First, it advances hospitality marketing research by modeling DM as an integrated higher-order construct rather than examining isolated tools. This approach more accurately reflects how luxury hotels compete in digitally intensive environments. Second, it refines theoretical understanding by integrating signaling theory and environmental stimulus theory to explain how digital cues influence both evaluative judgments and behavioral intentions. Third, by focusing on an emerging Vietnamese destination as the empirical setting, the study provides context-specific evidence on how international tourists rely on digital information under conditions of heightened information asymmetry and limited prior familiarity.

The findings also offer important managerial implications. Luxury hotels targeting international markets in comparable emerging destinations should manage DM as a coordinated strategic system. Managers should first establish a baseline digital infrastructure, including credible websites, consistent brand presentation, and active management of eWOM across OTAs and review platforms, before prioritizing additional resources toward higher-impact digital channels that enhance visibility, comparison efficiency, and experiential confidence. Although BR remains significant, the results indicate that operational digital performance exerts a substantially stronger direct effect relative to the indirect reputational pathway. Managers should therefore allocate resources to both long-term reputation building and continuous optimization of digital touchpoints that directly shape purchase intention.

The study is subject to several limitations. First, the empirical evidence was derived from a single-city setting and should therefore be interpreted within the contextual boundaries of Hue rather than generalized to the broader luxury hotel market. Second, although the findings identify key digital mechanisms influencing choice, the study does not determine optimal resource-allocation thresholds or minimum design standards across digital channels. Third, the model focuses on established DM practices and does not incorporate emerging AI-enabled interactions that increasingly shape digital customer journeys. Future research may address these limitations by employing longitudinal or experimental designs, conducting multi-site comparisons across emerging and developed destinations, and incorporating behavioral booking data and additional psychological constructs such as perceived risk, trust, and perceived value to improve explanatory depth and external validity.

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Green Airports: How to Combine Eco-Engineering Solutions, Social Responsibility and Economic Benefits

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ABSTRACT

Aviation produces at least 5% of global carbon and pollutant emissions. The green, sustainable, eco-friendly and silent airport concepts' implementation makes it possible to strengthen the aviation's contribution to the sustainable development agenda. **The aim** of the study is to systematize technically feasible engineering solutions for a complex object of air transport infrastructure, which lead to an increase in the project cost of construction or reconstruction, but at the same time reduce air pollution, noise, wastewater, waste, electricity and water, taking into account prolonged social and economic effects. **Methods**: a) drawing up a heat map of the appropriate solutions for airport facilities (terminal, airfield, airfield area, and hangar); b) selection and critical evaluation of engineering solutions to reduce emissions in the terminal and airfield design and construction with a forecast of economic benefits. **Findings** of the study reveal the confirmation of the advantages of implementing eco-engineering solutions for a green airport, including eco-design and data management, monitoring and forecasting energy consumption, water supply, technical parameters of airport operations to ensure flights and passenger safety in conditions of increased flight intensity, performed in the form of a critical assessment of the effects, and show the ranges as reducing the carbon footprint, as well as savings on future operating costs with objective financial constraints in the airport construction or reconstruction. **Conclusion.** The future savings effect provides an economic incentive, in addition to following responsible behavior, to build new carbon-neutral airports, combining concern for the environment, aviation safety, passenger comfort and the well-being of local residents.

Keywords: green airport; innovation; project management; construction economics; sustainability management; effectiveness; airport terminal engineering; social responsibility; transport safety; eco-design

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ОРИГИНАЛЬНАЯ СТАТЬЯ

«Зеленые» аэропорты: как совместить эко-инженерные решения, социальную ответственность и экономическую выгоду

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АННОТАЦИЯ

Авиаотрасль производит не менее 5% всех мировых выбросов углерода и загрязняющих веществ в атмосферу. Реализация концепций «зеленого», устойчивого, эко- и тихого аэропорта позволяет усилить вклад авиаотрасли в повестку устойчивого развития. **Целью исследования** является систематизация технически возможных к реализации инженерных решений сложного объекта авиатранспортной инфраструктуры, которые ведут к увеличению стоимости проектов строительства или реконструкции, но при этом обеспечивают снижение загрязнения воздуха, шума, сточных вод, отходов, потребления электричества и воды, с учетом пролонгированных общественного и экономического эффектов. Исследование выполнено с использованием **методов:** а) составления тепловой карты для определения целесообразности и реализуемости инженерных решений для объектов аэропорта (терминал, аэродром, приаэродромная территория, ангар); б) отбора и критической оценки инженерных решений по снижению выбросов как при проектировании и строительстве терминалов, так и на аэродромной территории с прогнозом экономической выгоды. **Результаты исследования** включают определение преимуществ реализации эко-инженерных решений для «зеленого» аэропорта, включая экодизайн и управление данными, контроль и прогнозирование энергопотребления, водоснабжения, технических параметров деятельности аэропорта для обеспечения полетов и безопасности пассажиров в условиях повышения интенсивности авиарейсов, выполненное в форме критической оценки эффектов, и показывают диапазоны как снижения углеродного следа, так и экономии на эксплуатационных расходах в будущем при объективных финансовых ограничениях в строительстве или реконструкции аэропортов. **Вывод:** эффект будущей экономии дает экономический стимул, помимо следования ответственному устойчивому поведению, строить новые углеродно-нейтральные аэропорты, объединяя заботу об окружающей среде, безопасность авиации, комфорт пассажиров и благополучие местных жителей.

Ключевые слова: «зеленый» аэропорт; инновации; управление проектами; экономика строительства; управление устойчивым развитием; эффективность; проектирование терминала аэропорта; социальная ответственность; транспортная безопасность; экодизайн

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Introduction

The aircraft industry and air transportation represent a combination of progressive, innovative technologies, with a history spanning over a century that includes the creation of civil airliners and combat aircraft, showcasing remarkable technological achievements and the development of reliable equipment that provides people with freedom and speed of movement. These industries have become leading for the economies of countries where the largest aircraft companies are located, as well as international airports and transport hubs of global importance, each of which has a passenger traffic of 50 to 100 million people per year. All this contributes to the development of the aircraft industry, transport, and the economy as a whole and to GDP growth; enhances the image of countries as logistics and tourism centers; and can act as a tool of soft power in political matters [1].

At the same time, airplanes are not an environmentally friendly mode of transport. Moreover, aircraft engines in the sky emit tons of carbon dioxide, water vapor and other pollutants from the combustion of aviation fuel and solids from engines. The design of large airliners provides for the possibility of dumping fuel in emergency situations to avoid disasters. Thus, about 50% of emissions are carbon oxides, 46% nitrogen oxides, 3% hydrocarbons and volatile organic compounds, and about 1% solid emissions. These are the factors accelerating global warming.

At the same time, airports represent territories and facilities on earth with very unfavorable ecology [2], and terminals and airfield infrastructure facilities generate CO_2 and NOx emissions of at least 5% of all air transport emissions and consume huge amounts of electricity, which are comparable to the energy consumption of a small city [3], and are sources of waste. In addition to air pollution, airports are a source of increased mechanical and aerodynamic noise and vibrations, which is another significant factor affecting human health [4].

Airport compliance with sustainability principles has become a particularly acute problem in the post-pandemic period [5]. During the harsh reality of the COVID-19 pandemic, civil aviation returned to its 1999 levels, flights around the world were suspended, and passenger flights decreased significantly by 60% on average worldwide [6]. The environmental situation around airports improved, leading to a nearly 50% reduction in carbon emissions and pollutants released into the atmosphere in 2020. But as the pandemic receded and air travel gradually recovered, airports' sustainable development, which contributes to an increased carbon footprint in the atmosphere, began to rise significantly again [7]. And the issue of reducing emissions from aviation transport is becoming more important than ever due to the movement of countries and industries toward carbon neutrality.

Modern airports are not only multi-transport hubs, but they have also become mini-cities today

[8], including shopping, hotel and business complexes, industrial zones and logistics centers that consume huge amounts of electricity that increase with digitalization [9]. Airports typically reside in the suburbs, yet they maintain a connection to the vibrant rhythm of life in cities and megacities. Therefore, there should be not only a certain integration with urban planning and construction policy but also the inclusion of airports in the city's green building [10]. In this case, the airport's design or reconstruction becomes not just a new project but the implementation of an integrated systematic approach to the sustainable development of territories with the priority of an ecological element.

The implementation of the environmental aspect of sustainable development [11] has led to the formation of the green airport concept [12] as an engineering and architectural facility that reduces the negative impact on the environment in the fields of air pollution, waste production, electricity and water consumption, and noise reduction.

The positions of experts on green airports are quite interesting in their desire to combine concern for the environment, aviation safety and the well-being of users, i.e. passengers of airliners and residents in the vicinity of the airport. Thus, social justice is formed. Objectively, noise and physical restrictions lead to lower housing prices near the airport [13].

That is why it is so important to identify a green airport as an object with certified architecture. This is facilitated by the development of international and national green building certifications [14] that exist in different countries of the world and encourage the use of eco-friendly and renewable energy sources. It is important to see the relationship between urban planning, when the city is focused on green building construction, and the functioning of airports as green facilities with a high degree of environmental friendliness and minimal possible impact on nature and society.

The emergence of the sustainable airports identification [15] should be considered innovative since the recognition of the importance of sustainable development objectives is carried out in relation to facilities that are important for different spheres of society — architecture, economics, transport, science and technology, healthcare, etc. A modern sustainable airport is a large area with buildings that are managed responsibly and efficiently and do not harm the environment and people, preserving natural resources — this is what determines the airport's effectiveness [16].

In this regard, the study would be incomplete without stating that the aviation industry itself is focused on eco-friendliness. Major aircraft manufacturing companies are developing new types of aircraft engines in an effort to reduce carbon dioxide emissions in the atmosphere and generally reduce the amount of aviation fuel burned. Their efforts are also focused on the use of environmentally friendly aviation fuels (both synthetic fuels and biofuels) — sustainable aviation fuel (SAF) — in order to achieve the industry's zero emissions target by 2050 [17]. SAF is able to reduce carbon emissions into the atmosphere by up to 65% and is already present in 31 countries (mainly in Europe and South America, where government support for the aviation industry is significant). More than 100 manufacturers produce such fuel in the amount of 51 million tons. This fuel is a good contribution to improving the eco-friendliness and sustainable development in aviation and a technical and economic solution, since no changes are required to the aircraft refueling infrastructure.

In their identification, green airports emphasize an important connection with the support of nature and the use of alternative energy sources — the term "eco-airport" is also used to strengthen this position [18]. In addition to the environmental and technological components in its architecture and engineering communications, an eco-airport must also be economically optimal and comply with socio-cultural values and social responsibility [19].

According to expert estimates by the Airports Council International (ACI WORLD) and the International Civil Aviation Organization (ICAO),[1] passenger traffic has recovered by the beginning of 2025 and is now above the pre-pandemic level and will double to 19.5 billion people by 2042. It is predicted that the Asia-Pacific region (especially India, China, Indonesia) will become the fastest-growing market due to the development of air travel and the construction of a new air infrastructure. Therefore, the concept of a smart airport [20] as safe for passengers has become popular now [21].

Despite the significantly similar concepts of a green, sustainable, eco-friendly, smart and silent airport, this study will use the green airport defini-

[1] ACA — Airport Carbon Accreditation: Joint ACI WORLD-ICAO passenger traffic report, trends, and outlook. URL: https://aci.aero/2025/01/28/joint-aci-world-icao-passenger-traffic-report-trends-and-outlook (accessed on 28.06.2025).

tion as an airport that is designed, built and operated using environmentally sustainable practices aimed at minimizing negative environmental impacts through reducing greenhouse gas emissions, efficient use of resources, waste management and conservation of biodiversity for the people's well-being and benefit.

