Technovation 148 (2025) 103335

Contents lists available at ScienceDirect

Technovation

journal homepage: www.elsevier.com/locate/technovation

Exploring the role of artificial intelligence in addressing sustainable development. A semantic analysis of AI patents

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ARTICLE INFO

Keywords:
Artificial intelligence
SDGs
Patents
Word2Vec
Semantic analysis

ABSTRACT

Artificial Intelligence (AI) is increasingly recognized as a transformative enabler of sustainable development. This paper offers a novel contribution by systematically mapping the landscape of AI-related technologies using Sustainable Development Goals (SDGs) as a reliable functional proxy of sustainable development. We implement an improved Term Frequency-Inverse Document Frequency (TF-IDF) weighted Word2Vec model, combined with a bigram-based filtering strategy, to capture the nuanced contribution of AI patents to SDGs thematic areas. Our results reveal both the breadth and depth of AI's impact, confirming its status of a general-purpose technology capable of driving cross-sectoral systemic transformations. By uncovering the interconnections between AI and sustainable development, this study contributes to the theoretical debate about digital and sustainable transitions and delivers practical insights for managers and policymakers, aiming to effectively manage these paradigm shifts. Finally, our work proposes a data-driven framework for tracking the evolution of sustainable-oriented AI evolutions while guiding policy design in support of Agenda (2030) goals.

1. Introduction

In an era of growing concerns over climate change and resource scarcity, sustainability has emerged as a pivotal force driving growth and adaptation for businesses aiming to achieve a more harmonious integration of economic, social, and environmental objectives (George et al., 2021; Scharlemann et al., 2020). On one hand, firms are increasingly under pressure to commit to sustainability goals across their business processes and activities (Delmas et al., 2019); on the other hand, the rapid expansion of digitalization and Artificial Intelligence has opened new avenues for supporting the implementation of sustainability, in general, and the pursuit of Sustainable Development Goals (SDGs) outlined in the 2030 Agenda, in particular (Gupta et al., 2021).

Although often considered as two separate phenomena (Kürpick et al., 2023; Isensee et al., 2020), digital and sustainable transitions represent the two foundational pillars of the actual phase of technological innovation (Kiron and Unruh, 2018). As evidenced by the European Union, there are more than some contact points between digital and sustainability paradigms that should be leveraged for long-term growth and resilience.

The convergence of sustainability and digital imperatives is beginning to gain attention across industries (e.g., Al Mubarak, 2023; Castro et al., 2021), pushing firms to invest more to realize the synergistic potential of these dual transitions. In this perspective and building on the assumption that the new set of digital solutions can contribute to advancing sustainability across various dimensions, George et al. (2021) refer to the field of digital sustainability, as the set of "*organizational activities seeking to advance the sustainable development goals through creative deployment of technologies*" (p.1000).

In this respect, the simultaneous advancement of digital and sustainable solutions is profoundly affecting businesses, reshaping business models and value co-creation processes, both in short and long-term (Vinuesa et al., 2020). For instance, among the technologies enabling this convergence, Artificial Intelligence (AI) has been recognized as one of the most promising drivers for sustainability (Nishant et al., 2020), with the potential of unlocking new pathways of progress across industries and businesses (Gruetzemacher and Whittleston, 2022). While AI technologies enhance business value creation, through increased revenues, cost efficiencies and process optimization (AlSheibani et al., 2020), they also provide new solutions to social and environmental

This article is part of a special issue entitled: AI x SDGs published in Technovation.

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https://doi.org/10.1016/j.technovation.2025.103335
Received 30 September 2024; Received in revised form 30 July 2025; Accepted 4 August 2025
Available online 17 August 2025
0166-4972/

challenges (e.g., Taghikhah et al., 2022) and can effectively foster equality and inclusion (Bolukbasi et al., 2016). However, the adoption and diffusion of AI-related technologies can have heterogeneous negative impacts (e.g., Acemoglu and Restrepo, 2018; Sætra, 2021; Grashof and Kopka, 2023) at both individual and societal levels, including job losses, ethical concerns, and governance challenges.