Objectively, geopolitical conflicts are becoming very noticeable and affect the organization of flights and deliveries of airliners, but forecasts of global passenger traffic growth, the success of environmentally friendly aircraft manufacturers, and increasing their profitability are becoming a driver of airport upgrades, such as new terminals and airfield areas being built and existing airports being upgraded to create new business models [22]. There is also a tendency to build multimodal transport centers, where the airport will be one of the facilities providing transfers [23]. An increase in the number of airports should be a green trend [24] and projects with excellent profit [25], because an increase in the number of flights and the number of passengers should not lead to an increase in the negative effect on nature.

Technologies that ensure energy conservation and energy efficiency for carbon-neutral airports, water and waste management, and the use of alternative energy sources are so important that everything related to aviation not only brings reliability, mobility, and speed but is also associated with a green contribution to the development of society.

Therefore, the aim of the study is to systematize technically feasible engineering solutions for a green airport, which is a complex component of sustainable air transport infrastructure. This approach may increase the project cost of construction and reconstruction while simultaneously reducing air pollution, wastewater, waste, electricity and water consumption, and noise, all while considering prolonged social and economic effects.

Materials and methods

The analysis of regulatory requirements, standards and the current state in the airport sector in different countries of the world was carried out on the basis of open data on official Internet sites from Airports Council International (ACI WORLD), Airports Council International Europe (ACI EUROPE), ACI Asia-Pacific & Middle East (ACI APAC and MID), Airport Carbon Accreditation (ACA), CAPA Centre for Aviation, International Civil Aviation Organization (ICAO) and the special program Carbon Offset and Reduction Scheme for International Aviation (CORSIA). This approach makes it possible to significantly increase the validity and reliability of the conducted research.

The study is based on reliable open data — there are 52,128 airports of various structures, large and small, public and private, in the world at the beginning of 2025. The largest number of airports is in the USA — 15,873. This is followed by 4,919 in Brazil, 2,180 in Australia, 1,485 in Mexico, 1,425 in Canada, 1,043 in the UK, 904 in Russia, 838 in Germany, 756 in Argentina, 689 in France.[2] In 2025, 2,181 airports in 170 countries were registered in ACI WORLD. Airports are typically certified in the quality management system based on the international standard ISO 14001:2015, which creates genuine opportunities to mitigate environmental harm, lower the risks of emergencies in airport buildings and other transport infrastructure facilities, and address environmental issues, including minimizing the extent of their consequences.

International airport certification, precisely from the perspective of achieving sustainable development goals and implementing a systematic and sound integrated approach, is most developed in Europe, where the Airport Carbon Accreditation (ACA) has been operating since 2009 based on the initiative of ACI WORLD. Since 2014, after the International Civil Aviation Organization (ICAO) joined this initiative, ACA has become a global program for the active management of carbon emissions at airports based on targets on 5 continents of the world. It is important that the program be based on an independent review by experts from 36 countries, which provides an opportunity to see both best practices (for example, modernization of lighting, water supply, heating, ventilation and air conditioning systems) and challenges in the implementation of sustainable airport development. The ASA classifies airports according to seven certification levels: Mapping, Reduction, Optimization, Neutrality, Transformation, Transition and Net Zero. There are 645 ACA-accredited airports in 97 countries worldwide[3]; 286 in Europe,

[2] Airports by Country 2025. URL: https://worldpopulationreview.com/country-rankings/airports-by-country (accessed on 28.06.2025).

[3] ACA — Airport Carbon Accreditation: Accredited Airports across the world. URL: https://www.airportcarbonaccreditation.org/accredited-airports (accessed on 28.06.2025).

and 21 airports located in India, Finland, Portugal, Sweden, and the Netherlands have the highest level of Level 5.

The "Eco-friendly Airport" electronic collection developed by the International Civil Aviation Organization (ICAO)[4] is important as a methodological basis for airport infrastructure development. These are not only environmental planning and design tools, but also specific recommendations for investors in the construction of sustainable buildings in order to not only make a profit but also create value and confirm responsible decisions.

Financing for the modernization of airports to the minimum optimal level of an eco-airport is carried out within the framework of the Voluntary Airport Lower Emissions (VALE) subsidy program, which improves air quality for ozone and carbon monoxide mainly through the purchase of ground vehicles for passenger service and liners with low levels of greenhouse gas emissions and noise.

The above-mentioned materials, methods and standards are the basis for the systematization of eco-engineering solutions that are used in the context of this study to identify technologies for the construction or modernization of green airports. The information data for recording was obtained based on the analysis of reports on sustainable development and environmental impact of ACA-certified green airports.

The study was carried out using the method of critical assessment and systematization of approaches to the implementation of projects to reduce environmental impact both in the design and engineering solutions of terminals and in the organization of ground operations in the airfield area with a forecast of the range of effects achieved in terms of reducing emissions and waste. At the same time, the criterion for selecting engineering solutions that are systematized by the heat map method is the economic criterion (range of reduction of future operating costs) — initially, the cost of building a new airport or its reconstruction or modernization is a capital expenditure. But it will be compensated in the future by saving on current expenses, which is confirmed by the use of cost-benefit analysis (CBA) and life cycle assessment (LCA). This approach allowed us to identify the prolonged effect over time as an investment and the value for eco-protection as a global public and local social effect.

[4] ICAO. Eco-Airport Toolkit e-collection. URL: https://www.icao.int/environmental-protection/Pages/Ecoairports.aspx (accessed on 28.06.2025).

Results

The conceptual framework of eco-protection engineering solutions for a green airport

The modern airport construction is not only always an original project with a striking architectural design, but also a technically complex project, conditionally lengthy and requiring significant investments. It is also a project that assumes compliance with green trends in modern conditions — and at least certification according to green standards gives a significant competitive advantage and a positive public image. Therefore, this study is aimed at systematizing approaches to the implementation of eco-protective engineering solutions in order to build or reconstruct airport buildings and territories in the green airport format, based on data from annual reports of certified green airports in different countries of the world and the ACA database (*Table 1*).

The importance of implementing eco-engineering solutions, however, raises the question of their expediency and application to various architectural and construction projects related to the airport. The heat map is a useful tool for presenting the types of these solutions for a green airport (*Table 2*) during new construction or reconstruction, which will be meaningfully disclosed later in the results of the study.

Architectural solutions

Passive design architectural solutions are used for green airports, which allow for achieving energy efficiency objectives. These solutions include creating indoor spaces with maximum natural light, using natural ventilation and thermal insulation. In practice, it is possible to achieve several goals: energy efficiency, first of all, but also the creation of an open-space atmosphere and the involvement of travelers in the life of air transport. So, a project with energy-efficient glazing on building facades will provide maximum thermal insulation and, therefore, reduce operating costs later.

In existing green airports, it has already become an architectural rule to create green areas in terminals and on terminal roofs to improve air quality and water flow management. It's beautiful in design, eco-friendly, and energy-efficient.

Table 1
ACA-certified green airports

Airport	Country	Level of Accreditation	Renewable energy (%)	Passenger traffic (million people per year)	Reduction of CO_2 (thousand tons per year)	Solar panels (MW)	Recycling of waste (%)	Water saving (%)
Stockholm-Arlanda Airport	Sweden	Net Zero (5)	95	19.8	380	15	88	50
Amsterdam Schiphol	Netherlands	Net Zero (5)	70	71.7	680	25	87	40
Helsinki Airport	Finland	Net Zero (5)	85	20.8	290	10	85	52
London Gatwick	United Kingdom	Transition (4+)	60	40.9	410	18	83	48
Chhatrapati Shivaji Maharaj (Mumbai International Airport)	India	Transition (4+)	100	43.9	300	40	85	60
San Francisco International	USA	Transformation (4)	65	57.0	520	8.5	92	45
Oslo Airport	Norway	Optimization (3)	90	28.5	450	12	90	55
Munich Airport	Germany	Optimization (3)	75	47.9	470	22	89	55
Singapore Changi	Singapore	Optimization (3)	55	68.3	550	35	91	65

Source: Compiled by the authors based on the data: ACA. Airport Carbon Accreditation Annual Reports. 2023–2024. URL: https://www.airportcarbonaccreditation.org/media/annual-reports (accessed on 09.10.2025); Chhatrapati Shivaji Maharaj Airport paves the way for a sustainable future. International Airport Review, 18.03.2021. URL: https://www.internationalairportreview.com/news/154935/chhatrapati-shivaji-maharaj-airport-sustainable-future (accessed on 09.10.2025); Avinor's Annual and Sustainability Report 2024. URL: https://om.avinor.no/siteassets/barekraft/avinor_ars — og-barekraftsrapport_2024.pdf (accessed on 09.10.2025); Swedavia. Annual and Sustainability Report 2022. URL: https://www.swedavia.com/about-swedavia/sustainability/ (accessed on 09.10.2025); San Francisco International Airport. Reports and Documents. URL: https://sustainability.flysfo.com/reports (accessed on 09.10.2025); Amsterdam Schiphol Airport. Sustaining Your World. URL: https://www.schiphol.nl/en/sustainability/road-to-the-most-sustainable-airports (accessed on 09.10.2025); FinAvia. Air quality and emissions. Helsinki Airport is carbon neutral. URL: https://www.finavia.fi/en/about-finavia/sustainability/sustainable-air-traffic/air-quality-and-emissions (accessed on 09.10.2025); Finavian vuosikertomus 2024. URL: https://www.finavia.fi/fi/tietoa-finaviasta/taloustiedot/vuosikertomukset/2024?navref=paragraph (accessed on 09.10.2025); London Gatwick Airport. Net Zero Roadmap. Towards Net Zero (Scope 1 & 2) Emissions 2030. May 2024. URL: https://www.aci-europe.org/downloads/content/London%20Gatwick%20-%20Net%20Zero%20Roadmap.pdf (accessed on 09.10.2025); Munich Airport. Environmental Statement 2023. URL: https://www.munich-airport.com/_b/0000000000000029038172bb673df76a/environmental-statement-2023-en1.pdf (accessed on 09.10.2025); Munich Airport. Our path to a CO2-free future. URL: https://www.munich-airport.com/net-zero-19071587 (accessed on 09.10.2025); Changi Airport Group. A Sustainable Changi — connecting and conserving our world. URL: https://www.changiairport.com/en/corporate/our-sustainability-efforts/environment.html (accessed on 09.10.2025).

In the projects of new airports, it is possible to implement ideas for organizing the airport terminal area as open spaces for passengers to move. This engineering creates the potential for optimal lighting (up to automatic on/off by motion sensors) but also allows optimization of the heating and ventilation systems by organizing the flow of passengers.

The airport area design for a green airport (although this should be considered more for a sustainable airport) should be carried out with the organization of platforms for public transport — buses and express trains. Despite the fact that modern airports are located in the suburbs, the organization of communication with the city (or even the metropolis) is an important part of the work

Table 2

Heat map of the application of eco-protection engineering solutions for various facilities of the green airport

Intensity of solution's application	Terminal	Airfield	Airfield territory	Ground facilities	Hangars and maintenance bases for aircraft and equipment
Architectural solutions					
Eco-friendly materials					
Energy consumption					
Water supply					
Wastewater treatment					
Waste management					
Noise reduction					

Designations:

mandatory application; recommended application; conditional application

of space designers. Passengers need to be offered eco-friendly transportation options, unlike their own cars or taxis, and public transport effectively solves this problem (especially if it is, for example, electric buses or high-speed railway express trains). At the same time, an interesting alternative solution should be to organize convenient parking spaces, for example, for electric or hybrid cars. This psychological approach, combined with an architectural solution, creates the right background and supports initiatives by citizens and travelers to use environmentally friendly vehicles. Using such organizational solutions significantly reduces the environmental impact.

The use of eco-friendly materials

The choice of eco-friendly materials and materials that require minimal maintenance (this is important for airport staff) plays a crucial role in airport terminal design, as it significantly reduces the carbon footprint from airport construction and further operation. Architects prefer materials with low energy consumption (as a rule, recycled materials). It is very important to follow a strategy of using local materials in order to support local manufacturers and take into account the traditions of the country or region of the air harbor location in the design.

A separate solution should be considered: the use of eco-friendly asphalt to cover the runway (for example, concrete with the addition of volcanic ash) — this is an innovative approach but requires very significant financing. This solution cannot be considered affordable for most airports. More comprehensive expertise is also required to ensure technical safety. But technologies are developing, and in the near future, eco-friendly materials will not only be universal for building construction but also for creating complex technical infrastructure facilities, increasing their technical properties and environmental friendliness.

Ensuring low energy consumption

The airport requires a large amount of energy to operate, which is used for lighting areas, ventilation and air conditioning systems, maintaining security, and many other tasks. Such high energy consumption can lead to significant costs and a negative impact on the environment. This scenario means that it is necessary to design an electrical system with a sufficiently high level of energy efficiency and energy conservation.

At the same time, a large amount of the necessary energy for airport operations must be produced by energy sources — therefore, to comply with eco protection, it is crucial to use alternative energy sources such as solar energy (photovoltaic panels), wind energy (wind turbines), hydropower and even thermal water energy. Depending on the geographical location of the airport, certain renewable energy sources may be available. From an economic point of view, such initiatives can bring a reduction in operating costs for electricity consumption. But it is also necessary to take into account the possibilities of bio-design or eco-design in modern green airports. This is not only original and aesthetically pleasing and attracts passengers temporarily staying in the terminal while waiting for a flight but also creates an eco-image of sustainability and environmental responsibility.

The terminal uses different lighting systems. Also, a huge number of energy consumption sources are located on the runway, at the airfield and in the airfield area. The various electrical and light signaling systems, radio receivers, lighting and technical support ensure the technical operation of the airport and flight safety; therefore, it must receive additional backup internal autonomous power supply to two external power sources. The sources of internal power supply can be both alternative energy sources and traditional backup diesel power plants. In the context of this study, alternative energy is a priority, but it is necessary to take into account the uninterrupted functioning of the airport's lighting and alarm systems, especially on the runway, which is provided by a traditional energy source.

An automatic control system is appropriate and economically beneficial for the airport's energy consumption as part of achieving sustainable development goals. This system includes a set of technologies and algorithms that optimize energy use and reduce costs. Automatic energy management systems can monitor and adjust the operation of lighting installations, control heating and air conditioning systems, passenger flow control systems, and monitor the energy efficiency of various systems and equipment.

Given the importance of managing operating costs, as well as taking into account the impact of power equipment and appliances on carbon emissions into the environment, such a function as flexible control of energy flows allows one to control the operation of all electrical devices in real time to reduce energy consumption based on the data analysis and enable energy-saving modes as needed, depending on the daytime, weather conditions, the presence of people on the premises, changes in flight density or changes in passenger traffic, and schedule changes.

It is especially important to note the use of microprocessor controllers, sensors and sensors for monitoring temperature, illumination and other parameters in the power supply system (lighting, air conditioning and supply and exhaust ventilation, operation of escalators, travelators and automatic doors) in various areas of the airport (waiting area, workrooms, etc.) and airfield territory, allowing you to make the airport not only green but also progressive in terms of applied technologies. At the same time, the comfort of the working conditions of the airport staff and airline representatives and the safety of passengers and crew members of airliners should not be violated in any way. A special area of responsibility is the provision of power supply to the dispatch service and the technical complex for take-off and landing of aircraft in order to prevent emergency situations.

Special attention is paid to the system of technical flight support systems at the airport. The energy supply of video surveillance systems, radars, communication and navigation systems and security systems, including biometric control and inspection areas, is a field of work that requires competent optimization. As a rule, high-tech and expensive equipment and devices are used here, which must work smoothly and ensure safety for people. Therefore, backup energy supply should be organized in parallel with alternative energy sources, however, savings in operating costs do not matter here, as opposed to the importance of eco-friendliness of energy consumption solutions.

The development of modern technologies, in particular artificial intelligence, should also find application in complementing the functionality of an automatic energy consumption system for a green airport. For example, algorithms and artificial intelligence process historical data on energy consumption, weather conditions, passenger traffic, and the number of flights, make forecasts, and optimize control of lighting, heating, air conditioning, and ventilation to adapt (minimize) energy consumption during peak periods. This is one of the main functions for a green airport — to reduce energy consumption without prejudice to its activities as a complex technical complex for passenger and airplane services, which means it will increase energy efficiency.

Water supply organization

The airport utilizes its water resources in a continuous water supply system for various tasks: a) water for household and technical needs, including maintenance in the terminal, aircraft maintenance and runway irrigation; b) drinking water; c) water for firefighting, the volume of which must be at least 5,000 m^3.

When planning the terminal building, it is necessary to provide for blocking the water supply in emergency situations based on the organization of water supply in the airport terminal areas, as well as to provide for the organization of reuse of water resources. For example, through connection to the ring water supply system of the fire extinguishing system or reuse of water for toilets in the organization of dual water supply. These responsible engineering solutions can help reduce the use of water resources.

To save energy, hot water supply may not be used or used in limited quantities only at large airports when providing services to passengers and for the needs of companies providing catering services at the airport.

An interesting solution to provide passengers with drinking water and, at the same time, an environmentally friendly solution is the organization of drinking fountains at the airport — this reduces the consumption of water in plastic packaging.

Water supply at the airport is usually characterized by constant volumes; therefore, individual eco-engineering solutions are able to contribute to the concept of a green airport, forming sources for eco-responsible behavior of airport owners.

Wastewater treatment

The airport, using water resources, is a source of wastewater generation — as a rule, due to the use of water for technical purposes all year round when stormwater runoff is formed and the formation of toxic wastewater in winter when deicing treatment of airplanes is carried out. After accumulating pollutants on airplanes during its operation, the wastewater then contains large amounts of petroleum products, various chemicals that are difficult to clean, and metal dust.

Based on the structure of the effluents, their purification systems should be provided:

- standard cleaning for storm drains;
- multi-stage wastewater treatment in winter and spring from snowmelt;
- special cleaning for industrial effluents from deicing liquid for aircraft and reagents for the runway in the cold season.

Sewage treatment plants are designed together with the construction of the main terminal or are planned during the reconstruction of the airport — this ensures systematic activities to reduce the impact of airport wastewater pollutants. It is also necessary to provide a cleaning system and a special algorithm for actions in case of accidental spills of aviation fuel at the airport, since a very high concentration of petroleum products is formed here and rapid actions are required to prevent damage to the environment.

Waste management

In the airport construction or reconstruction project, it is absolutely necessary to provide a waste management system, from waste collection to recycling. Of course, the aspects of waste management are most pronounced during the departing and arriving aircraft flights, but this system should be designed before the airport opens in the form of special facilities for sorting, composting and recycling waste — because it is cheaper and, above all, more rational for the realization of environmental responsibility to society.

One of the modern solutions at airports can be considered — the introduction of a strategy of a "paperless" system for selling tickets and boarding passes for passage to the screening areas and further clean areas of the airport and for boarding. This solution is primarily based on the use of digital technologies and contributes to the competitiveness and convenience of most passengers, but it is in the context of a green airport that this solution, as well as the use of biodegradable dishes for passenger meals, can contribute to the creation of a certain model of responsible behavior for aviation customers.

Noise reduction

Noise from airplanes seriously affects the health and well-being of people living in the vicinity of the airport. No matter how positive the emotions of being able to make fast and comfortable flights are, an airplane is not only a source of emissions into the atmosphere but also a source of noise and acoustic discomfort. This phenomenon is especially true with the growth of passenger traffic and the increase in the number of flights during the day and at night. Just like the vehicles that ply the airfield and transport passengers, baggage, or technicians, they have the same sources of negative impact.

Airports make audio announcements, which creates background white noise and increases stress and strain on the hearing aids of passengers and airport staff. To reduce the negative effect, some airports are abandoning sound announcements — these are the so-called silent airports. Unfortunately, this strategy may result in higher energy consumption due to the increased number of information monitors required for passenger convenience.

Automated electric buses and transport cars have already begun to be used at modern airports, and robots are also being used to check the condition of engineering communications and facilities and the condition of the runway. They are eco-friendly and silent, which creates a new solution to enhance the airport's environmental friendliness.

Special noise-canceling materials and fences should be used for residential areas to protect and soundproof and improve the quality of life of people near airports.

While it's not an engineering solution, a very stimulating approach can be applied in collaboration with airlines to mitigate noise pollution from airplanes. These are payments when the number of flights increases, which can be used to reduce noise and improve the acoustic environment around the airport, including for the construction and maintenance of a landscape park.

Discussion

Green airports are becoming a new reality in order not only to provide flights and organize passengers but also to make their own significant contribution to sustainable development when the aviation industry strives to reduce hydrocarbon emissions to zero by 2050 and implements the trend towards eco-friendliness.

Since its inception, aircraft companies have been and continue to be representatives of the industry of innovation and the development of modern technologies that make it possible to technologically improve aircraft and increase their fuel efficiency. This progress enables airports, as representatives of the aviation industry, to also strive to introduce new technologies that allow them to provide services to passengers and airlines in a new capacity, with an emphasis on using alternative energy sources, reducing environmental impact and reducing emissions into the atmosphere and land, and reducing noise exposure.

A fair and objective limitation for the active dissemination of the green airport concept is the significant amount of investment required for the organization of the design of various architectural and engineering solutions, as well as the purchase of necessary equipment, devices and materials and the execution of construction work.

The use of cost-benefit analysis (CBA) in a conditionally typical green airport project, taking into account the ACA and ICAO[5] requirements and the forecast passenger traffic of 5 million people per year, shows: a) average capital expenditures on eco-engineering solutions are \$35–\$45 million (including solar panel installation, \$15–\$20 million; LED lighting and automation \$6–\$8 million, rainwater harvesting system \$3–\$5 million, waste management system \$2–\$3 million, LEED certification \$0.5–\$1 million); b) benefits per year as savings of \$5–\$8 million (electricity \$3–\$5 million, water supply \$0.5 million, waste \$0.5 million). Thus, the average payback period for eco-engineering solutions for a small green airport will be 9–10 years. For airports with passenger traffic of 50 million people per year and above, the CBA will be complicated by a large number of indicators to evaluate and a longer payback period — however, this circumstance expands the possibilities for green airports.

The recognition of the benefits of implementing eco-engineering solutions for a green airport, carried out in the form of an assessment of the effects (*Table 3*) and with the additional life cycle assessment (LCA) results to assess the environmental impact at all stages from construction to operation of the large green airports from *Table 1* and ACA Level 1 airports,[6] shows both a reduction in the carbon footprint and the possibility of saving on operating costs in the future. This provides an economic incentive, in addition to following responsible sustainable behavior, to build new green airports or reconstruct/modernize existing facilities.

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[5] ICAO. Eco-Airport Toolkit e-collection. URL: https://www.icao.int/environmental-protection/Pages/Ecoairports.aspx (accessed on 28.06.2025).