In that context, literature has argued that AI's dual impact on business and society, particularly in conjunction with the simultaneous advancement of digital and sustainable solutions, could be explained through different theoretical and analytical lenses, emphasizing its role either as a general-purpose technology (GPT) or as a non-neutral technology. Specifically, the economic implications of AI, as a GPT have been extensively explored (e.g., Ballestar et al., 2020; Chen et al., 2023; Kopka and Fornahl, 2024). Drawing on the resource-based view (RBV), AI has been recognized as a strategic asset enhancing firms' growth potential, innovation capabilities (Moderno et al., 2024), and overall performance (Ristyawan, 2020), while also addressing environmental issues (Di Vaio et al., 2020). From a productivity standpoint, AI enables the effective use of IoT and data analytics (Franco and Nuccio, 2021), allowing for the optimization of resources, restructuring of processes and services, and the restyling of customer engagement behavior (Perez-Vega et al., 2021), thereby supporting the transition towards sustainability. For instance, in the agrifood industries, AI-related solutions, such as remote sensors and real-time monitoring devices, have contributed to reducing environmental footprints (Dayıoğlu and Turker, 2021). Similarly, Shrouf et al. (2014) demonstrated how the extensive application of AI and IoT represents the foundational basis of smart factory architectures with sustainability at their core. More broadly, AI has been successfully associated with more efficient and higher-performing supply chain management (SCM) applications (Shoushtari et al., 2021; Toorajipour et al., 2021), thereby contributing to both green and circular economy approaches.

In this perspective, Demirel et al. (2022) explored the relationship between firms' eco-innovation efforts and their growth performance, underlining the importance of a well-defined digitalization strategy and the urgent need to improve digital skills and capabilities to enable a successful net-zero transition. Similarly, in their recent systematic literature review, Truant et al. (2024) developed a conceptual framework addressing key drivers and barriers to the implementation of smart circular economy (SCE)- defined as the intersection between circular economy and the wide range of digital technologies such as AI, blockchain, cyber-physical systems, big data and IoT. By integrating different theoretical approaches, the authors categorize factors that could act as enablers, turning structural constraints into catalysts for this transition. Moreover, the service sector, due to the predominantly intangible nature of its outcomes, has been identified as fertile ground for AI applications oriented towards sustainability.

For instance, Azadi et al. (2023) assessed the sustainability of cloud computing service providers, focusing on social and environmental dimensions of sustainability. Similarly, Bai et al. (2020) evaluated Industry 4.0 technologies, showing that mobile technology has had the most significant impact on sustainability across industries. In the same way, Pandya and Kumar (2023) identified AI, Big Data Analytics, and IoT as core enablers of sustainability transitions in micro and small and medium-sized companies (MSMEs). Nonetheless, previous studies (e.g., Vinuesa et al., 2020; Lee and Yan, 2024; Lin et al., 2024) have shown that the relationship between artificial intelligence and sustainability is far from linear. While digital technologies can promote sustainability, they can also lead to increased resources consumption, thereby exacerbating problems of waste and environmental pollution (Brevini, 2020). Kopka and Grashof (2022) and Mazzi et al. (2023) illustrated this paradox, demonstrating that although AI-related advancements may contribute to energy saving and productivity gains, they are also highly energy and computationally intensive, often resulting in a higher carbon footprint. Differently, Dauvergne (2022) argues that AI is not substantially advancing sustainability, due to its negative impacts on resource extraction, waste accumulation, and supply chain vulnerabilities, ultimately making ecosystems more fragile and amplifying the marginalization of some communities.