[6] ACA — Airport Carbon Accreditation. Accredited Airports across the world. URL: https://www.airportcarbonaccreditation.org/accredited-airports/

Table 3

Forecast effects for different eco-protection of airport engineering solutions

Solution characteristics	Range of carbon footprint reduction, %	Range of reduction in energy or fuel consumption, %	Range of reduction in emissions of pollutants into the atmosphere or wastewater or waste, %	Range of savings on operating costs in the future, %
Architectural solutions				
Passive design of the airport building / energy-efficient eco-design	5÷20	5÷15	2÷10	10÷20
Indoor spaces with natural light / Open spaces	2÷4	3÷10	1÷2	3÷8
Integration with public transport platforms	8÷20	5÷12	4÷8	3÷5
Using eco-friendly/recycled materials	5÷20	5÷15	2÷10	10÷20
Landscaping, creation of green areas (walls) and green roofs in terminals	6÷15	1÷2	3÷7	x
Ensuring energy consumption				
Alternative energy sources	3÷20	x	3÷10	5÷15
Power supply of electrical and light signaling systems, electrical receivers for flight lighting (three sources)	2÷3	2÷5	x	1÷3
Implementation of an automated energy management system based on consumption data analysis and flexible control	5÷8	x	x	x
LED lighting and motion sensors	1÷2	3÷5	x	3÷5
Using microprocessor controllers, sensors, and sensors to monitor temperature, light, and other parameters	1÷2	3÷5	x	3÷5
Using artificial intelligence to predict energy consumption and situational optimization of lighting, heating, air conditioning, ventilation control	2÷5	x	x	2÷5
Water supply organization				
Ring water supply system	2÷5	3÷5	3÷15	5÷14
Blocking the water supply in emergency situations	1÷2	x	x	x
Restriction of hot water supply	3÷8	3÷8	3÷5	5÷10
Drinking fountains for passengers	x	x	x	1÷2
Rainwater collection system	2÷5	x	3÷5	3÷6
Wastewater treatment:				
Multi-stage wastewater treatment from snowmelt	3÷5	x	5÷20	x
Special cleaning of industrial effluents from deicing liquid for aircraft and runway reagents in the cold season	3÷15	x	5÷20	x
Cleaning system and special algorithm of actions in case of accidental spills of aviation fuel	3÷10	x	3÷10	x
Waste management				
Waste recycling	3÷8	x	3÷10	2÷3
Biodegradable tableware (reducing or banning the use of plastic)	3÷8	x	30÷50	3÷10
Paperless sale of tickets and boarding passes	3÷8	3÷5	20÷50	5÷15
Noise reduction				
The “quiet airport” concept	8÷15	x	x	x
Sound insulation structures	3÷10	x	5÷8	x
Silent electric transport and work	5÷20	3÷8	5÷20	2÷4
Landscape Park	5÷15	x	x	x

Source: Compiled by the authors.

The effects were assessed based on an analysis of the actual engineering solutions of green airports in the ACA, ICAO,[7] IATA[8] and ACI[9] certification systems: 1) lower limit of the range fixed as the average among Level 1 airports located in Central Europe to exclude the factor of significant influence of climatic conditions, 2) upper limit of the range fixed as the average among Level 5 airports, including Stockholm-Arlanda Airport, Amsterdam Schiphol, Helsinki Airport (*Table 1*). Calculations of carbon footprint reduction ranges are performed in the ICAO Carbon Emissions Calculator,[10] which allows us to obtain reasonable estimates if we strictly follow the guidelines. The range of future savings on operating costs has been determined by experts.

The study reveals that less than 25% of ACA-registered airports possess green certification or are actively pursuing carbon reduction. This is explained both by financial budget constraints in countries with different socio-economic situations for the airport's construction or reconstruction and by access to modern eco-technologies and equipment to implement eco-engineering solutions for a green or sustainable airport.

Practice shows that each airport is a unique complex structure that takes into account the features of the terrain, the surrounding area, and connections with the nearest urban agglomerations. In order to build an airport, in addition to financing, highly qualified specialists in engineering and technology are required, which are concentrated in developed countries, and it takes time to learn and gain experience in order to implement the green airport concepts in developing countries. There are also certain difficulties with the introduction of new technologies so that they do not violate safety and flight management regulations, as well as airfield area logistics. The population sometimes disapproves of the construction of new airports due to concerns about their livelihoods. Therefore, it is important to work with the public, and the commitment to build a green airport is an important step towards compromise.

Given the difficulties of the airport construction or reconstruction process itself, it should also be noted that carbon management procedures need to be developed, including assessment, monitoring, reporting and planning to reduce the airport's carbon footprint. In fact, in addition to the construction or reconstruction plan, a strategy for the sustainable development of such a green airport should be developed in order to systematically identify key parameters for the development of eco-friendliness and the phased reduction of carbon footprint, taking into account the contribution of each architectural and construction facility of the airport and the functioning processes of all airport services. This approach will allow for step-by-step implementation of tasks in order, for example, to consistently achieve the appropriate ACA certification level.

In general, the integration of aircraft companies and airlines in terms of enhancing corporate social responsibility will be enhanced by interaction with green-certified airports, creating an image of aviation as technologically progressive and socially responsible.

Conclusion

A green airport is an important response to the modern world with the development of technology and with unprecedented speeds and capabilities. Historically, aviation has given a lot to society — airplanes, transport mobility, travel, etc. But aviation has also significantly affected the state of the atmosphere and the environment, which is why the goal of striving for carbon neutrality by 2050 has been adopted. Upgrading aircraft engines and using environmentally friendly jet fuel alone cannot fully achieve this goal. Therefore, airports as objects of air transport infrastructure have become an important part of the realization of this goal. The use of eco-friendly engineering solutions at airports can reduce harmful emissions by 50%.

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[7] ICAO Environmental Report 2025. URL: https://www.icao.int/sites/default/files/environmental-protection/Documents/EnvironmentalReports/2025/ICAO-EnvReport-2025.pdf (accessed on 09.10.2025); ICAO Doc 9829, Guidance on the Balanced Approach to Aircraft Noise Management. URL: https://www.icao.int/environmental-protection/aircraft-noise (accessed on 09.10.2025).

[8] IATA CO2 Connect. Connecting primary data from airlines to CO2 emissions calculations. URL: https://www.iata.org/en/services/data/environment-sustainability/co2-connect (accessed on 09.10.2025).

[9] ACI. ESG Global Reporting Framework and Guidance for Airports. URL: https://store.aci.aero/product/esg-global-reporting-framework-and-guidance-for-airports (accessed on 09.10.2025); ACI. 2024 Airport Key Performance Indicators. URL: https://store.aci.aero/product/2024-airport-key-performance-indicators (accessed on 09.10.2025).

[10] ICAO Carbon Emissions Calculator (ICEC). URL: https://www.icao.int/environmental-protection/environmental-tools/icec (accessed on 09.10.2025).

This study showed that in order to build or reconstruct a green airport, it is necessary to carry out a complex of work on the ergonomic eco-design, the introduction of energy consumption and water management methods, and the use of eco-friendly and alternative energy sources, as well as the use of modern information systems for data management, monitoring and forecasting the technical parameters of airport operations as a complex technical support system, passengers' safety, equipment and the surrounding area. All these decisions are based on major investments, but the effect should be to reduce the impact on the environment and foster beneficial climate change while at the same time ensuring social justice and responsible recognition of financial benefits to society for the sake of eco-friendliness.

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Cryptocurrencies as Volatility Shock Hedges: A Regime-Dependent Fuzzy Copula Analysis of Crypto, Oil, and Equity Markets

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ABSTRACT

In the context of increasing integration across global financial markets, understanding the dynamic relationships between energy, digital assets, and equity markets is crucial for effective portfolio management and risk mitigation. **Purpose:** This study examines the potential hedging benefits of cryptocurrencies against volatility shocks by analyzing nonlinear and regime-dependent co-movements among crude oil, Bitcoin, and equity markets. **Method:** The research utilizes a fuzzy copula framework that incorporates Gaussian, Student-t, Clayton, and Gumbel copulas to capture asymmetric and tail-dependent dependence structures. Fuzzy-weighted dependence measures are employed to evaluate dynamic linkages across low-, medium-, and high-volatility regimes, facilitating smooth regime transitions and localized dependence analysis. **Results:** The findings indicate a weak average dependence under normal market conditions, suggesting limited hedging effectiveness of cryptocurrencies. However, statistically significant upper-tail dependence is observed during periods of heightened volatility, indicating a deterioration in diversification benefits under market stress. **Contributions:** The study provides insights for investors, portfolio managers, and policymakers by highlighting the regime-contingent hedging role of cryptocurrencies. The results emphasize the importance of nonlinear and regime-sensitive models in portfolio allocation, risk management, and financial stability assessment.

Keywords: Copula-GARCH; fuzzy logic; co-movement; Bitcoin; oil market; Nifty 50; volatility shocks; regime-switching

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ОРИГИНАЛЬНАЯ СТАТЬЯ

Криптовалюты как средство хеджирования от шоков волатильности: анализ крипторынков, нефтяных рынков и рынков акций с использованием нечеткой копулы

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АННОТАЦИЯ

В условиях растущей интеграции глобальных финансовых рынков понимание динамичных взаимосвязей между энергетическими рынками, рынками цифровых активов и фондовыми рынками имеет решающее значение для эффективного управления портфелем ценных бумаг и снижения рисков. **Цель:** в данном исследовании рассматриваются потенциальные преимущества криптовалют для хеджирования шоков волатильности путем анализа нелинейных и зависящих от режима взаимосвязей между рынками сырой нефти, биткоина и акций. **Метод:** в исследовании используется структура нечеткой копулы, которая включает копулы Гаусса, Стьюдента, Клейтона и Гумбеля для учета асимметричных структур и распределений, зависящих от хвоста. Для оценки динамических связей в условиях низкой, средней и высокой волатильности используются взвешенные по нечетким параметрам меры зависимости, что облегчает плавные переходы

между режимами и локальный анализ зависимости. **Результаты:** результаты показывают слабую среднюю зависимость при нормальных рыночных условиях, что свидетельствует об ограниченной эффективности криптовалют в хеджировании. Однако в периоды повышенной волатильности наблюдается статистически значимая зависимость в верхнем хвосте распределения, указывающая на ухудшение преимуществ диверсификации в условиях рыночного стресса. **Научный вклад:** исследование предоставляет ценную информацию для инвесторов, управляющих портфелями и политиков, подчеркивая роль криптовалют в хеджировании в зависимости от режима. Результаты подчеркивают важность нелинейных и чувствительных к режиму моделей в распределении портфеля, управлении рисками и оценке финансовой стабильности.
Ключевые слова: GARCH-копула; нечеткая логика; совместное движение; биткойн; нефтяной рынок; Nifty 50; шоки волатильности; переключение режимов

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1. Introduction

In an increasingly interconnected global financial system, analyzing the co-movements among crude oil, cryptocurrencies, and stock markets has become essential for understanding cross-asset dynamics and risk propagation [1, 2]. Crude oil continues to serve as a vital determinant of macroeconomic activity, while cryptocurrencies — particularly Bitcoin — represent a decentralized and volatile asset class with growing financialization and institutional adoption. Stock markets, on the other hand, reflect investor sentiment and broader economic performance. Understanding the interdependencies among these heterogeneous assets is crucial for risk diversification, hedging strategies, and policy formulation in the face of shocks such as pandemics, geopolitical conflicts, and energy transitions [3, 4].

From the perspective of emerging economies such as India, this study assumes even greater significance. India's position as one of the world's largest energy importers makes its stock market (Nifty 50 index — the benchmark in the Indian Stock Market.) highly sensitive to global crude oil price movements. Fluctuations in oil prices directly influence inflation expectations, current account balances, and sectoral profitability, especially in energy-intensive industries. Simultaneously, the rapid growth of cryptocurrency adoption in India [5], amid evolving regulatory frameworks, has created a new channel for speculative and cross-border capital flows. These interactions underscore how global energy price volatility and digital asset fluctuations can transmit shocks into the Indian financial system, affecting both domestic market stability and global portfolio diversification patterns. The investigation of co-movement among crude oil, Bitcoin, and Nifty returns therefore provides crucial insights into how India's market dynamics are shaped by global financial forces [6, 7] and, conversely, how emerging market behavior contributes to broader patterns of global financial interconnectedness and systemic risk transmission.

Recent studies have highlighted complex and time-varying connectedness across financial, commodity, and crypto markets, with significant evidence of spillover effects during turbulent periods. For instance, a study by [3] found strong risk spillover between Bitcoin, crude oil, and equity markets during crisis, while [8] revealed energy-stock co-movements amplified by pandemic-induced uncertainty. Similarly, [9] documented the causal link between Bitcoin and energy commodities, emphasizing the intertwined nature of digital and physical energy markets. [10] further demonstrated that cryptocurrencies, oil, gold, and US stocks exhibit quantile-dependent volatility interdependencies, suggesting asymmetric responses across different market states. These findings indicate that the direction and strength of co-movement vary over time and depend on prevailing market conditions, such as bullish or bearish regimes [11, 12].

Moreover, [13] underscored the mediating role of oil prices in shaping the relationship between cryptocurrencies and other non-fungible assets, suggesting that crude oil continues to influence the valuation and correlation of emerging digital markets. Similarly, [14] incorporated investor sentiment data from Google Trends to uncover hidden spillovers across financial, crypto, and commodity markets, revealing that sentiment-driven linkages intensify during episodes of global uncertainty. Collectively, these studies confirm that asset interdependencies are nonlinear, asymmetric, and regime-sensitive, underscoring the need for more flexible dependence modeling frameworks.

Traditional approaches — such as linear correlation or GARCH (Generalized Autoregressive Conditional Heteroskedasticity)-based volatility models [4, 15, 16] — are limited in capturing such nonlinear and tail-specific relationships. While correlation coefficients quantify only average dependence, they fail to detect extreme co-movements that occur during market stress. In this context, the copula approach has gained prominence as a robust tool to model joint distributions and dependence structures independently of marginal behaviors [6, 15].

The copula framework has emerged as a robust statistical approach for modeling the dependence structure among multivariate financial variables, as it allows the joint distribution of returns to be decomposed into marginal distributions and a copula function that captures their dependence structure [17]. Copulas enable researchers to identify distinct types of dependencies — such as symmetric, asymmetric, or tail-specific linkages — providing a deeper understanding of how financial assets co-move under normal and extreme market conditions. They are particularly useful in quantifying risk measures such as Value-at-Risk (VaR) and Expected Shortfall, where the choice of copula significantly influences portfolio loss predictions and stress scenario assessments. The copula approach thus provides a flexible tool to simulate extreme events and evaluate portfolio risks beyond the linear correlations typically captured by classical econometric models.

Copula models have been widely applied to understand changing dependence structures in commodity and financial markets. Copula-based models such as Gaussian, Clayton, and Gumbel copulas [18, 19] allow researchers to identify tail dependence, i.e., the likelihood of simultaneous extreme returns across markets, which is critical for risk management and contagion analysis [20].

However, standard copula models treat market states as discrete and static, whereas financial systems are inherently dynamic and uncertain, often exhibiting fuzzy transitions between low, medium, and high volatility phases [21]. The practical application of traditional copulas often encounters possibilistic uncertainty — arising from limited historical data, imprecise parameter estimation, and ambiguity in predicting future market movements. This limitation motivates the use of the fuzzy copula framework, which blends fuzzy logic with traditional copula theory to capture dependence structures that evolve continuously across overlapping market states [22]. By assigning membership weights to different volatility regimes, fuzzy copulas provide a granular view of dependence intensity, accommodating ambiguous boundaries that better reflect real-world market behavior [23, 24]. This innovative approach extends beyond crisp regime classification to reveal localized co-movements and asymmetric linkages that conventional models may overlook.

A study [25] employed a copula-based multivariate GARCH framework to assess the dynamic conditional dependence among various commodity futures markets — including energy, metals, grains, and agricultural commodities — over different market regimes. Their results showed that the dependence structure evolves over time, reflecting regime shifts and market transitions influenced by financialization and investor sentiment. Moreover, they utilized the fuzzy c-means clustering method to classify these market states, highlighting the inherent uncertainty and gradual transitions between volatility regimes rather than abrupt structural breaks.

Recent studies, such as [24], have proposed fuzzy clustering of time series using copula-based lower tail dependence coefficients to identify flexible classification structures in global equity indices. By combining fuzzy entropy regularization with copula dependence measures, such models effectively capture ambiguous, overlapping states of co-movement — a more realistic representation of financial behavior where assets rarely shift between risk regimes in a discrete manner. The fuzzy copula approach therefore enhances traditional dependence modeling by accommodating partial memberships, gradual transitions, and asymmetric tail behaviors within multivariate systems.

Accordingly, the present study introduces a fuzzy copula-based framework to analyze the co-movements among crude oil, Bitcoin, and the Indian stock market (Nifty 50) over the period January 2021 to October 2025. By integrating fuzzy-weighted dependence measures with Gaussian, t, Clayton, and Gumbel copula families, this study aims to uncover nonlinear, tail-dependent, and regime-specific relationships among these asset classes. The findings are expected to offer new insights into portfolio diversification, market integration, and systemic risk under varying market conditions — contributing to the growing literature on cross-asset contagion in the era of digital finance and energy transition.

2. Material and methods

This study investigates the co-movement and dependence structure among crude oil, Bitcoin, and the Indian stock market (Nifty 50) over the period January 2021 to October 2025. Daily closing prices of all three assets were collected, and logarithmic returns were computed as:

$$r_t = \ln\left(\frac{P_t}{P_{t-1}}\right), \tag{1}$$

where P_t and P_{t-1} represent the price at time t and $t-1$, respectively.

2.1. Preliminary analysis

A preliminary analysis was performed to explore the characteristics of each return series. Descriptive statistics, trend plots, and year-wise box plots were used to visualize dispersion, skewness, and outlier behavior. Stationarity was verified through Autocorrelation Function (ACF) and Partial Autocorrelation Function (PACF) plots along with Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests. The preliminary evidence confirmed that all three-return series were stationary, satisfying the prerequisite for copula-based dependence modeling.

2.2. Copula modeling framework

To model the joint dependence structure, the study applied Copula theory, which allows the joint distribution of random variables to be expressed in terms of their marginal distributions and a dependence function. According to [26], for continuous random variables $X_1, X_2, \dots, X_n$ with joint distribution $F(x_1, x_2, \dots, x_n)$ and marginal distributions $F_1(x_1), F_2(x_2), \dots, F_n(x_n)$, there exists a copula C such that:

$$F(x_1, x_2, \dots, x_n) = C\left(F_1(x_1), F_2(x_2), \dots, F_n(x_n)\right), \tag{2}$$

where $C:[0,1]^n \to [0,1]$ captures the dependence structure between variables independent of their marginal distributions.

The joint density function can be expressed as:

$$f(x_1, x_2, \dots, x_n) = c(u_1, u_2, \dots, u_n)\prod_{i=1}^{n} f_i(x_i), \tag{3}$$

where $u_i = F_i(x_i)$, and $c(u_1, \dots, u_n)$ is the copula density function.

Four copula families were applied:

- Gaussian Copula — models' symmetric dependence:

$$C_{Gauss}(u, v; \rho) = \Phi_\rho\left(\Phi^{-1}(u), \Phi^{-1}(v)\right), \tag{4}$$

- t-Copula — accounts for symmetric tail dependence:

$$C_t(u, v; \rho, \nu) = t_{\rho,\nu}\left(t_\nu^{-1}(u), t_\nu^{-1}(v)\right), \tag{5}$$

- Clayton Copula — captures lower-tail dependence:

$$C_{Clayton}(u, v; \theta) = \left[\max\left(u^{-\theta} + v^{-\theta} - 1, 0\right)\right]^{-\frac{1}{\theta}}, \theta > 0, \tag{6}$$

- Gumbel Copula — represents upper-tail dependence:

$$C_{Gumbel}(u, v; \theta) = \exp\left\{-[(-\ln u)^\theta + (-\ln v)^\theta]^{\frac{1}{\theta}}\right\}, \theta \geq 1. \tag{7}$$

Dependence parameters (ρ, θ, ν) were estimated via maximum likelihood estimation (MLE).

2.3. Fuzzy copula framework

While copulas effectively capture nonlinear and tail dependencies, they assume a crisp separation of market regimes. In reality, financial markets transition gradually between states such as low, medium, and high volatility. To address this, the study employed a fuzzy copula framework, integrating fuzzy logic into copula modeling to represent imprecise or overlapping dependence structures.

Each data point is assigned a membership degree $\mu_i(x) \in [0,1]$, representing the extent to which it belongs to a volatility regime i. The fuzzy-weighted copula dependence between two variables X and Y can be represented as:

$$\rho_{Fuzzy} = \frac{\sum_i \mu_i(X)\mu_i(Y)\rho_i}{\sum_i \mu_i(X)\mu_i(Y)}, \tag{8}$$

where ρ_i is the dependence coefficient (e.g., Spearman's ρ or Kendall's τ) within regime i. To measure the divergence between fuzzy and empirical distributions, Kullback–Leibler (KL) divergence was employed:

$$D_{KL}(P \| Q) = \sum_i P_i \ln\left(\frac{P_i}{Q_i}\right). \tag{9}$$

This allows the model to quantify uncertainty in parameter estimation due to limited data or incomplete knowledge of future price behavior. The Fuzzy Copula–GMM (generalized method of moments) framework was used to estimate dependence parameters under uncertain conditions.

2.4. Computational implementation

All analyses were implemented using both Python and R environments. Python libraries — *pandas*, *numpy*, *scipy*, *matplotlib*, *seaborn*, and *openpyxl* — were used for data handling, visualization, and dependence estimation. The R environment (version 4.3) with packages *curl*, *urca*, *tidyverse*, *ggplot2*, *gridExtra*, and *PerformanceAnalytics* facilitated unit root testing, descriptive statistics, and graphical validation.

3. Data analysis and results

3.1. Primary analysis

Figures 1 to 3 provides the trend of Nifty, crude oil, and Bitcoin (BTC) returns during the period from January 2021 to October 2025. The analysis reveals that all three series experienced heightened volatility during 2021–2022, coinciding with the global post-pandemic recovery and geopolitical disruptions. Nifty exhibited moderate fluctuations with an overall upward trajectory, indicating steady market normalization and improving investor confidence through 2023–2025. In contrast, crude oil showed pronounced volatility in 2021–2022 due to supply chain shocks and geopolitical tensions, followed by a period of cyclical stabilization after 2023. Bitcoin, meanwhile, displayed the highest variability among the three, reflecting speculative trading behavior and sensitivity to global regulatory changes. However, its volatility gradually subsided after 2023, signaling a maturing digital asset market. Further, Nifty demonstrated consistent stability, crude oil followed a cyclical pattern tied to external shocks, and Bitcoin underwent a sharp transition from extreme volatility toward relative steadiness. This convergence toward stability across all three markets in recent years suggests improved market integration, reduced uncertainty, and evolving investor behavior across traditional and digital assets.

Table 1 presents the summary statistics of all return series — Nifty, crude oil, and Bitcoin — exhibit near-zero means, indicating the absence of systematic upward or downward trends in their daily returns. Among them, Bitcoin displays the widest range (–0.2593 to 0.1918), reflecting its high volatility and speculative nature compared with traditional assets. Crude oil returns also show large fluctuations, particularly between the first and third quartiles, capturing global price shocks. In contrast, Nifty returns are relatively stable with a narrower dispersion, consistent with its diversified market base.

The Jarque–Bera test results reject normality for all three series ($p < 0.001$), confirming the presence of fat tails and non-Gaussian behavior typical of financial returns. The ARCH LM tests are significant for Nifty and crude oil, and marginally significant for Bitcoin, indicating volatility clustering — periods of alternating high and low volatility over time.

The Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) tests both confirm that all return series are stationary at level, meaning that shocks to returns are short-lived, and the series revert to their mean over time. The ACF and PACF plots (*Figs. 4 and 5*) further support this result, as all series show rapid decay of autocorrelations and minimal partial autocorrelation beyond lag 1, confirming weak serial dependence.

Overall, these diagnostics validate that the Nifty, crude oil, and Bitcoin return series are stationary but heteroskedastic, making them well-suited for copula-based dependence modeling to capture nonlinear and regime-specific co-movement structures.