Against this backdrop, balancing the positive and negative effects of AI evolution is essential to ensure its responsible and ethical use (Yeung, 2018), while also contributing to global sustainability goals (Kulkov et al., 2024). With the rapid growth of AI for sustainable development and its expanding role in a wide range of industries (Chaudhuri et al., 2022), it has become crucial to explore not only its potential but also its versatility. To do so, one promising approach is the investigation of patent activity, which represents a robust proxy to trace innovation trajectories and emergent trends. Patents not only protect inventions but also give inventors a temporary competitive edge in the market (Kemp, 2023). Although not all inventions are patented, and not all patents lead to successful innovations, patent data remains a key indicator of a company's investments in high-skilled competencies and high-cost innovation areas like sustainable AI-driven solutions (Liu et al., 2020). While existing studies provide valuable insights into AI's role across various industries, the intersection between AI patents and sustainability has opened to new research avenues (Kopka and Grashof, 2022; Singh et al., 2024). However, there is still limited understanding of AI's applications for achieving sustainable goals. This paper aims to fill this research gap by investigating the patent landscape of AI technologies, focusing on their alignment with Sustainable Development Goals (SDGs), considered as a functional proxy of sustainable development.

The research goal of this paper is twofold: first, it offers a preliminary quantification of the extent to which AI-related technologies contribute to the achievement of sustainable goals; second, it assesses how AI-related technologies are distributed across different sustainable thematic areas. Specifically, the significance of this study extends beyond academic interests. Given the increasing institutional and entrepreneurial attention toward tools and strategies for effectively managing the twin transition, this research aims to offer a concrete contribution to its governance. By providing a preliminary mapping of the intersection between AI technologies and various sustainability domains, our study provides policymakers, entrepreneurs and researchers with valuable insights to support both the design and the implementation of sustainable development. In that perspective - also providing a systematic semantic mapping approach of AI patents and their alignment with sustainable development goals-our study offers an actionable guideline for investment, innovation planning strategies and policy design while also contributing to the actual debate about the mechanisms through which AI technologies can shape sustainable development pathways.

Against this backdrop, this study not only contributes to the broader literature concerning the progressive convergence between AI technologies and sustainable development, through the following research question: *How can Artificial Intelligence address Sustainable Development?* The rest of the article is structured as follows. The following section gives an overview of the literature and combines the concepts of AI and sustainability. In the third section methodology and data are described. The fourth section shows the empirical analysis as well as the corresponding results. Finally, discussion and conclusions, and theoretical, practical and policy implications are presented.

2. Theoretical background

2.1. The grand challenges for sustainable development

Our planet faces complex grand challenges that demand urgent and coordinated collective actions (Holland et al., 2024) to spur global competitiveness and growth, extending beyond traditional productivity, and requiring the integration of both social and environmental dimensions. These multifaceted challenges, ranging from climate change and resource depletion to inequality and social justice, require systemic and cross-industry solutions to facilitate the transition toward a more sustainable future (Mazzucato, 2011).

In this sense, sustainability represents a holistic concept that clearly calls for broad changes in technology, innovation, and corporate business models, to realign traditional systems around entirely new values (Sebhatu and Enquist, 2022). For many organizations, the pursuit of sustainability represents an aspirational blueprint for action, not only to mitigate risks associated with environmental dynamism, but also to gain a competitive advantage by unlocking new market opportunities (Scheyvens et al., 2016). A key component of this transition involves expanding the boundaries of corporate responsibility, encouraging firms to account for their societal and environmental impacts (Muñoz et al., 2018). In this perspective, companies are increasingly committing to social responsibility, not only through voluntary initiatives, but also through a comprehensive redesign of firms' strategic behaviors and business processes (Nidumolu et al., 2009; Schlüter et al., 2017). By prioritizing a mindset of care and responsibility, companies can anchor sustainable development to their core, by adopting socially and environmentally friendly relevant business practices for people, communities and public institutions (Arenas-Torres et al., 2021). This, in turn, will become a lever to spread a sustainability culture, while enhancing competitive positioning (Wang et al., 2022). In this context, the sustainability transition is expected to go beyond traditionally profit-centered systems, incorporating economic viability, social and environmental dimensions for value creation (Telepatra et al., 2019). Ghobakhloo et al. (2021) identified Industry 4.0 and innovations as the most prominent factors promoting knowledge exchange, manufacturing and organizational capabilities building to manage sustainable development. Weissbrod and Bocken (2017) stressed the importance of experimentation capabilities to foster innovation activities aimed at generating economic, social and environmental value, particularly in highly dynamic environments. Differently, Sebhatu and Enquist (2022) emphasized stakeholder engagement as the primary driver of value creation also impacting on business decision-making mechanisms, helping to align operational activities with broader social goals. Moreover, Patuelli et al. (2022) stressed the importance of personal beliefs and governance aspects in pursuing sustainable goals, particularly those connected to environmental and social aspects (e.g., quality education, decent work and economic growth, climate action, clean water and energy, etc.). In contrast, Rosamartina et al. (2022) found a positive moderating role of entrepreneurial orientation towards sustainability in the relationship between digital reputation and firm performance. In the same line, Gutiérrez-Ponce (2023) highlighted that firms committed to sustainable objectives exhibit higher performance. In this intricate landscape, firms are increasingly expected to play a proactive role in achieving sustainability through their operativity.

To achieve sustainability firms can adopt different policies and strategies. For instance, Jacobsen et al. (2020) defined a firm-level roadmap for sustainable development, composed of four main categories of sustainable practices, including inspiring and informing, productizing, co-creating and system buildings. Similarly, firms may develop zero-waste systems (Fonseca et al., 2022), implement recycling protocols and energy-saving approaches (Durrani, 2019; Agrawal et al., 2023), and preserve the environmental resources (Silva and Gouveia, 2020). Moreover, firms are increasingly engaging in nurturing social dialogue within their business ecosystems, also enhancing working conditions and stakeholder engagement, thus enabling individual and collective growth processes (Ferreira et al., 2022) while unlocking value co-creation approaches (López-Concepción et al., 2022). Hence, in this integrated view, each dimension contributes to holistic value creation (Lynch and Ferasso, 2023).

In recent years, the discourse on sustainability—and the corresponding policies and strategies that both firms and governments should adopt to foster it—has been significantly shaped by the United Nations' work on the Sustainable Development Goals (SDGs) and the broader Agenda 2030 framework (UN, 2015). The SDGs offer a comprehensive taxonomy of sustainability-related grand challenges, serving as a structured framework for realigning economic systems, governance mechanisms, and public policy priorities. Comprising 17 interlinked goals, the SDG framework presents a universal roadmap for advancing sustainable development by addressing a wide spectrum of environmental and social challenges. These include, but are not limited to, climate change, food security, access to clean water, education, biodiversity conservation, and the promotion of sustainable energy, industrialization, consumption, and production. Furthermore, beyond their prescriptive function, the SDGs can also be employed as an analytical lens through which to evaluate corporate sustainability intentions and behaviors. This perspective facilitates the identification of which specific dimensions of sustainability are being addressed by firms' strategic actions, operational practices, and innovation strategies - for instance, through the development or adoption of digital technologies, among which AI.

2.2. Digital innovation, artificial intelligence, and sustainable development

Following the global adoption of sustainability, and the proliferation of various sustainable practices that firms can implement to support their realization, digital technologies have been found to be a relevant driver for achieving expected targets (Seele and Lock, 2017; Camodeca and Almici, 2021; Guandalini, 2022). Gebhardt (2017) highlighted that the integration of two seemingly conflicting concepts, such as sustainability and digitalization, has actually led to a paradigm shift in social and ecological systems. Similarly, while emphasizing the potential tensions between sustainability and organizational goals, Markman et al. (2016) identified digital sustainability as a potential strategy to foster societal and environmental changes rather than simply mitigating negative impacts. In this direction, the Cybercom Group (2021) describes digital sustainability as "*the means by which digitalization, as a key part of the fourth industrial revolution, can deliver on the global sustainability goals*". Popkova et al. (2022) clearly found a positive relation between advancements in digital technologies (such as IoT, big data analytics, and automatization), and sustainable development outcomes, both in developing and developed countries.