Figure 4 shows the autocorrelation structures of Nifty, crude oil, and Bitcoin returns. All three series display rapid decay of autocorrelation values, confirming weak serial dependence and stationarity of the return data. Minor short-term lags are visible in Nifty and crude oil, suggesting limited persistence in daily returns, while Bitcoin exhibits near-zero autocorrelation across all lags, indicating high randomness in its return generation process. This supports the suitability of copula-based modeling, as dependencies arise cross-sectionally rather than temporally. *Figure 5* depicts the partial autocorrelation functions, further confirming that each return series is weakly autocorrelated. The PACF spikes at lag 1 for Nifty and crude oil are marginal but statistically insignificant beyond the first lag, validating the absence of long memory. Bitcoin's PACF remains negligible across all lags, consistent with a random walk pattern. These observations justify the use of copula models focusing on contemporaneous relationships instead of lagged dependencies.

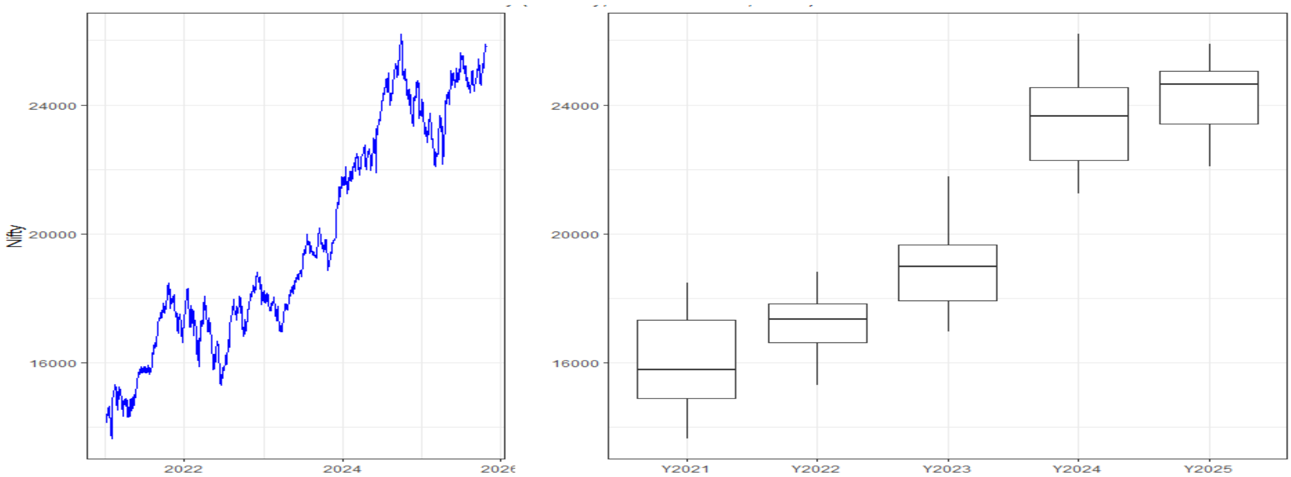

Fig. 1. **Trends and year-wise box plot summary of Nifty (2021–2025)**

Source: Developed by the author using R.

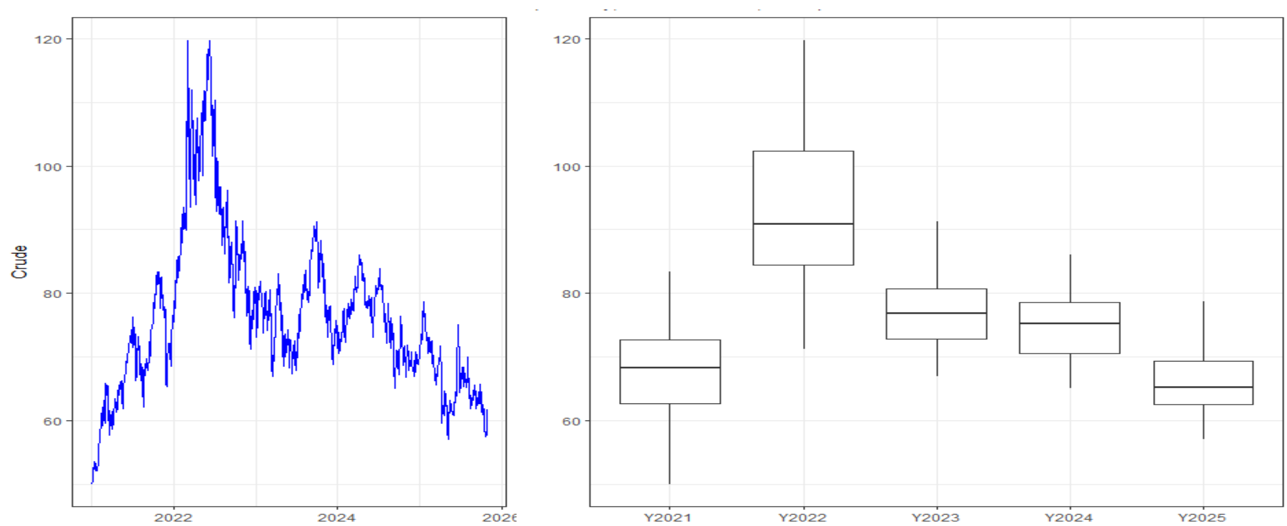

Fig. 2. **Trends and year-wise box plot summary of crude oil (2021–2025)**

Source: Developed by the author using R.

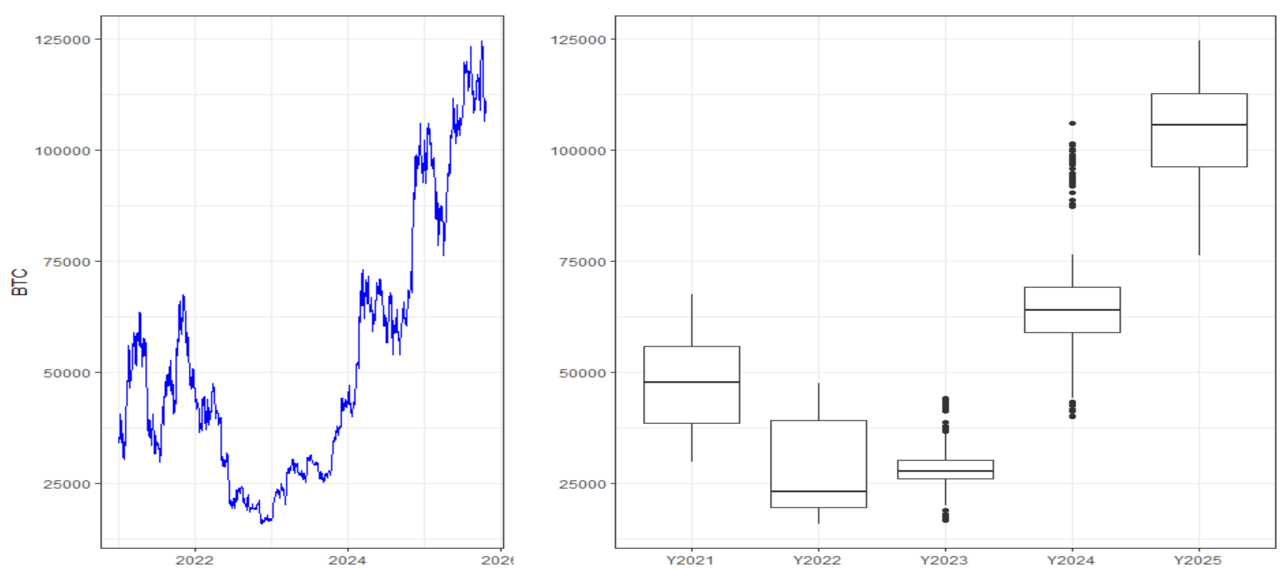

Fig. 3. **Trends and year-wise box plot summary of bitcoin (BTC) (2021–2025)**

Source: Developed by the authors using R.

Table 1

Summary statistics and unit root test results for return series (January 2021–October 2025)

Statistic / Test	Nifty_r	Crude_r	BTC_r
Minimum	−0.0611	−0.1344	−0.2593
1st Quartile (Q1)	−0.0042	−0.0124	−0.0170
Median	0.0007	0.0015	0.0005
Mean	0.0005	0.0002	0.0011
3rd Quartile (Q3)	0.0057	0.0140	0.0191
Maximum	0.0463	0.1354	0.1918
Jarque–Bera (Normality)	923.17 ($p < 0.001$)	785.35 ($p < 0.001$)	1647.3 ($p < 0.001$)
ARCH LM (Heteroskedasticity)	χ^2 = 105.78, p < 0.001	χ^2 = 102.41, p < 0.001	χ^2 = 21.53, p = 0.043
ADF Test (Stationarity)	DF = −33.958, p = 0.01	DF = −34.176, p = 0.01	DF = −35.487, p = 0.01
PP Test (Stationarity)	Z(α) = −1127.1, p = 0.01	Z(α) = −1023.8, p = 0.01	Z(α) = −1206.8, p = 0.01
Conclusion	Stationary with volatility clustering	Stationary with volatility clustering	Stationary with moderate volatility clustering

Source: Author's calculation using R.

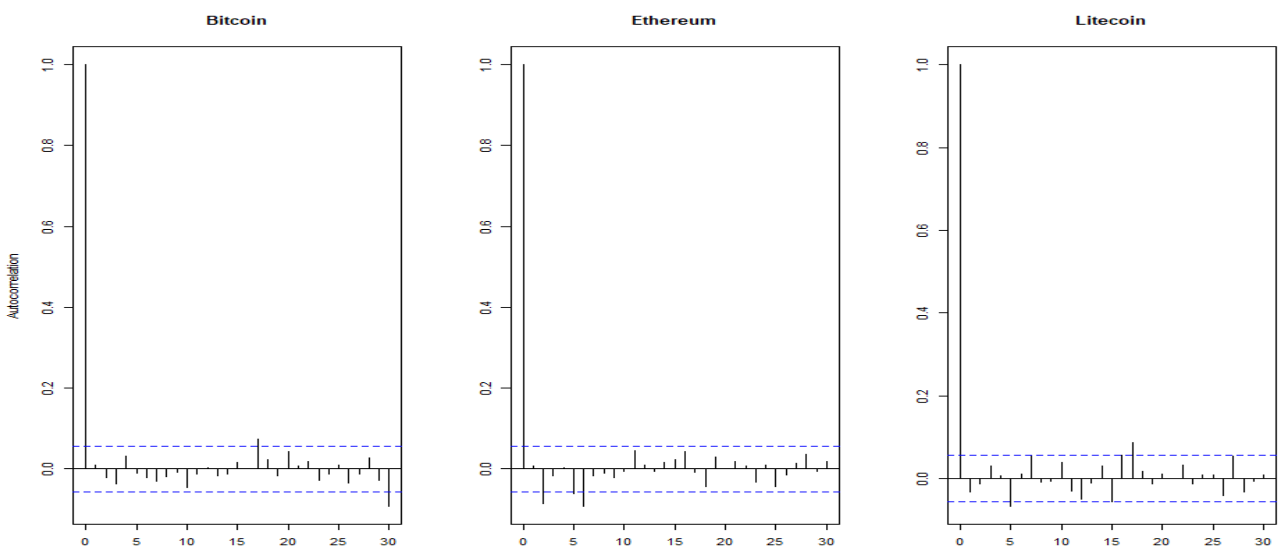

Fig. 4. **Autocorrelation functions (ACF) of Nifty, crude oil and BTC return series**

Source: Developed by the author using R.

Figure 6 visualizes the correlation structure between crude oil and Bitcoin returns, showing a dispersed cloud of data points without any clear linear alignment. This pattern confirms the results of the conventional correlation analysis, which reveals an insignificant linear relationship between the two assets. The absence of a consistent pattern indicates that traditional linear methods fail to capture the true nature of their dependence. However, the presence of localized clusters in certain regions suggests short-lived, regime-specific co-movements during extreme market conditions. These observations highlight the limitation of classical correlation measures and underscore the importance of adopting non-linear dependence models, such as copula and fuzzy-based approaches, which are better suited to identify asymmetric, tail, and state-dependent relationships between heterogeneous assets like crude oil and Bitcoin.

3.2. Dependence between Nifty and crude oil returns

This section presents the dependence structure among the return series of Nifty, crude oil, and

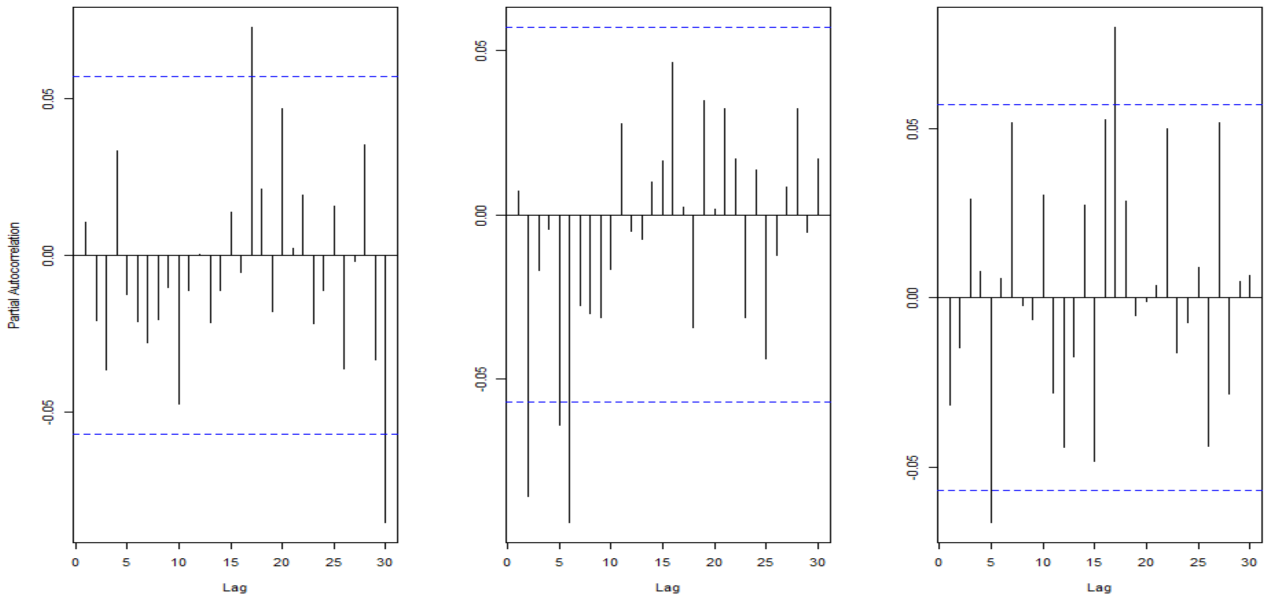

Fig. 5. **Partial autocorrelation functions (PACF) of Nifty, crude oil and BTC return series**

Source: Developed by the author using R.

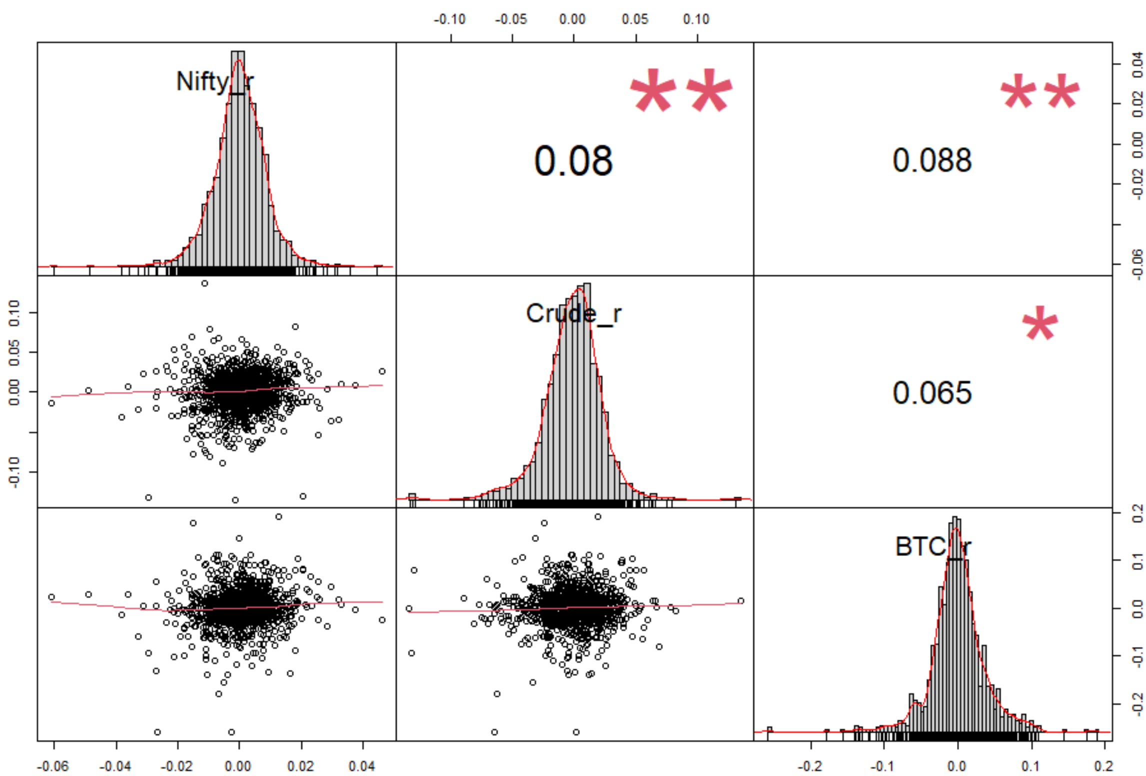

Fig. 6. **Correlation analysis of crude oil and BTC return series**

Source: Developed by the author using R.

Bitcoin (BTC) based on classical rank correlations, Gaussian copula correlations, and fuzzy copula analysis. Pairwise results are discussed with detailed fuzzy-state breakdowns, copula fits, and interpretive remarks.

The results presented in *Table 2* indicate a negligible dependence between Nifty and crude oil returns across multiple correlation measures. The Spearman's rho ($\rho = 0.0911$, $p = 0.0017$) and Kendall's tau ($\tau = 0.0625$, $p = 0.0013$) reveal a statistically significant yet economically weak monotonic association between crude oil prices and Nifty returns. Similarly, the Gaussian copula correlation ($\rho = 0.0851$) confirms the presence of a very mild

Table 2
Dependence measures between Nifty and crude oil returns

Measure	Estimate	p-value	Interpretation
Spearman's ρ	0.0911	0.0017	Negligible monotone dependence
Kendall's τ	0.0625	0.0013	Negligible concordance
Gaussian Copula ρ	0.0851	–	Negligible linear dependence (normal scores)

Source: Author's calculation using R.

Table 3
Fuzzy-weighted dependence breakdown between Nifty and crude oil returns

Fuzzy Set Combination	Weighted Spearman	Weighted Kendall-like	Total Weight	Interpretation
Low-Low	0.3428	0.0724	21.54	Moderate positive dependence in lower regime
Low-Medium	–0.0030	–0.0018	62.79	No meaningful dependence
Low-High	–0.4417	–0.1351	17.91	Strong inverse dependence (cross-regime)
Medium-Low	0.1679	0.0916	79.63	Weak positive linkage
Medium-Medium	0.0841	0.0575	968.50	Weak but stable association
Medium-High	–0.0704	–0.0165	70.00	Weak inverse relation
High-Low	–0.2224	0.0142	19.42	Negative cross-regime dependence
High-Medium	0.0651	0.0461	81.72	Slight positive co-movement
High-High	0.3047	0.0675	24.57	Moderate upper-tail dependence

Source: Author's calculation using R.

linear dependence when transformed to normal scores, reinforcing the observation that the relationship between the two markets is largely random with only occasional localized co-movements. This weak dependence highlights the limited spillover effects between the Indian equity index and the global crude oil market during the study period, indicating a limited co-movement between crude oil prices and Nifty returns rather than any causal relationship.

The fuzzy-weighted dependence analysis in *Table 3* reveals a nuanced and regime-specific pattern between Nifty and crude oil returns. In the Low-Low regime, both variables display a moderate positive dependence (Weighted Spearman = 0.3428; Weighted Kendall-like = 0.0724), implying that when both markets are in low-return phases, their movements tend to align positively. The Low-High combination, however, shows a strong inverse dependence (–0.4417; –0.1351), indicating that when crude oil prices rise sharply while Nifty remains low, the relationship turns distinctly negative — reflecting potential cost-push pressures or investor flight from equities during oil price surges.

In the Medium-Medium regime, which dominates with the highest total weight (968.50), the dependence remains weak but stable, suggesting that most market observations lie in this zone with limited but consistent co-movement. The Medium-Low and High-combinations indicate weak positive linkages, pointing to partial co-movement when one market shifts toward stability or moderate performance. Conversely, the Medium-High and High-Low regimes reflect weak to moderate negative dependence, capturing op-

Table 4

Copula model fit statistics for the Nifty-crude oil returns

Copula	Log-Likelihood	Parameter	Interpretation
Gaussian	4.297	–	Weak symmetric dependence
t-Copula	13.917	ν = 8	Slight tail dependence
Clayton	6.483	θ = 0.1332	Weak lower-tail association
Gumbel	435.441	θ = 1.0666	Mild upper-tail dependence (best fit)

Source: Author's calculation using R.

Table 5

Dependence measures between Nifty and Bitcoin returns

Measure	Estimate	p-value	Interpretation
Spearman's ρ	0.0639	0.028	Negligible monotone dependence
Kendall's τ	0.0429	0.027	Negligible concordance
Gaussian Copula ρ	0.0769	–	Negligible linear dependence

Source: Author's calculation using R.

posite movements during transitional or volatility-driven phases.

Finally, the High-High regime exhibits a moderate upper-tail dependence (0.3047; 0.0675), implying that in periods of simultaneous high returns, both Nifty and Crude Oil tend to move together, albeit not strongly. This pattern may reflect periods of strong macroeconomic conditions or global demand expansion, where rising economic activity simultaneously drives equity market performance and increases demand for crude oil, leading to a positive co-movement. In contrast, the inverse relationship observed in the Low-High regime may capture periods of cost-push pressures or market stress, where rising oil prices adversely affect equity returns. These findings suggest that dependence between Nifty and crude oil is asymmetric and largely driven by regime-specific dynamics — stronger at the extremes (low-low and high-high) and weak or inverse in cross-regime transitions influenced by underlying economic conditions.

The results suggest negligible overall dependence between Nifty and crude oil returns, though the fuzzy-weighted analysis uncovers *localized structure*: positive correlation during simultaneous low or high return regimes, and negative dependence across opposite states. As shown in *Table 4*, the Gumbel copula provides the best fit with a log-likelihood of 435.441, indicating mild upper-tail dependence between Nifty and crude oil returns — suggesting that co-movements strengthen during high-return periods. The t-Copula ($\nu = 8$) also captures slight tail dependence, consistent with occasional joint extremes. Both the Gaussian and Clayton copulas show weak dependence structures, with the Clayton indicating limited lower-tail association. The Gumbel copula offers the best fit, indicating mild upper-tail dependence. Overall, the results highlight asymmetric dependence dominated by upper-tail co-movements, aligning with the fuzzy analysis that shows stronger interaction during extreme market phases.

3.3. Dependence between Nifty and Bitcoin returns

Table 5 shows that the overall dependence between Nifty and Bitcoin returns is negligible across all measures. The Spearman's ρ of 0.0639 ($p = 0.028$) and Kendall's τ of 0.0429 ($p = 0.027$) indicate very weak monotonic and concordant relationships, suggesting that the two markets move largely independently. Similarly, the Gaussian Copula correlation of 0.0769 reinforces the absence of any meaningful linear association between their normal-score transformations. These results imply that Bitcoin's price dynamics are largely decoupled from Nifty's performance, re-

Table 6

Fuzzy-weighted dependence breakdown between Nifty and Bitcoin returns

Fuzzy Set Combination	Weighted Spearman	Weighted Kendall-like	Total Weight	Interpretation
Low-Low	0.4205	0.1040	18.52	Strong positive linkage in downturns
Low-Medium	0.0424	0.0327	62.79	Weak positive association
Low-High	−0.2661	−0.0332	17.52	Inverse dependence (cross-regime)
Medium-Low	0.1429	0.0698	58.37	Weak positive co-movement
Medium-Medium	0.0590	0.0387	970.41	Very weak stable association
Medium-High	−0.0033	0.0069	82.66	No meaningful relation
High-Low	−0.2904	−0.0346	16.28	Negative cross-regime dependence
High-Medium	0.0528	0.0236	81.94	Weak positive dependence
High-High	0.3023	0.0378	24.19	Moderate upper-tail dependence

Source: Author's calculation using R.

flecting distinct market structures and investor bases with minimal spillover effects.

The fuzzy-weighted dependence results in *Table 6* reveal that the relationship between Nifty and Bitcoin returns is weak overall but varies across regimes. A strong positive linkage is observed in the Low-Low regime, indicating that both assets tend to move together during downturns, possibly reflecting synchronized risk aversion or liquidity withdrawals. The Low-High and High-Low combinations show inverse dependence, suggesting opposite behavior when one market experiences gains while the other declines. The Medium-Medium regime, which carries the highest weight, exhibits a very weak yet stable association, signifying largely independent performance under normal market conditions. In the High-High zone, a moderate upper-tail dependence is observed, implying that during bullish phases, Bitcoin and Nifty occasionally move in the same direction. Overall, dependence is minimal in normal conditions but becomes more evident during extreme market states.

The classical dependence between Nifty and BTC is weak, but the fuzzy copula breakdown identifies positive co-movement in both *low-low* and *high-high* regimes. The Gumbel copula fits best (log-likelihood = 453.193), suggesting a slight upper-tail dependence between Nifty and Bitcoin returns — indicating limited co-movement during periods of simultaneous market optimism (see *Table 7*). The t-Copula ($\nu = 10$) captures minor tail dependence, consistent with occasional joint extremes, while both the Gaussian and Clayton copulas reflect weak and nearly symmetric dependence structures. Overall, the results confirm that the linkage between Nifty and Bitcoin is generally weak, with mild synchronization price rises in extreme market conditions.

3.4. Dependence between crude oil and bitcoin returns

Table 8 indicates that the relationship between crude oil and Bitcoin returns is statistically insignificant and economically negligible. Both Spearman's ρ (0.0509, $p = 0.080$) and Kendall's τ (0.0343, $p = 0.077$) are small and not significant at the 5% level, suggesting an absence of consistent monotonic or concordant movement between the two assets. Similarly, the Gaussian Copula correlation of 0.0572 reinforces the lack of meaningful linear association. These findings imply that Bitcoin's return dynamics are largely independent of global oil price fluctuations, reflecting the distinct nature and drivers of the cryptocurrency and commodity markets.

The fuzzy-weighted dependence results in *Table 9* show generally weak but regime-dependent

Table 7
Copula model fit statistics for the Nifty–Bitcoin returns

Copula	Log-Likelihood	Parameter	Interpretation
Gaussian	3.509	–	Weak symmetric correlation
t-Copula	8.325	$\nu = 10$	Minor tail dependence
Clayton	5.783	$\theta = 0.0897$	Negligible lower-tail dependence
Gumbel	453.193	$\theta = 1.0448$	Slight upper-tail dependence (best fit)

Source: Author's calculation using R.

Table 8
Dependence measures between crude oil and Bitcoin returns

Measure	Estimate	p-value	Interpretation
Spearman's ρ	0.0509	0.080	Not significant; negligible dependence
Kendall's τ	0.0343	0.077	Not significant
Gaussian Copula ρ	0.0572	–	Negligible linear dependence

Source: Author's calculation using R.

relationships between crude oil and Bitcoin returns. A moderate positive linkage appears in the Low-Low regime, suggesting that both assets may experience mild co-movement during downturns. The Low-High and High-Low regimes reveal negative cross-regime dependence, indicating opposite movements when one market strengthens while the other weakens. The Medium-Medium regime, which dominates with the highest weight, shows minimal association, implying near-independence under typical market conditions. In contrast, the High-High regime exhibits moderate upper-tail dependence, suggesting occasional co-movement during strong bullish periods. Overall, the relationship between crude oil and Bitcoin remains weak, with dependence becoming more evident only at market extremes.

Crude oil and BTC returns exhibit no significant overall correlation. However, fuzzy decomposition highlights positive dependence during joint downturns (*low-low*) and joint upswings (*high-high*). The best-fitting Gumbel copula reveals a weak but consistent upper-tail relationship, suggesting that both assets tend to rise together during bullish phases.

As shown in *Table 10*, the Gumbel copula achieves the highest log-likelihood value (463.440), indicating that the crude oil and Bitcoin return exhibit mild upper-tail dependence, or limited co-movement during bullish market conditions. The t-Copula ($\nu = 20$) captures mild symmetric tail dependence, suggesting occasional simultaneous extreme movements in both directions. The Gaussian and Clayton copulas reflect weak linear and lower-tail associations, respectively, implying minimal correlation under normal conditions. Overall, dependence between crude oil and Bitcoin remains weak but becomes more noticeable during simultaneous high-return periods.

3.5. Comparative summary

Across all pairs, conventional dependence correlation measures are weak, but fuzzy copula results expose *nonlinear and asymmetric co-movements* (see *Table 11*). The consistent dominance of the Gumbel copula indicates an overarching *upper-tail dependence pattern*, implying that these assets may rise concurrently in bullish market extremes.

4. Discussion

The results offer significant insights into the relationships between crude oil, Bitcoin, and the Nifty 50 index, indicating that these connections are not strong when assessed using conventional metrics such as Spearman's ρ and Kendall's τ.

Table 9
Fuzzy-weighted dependence breakdown between crude oil and Bitcoin returns

Fuzzy Set Combination	Weighted Spearman	Weighted Kendall-like	Total Weight	Interpretation
Low-Low	0.3304	0.0543	19.28	Moderate positive relation in downturns
Low-Medium	0.0568	0.0339	79.14	Weak dependence
Low-High	−0.1575	0.0574	19.81	Weak inverse relation
Medium-Low	0.0429	0.0191	57.95	Weak positive linkage
Medium-Medium	0.0470	0.0322	965.20	Minimal association
Medium-High	−0.0207	−0.0103	82.50	Very weak inverse dependence
High-Low	−0.2412	−0.0131	15.48	Negative cross-regime effect
High-Medium	0.0694	0.0404	70.15	Weak positive association
High-High	0.3154	0.0463	21.86	Moderate upper-tail dependence

Source: Author's calculation using R.

Table 10
Copula model fit statistics for the crude oil and Bitcoin returns

Copula	Log-Likelihood	Parameter	Interpretation
Gaussian	1.940	–	Weak linear correlation
t-Copula	2.876	$\nu = 20$	Mild symmetric tail dependence
Clayton	2.737	$\theta = 0.0711$	Weak lower-tail association
Gumbel	463.440	$\theta = 1.0356$	Upper-tail dependence (best fit)

Source: Author's calculation using R.

Table 11
Summary of dependence measures and best-fitting copulas among Nifty, crude oil, and Bitcoin return pairs.

Pair	Spearman's ρ	Kendall's τ	Gaussian ρ	Best-Fitting Copula	Copula Parameter	Dependence Type
Nifty-Crude	0.091	0.063	0.085	Gumbel	$\theta = 1.0666$	Mild upper-tail, regime-specific
Nifty-BTC	0.064	0.043	0.077	Gumbel	$\theta = 1.0448$	Weak upper-tail, localized co-movement
Crude-BTC	0.051	0.034	0.057	Gumbel	$\theta = 1.0356$	Weak upper-tail, simultaneous rallies

Source: Author's calculation using R.

This suggests that the linear and monotonic relationships are limited. This aligns with previous studies, for example [27–29], reporting weak average linkages between traditional financial assets and cryptocurrencies.

However, the copula-based results reveal that dependence is asymmetric and distribution-dependent. The consistent selection of the Gumbel copula across pairs underscores the presence of upper-tail dependence, implying that co-movements become more significant during extreme positive market conditions. This behavior is consistent with findings of [11, 30] on nonlinear and tail-based dependence structures in financial markets.

The findings from the fuzzy copula approach enhance our comprehension by highlighting how dependence varies with different states. Rather than presuming constant relationships, this fuzzy model reveals how dependence shifts across low, medium, and high return scenarios. The analysis indicates that the medium–medium scenario holds the greatest significance, signifying stable yet weak connections during typical market conditions. Conversely, more pronounced dependence-both positive and negative-appears in extreme scenarios, especially in combinations like low-high and high-low. These trends suggest uneven adjustments, where disturbances in one market may not spread uniformly but are influenced by the current state of the other market. This supports the view that financial market relationships are state-dependent and evolve gradually, rather than exhibiting abrupt shifts [31]. Overall, the results suggest that dependence among these markets is episodic and nonlinear, shaped by global shocks and changing investor sentiment, reinforcing the importance of advanced modeling frameworks for capturing such complexities.

5. Conclusions

This study examined the nonlinear dependence and co-movement dynamics among crude oil, Bitcoin, and the Indian stock market (Nifty 50) using a fuzzy copula-based approach. Conventional correlation and linear models revealed weak and statistically insignificant average dependence, indicating that the relationships among these asset classes cannot be adequately captured through standard measures. However, the fuzzy copula framework uncovered distinct regime-specific and tail-dependent linkages, particularly highlighting moderate upper-tail dependence between oil and cryptocurrency returns during periods of extreme volatility.

The fuzzy copula analysis provides a richer picture of dependence among Nifty, crude oil, and Bitcoin returns than conventional correlation metrics. Although the overall dependence appears weak, the fuzzy decomposition highlights *state-dependent relationships* — notably stronger co-movements in extreme low and high regimes. This suggests that market linkages intensify under stress or exuberance, supporting the notion of asymmetric contagion across asset classes. The Gumbel copula's consistent superiority indicates mild upper-tail dependence, implying simultaneous price increases across assets during bullish conditions. From a portfolio management perspective, these findings underscore that traditional diversification benefits may weaken during market rallies, while during normal conditions, interdependence remains minimal. Thus, fuzzy copula models can better capture localized and nonlinear dependence patterns, offering valuable insights for risk diversification, hedging, and stress-testing in multi-asset portfolios.

The findings highlight the critical role of nonlinear modeling frameworks in portfolio risk assessment, hedging design, and systemic risk monitoring, particularly in emerging economies such as India, where global commodity and digital asset shocks increasingly impact domestic financial stability. Researchers may leverage this study in future investigations employing higher-dimensional copulas or time-varying fuzzy systems to capture evolving dependence structures within global financial networks.

This study concentrates on the Indian stock market, offering insights into regime-dependent co-movements among cryptocurrencies, crude oil, and equity markets within this emerging economy. However, the results may not be directly applicable to equity markets in other countries. Comparative studies on international equity markets are necessary to contextualize these findings more broadly. The analysis omits fixed-income instruments, such as bonds, which are crucial for diversification and portfolio management due to their sensitivity to interest rate dynamics affecting equities, oil, and digital assets. Incorporating fixed-income assets in future research would provide a more comprehensive understanding of cross-asset dependencies and hedging potential. Furthermore, the identified relationships reflect statistical dependencies rather than structural links, limiting their predictive utility for hedging. The study does not primarily address the temporal stability of these dependencies, which is vital for developing robust long-term diversification and hedging strategies. Future research should investigate the persistence and evolution of these relationships over time to enhance practical relevance.

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