Accordingly, with a specific focus on AI- widely regarded as a transformative force across industries- Vinuesa et al. (2020) categorize its positive and negative impacts on the various sustainability pillars. Similarly, Palomares et al. (2021) offer a comprehensive overview of AI and its associated technologies, such as big data, blockchain, cloud, virtual and augmented realities, to all sustainability dimensions, spreading its benefits across industries. Nasir et al. (2023) expand the discussion by examining AI from the four perspectives of curricula, frameworks, projects, and research. Their findings highlight an uneven focus across sustainability dimensions, with a strong emphasis on business-related dimensions, and notable gaps in areas like gender equality, biodiversity and ecosystems' protection. Reyes-Menendez et al. (2023) further explore AI's role in advancing Science, Technology, and Innovation (STI) towards achieving sustainability, advocating for a more strategic and coordinated research agenda to fully integrate AI into environmental sustainability across all its components. In terms of specific Sustainable Development Goals, prior research has addressed the contribution offered by AI to their achievement. For instance, Gupta and Degbelo (2023) disentangled the AI contributions to SDG 11 (Sustainable Cities and Communities), while Nahar (2024) adopted a cross-country design to uncover AI contribution to achieve most of SDGs, except for SDG 10 (Reduced Inequalities), SDG 12 (Responsible Consumption and Production), SDG 14 (Life Below Water) and SDG15 (Life and Land).

Despite the widely acknowledged positive effects of AI for sustainable development, a growing body of literature has shed light on potential negative effects of AI, in terms of its sustainability (Yigitcanlar and Cugurullo, 2020), ethical considerations (Floridi et al., 2021; Astobiza et al., 2021), and broader societal impacts (Braganza et al., 2021). One of the most prominent concerns is the resource consumption and environmental footprint of AI technologies, as large-scale AI models require immense computational power, leading to a significant demand for energy (Brevini, 2020). Furthermore, concerns about data privacy, and lack of transparency in AI-decision making processes have been widely discussed in literature (e.g. Bolukbasi et al., 2016; Lutz, 2019), as these technologies often rely on large-scale data collection and algorithm processes that are not transparent. Specifically, AI-systems, especially if relying on machine learning models, have been described as "black boxes" making it difficult to trace how specific information are collected and processes in training phases, thereby impacting public trust (Pedreschi et al., 2019) and potentially exacerbated social inequalities in case of discriminatory outcomes (Leavy et al., 2020). More recently, Shahriar et al. (2023) categorized privacy risks across the entire AI lifecycle-individuating the risk of identification, risk of inaccurate decisions, risk of non-transparent AI and of non-compliance with regulations and discussing the corresponding mitigation strategies during project planning, data collection, data preparation and model development stages. These issues are critical for those AI solutions aimed at enhancing the targets of sustainable development, that usually require the collection and the storage of high dimensional fine granular data, that usually contain personal attributes of individual, to gather good outcomes. This could be a problem with respect to end-users' privacy (Holzinger *et al.*, 2021), also exposing them to a higher probability of being identified by cross-referencing with other public databases (Altman et al., 2018) and of unauthorized profiling (Ploug, 2023). As a result, increasing attention has been posed to the need of designing and implementing specific privacy protocols for AI solutions, and stricter ethical standards (Siau and Wang, 2020) In addition to privacy concerns, AI poses several threats to employment, particularly in manufacturing industries, where it can lead to widespread job displacement of low-skilled and routine jobs (Tiwari, 2023). These risks, coupled with data-related challenges, suggest that AI could act as both a facilitator and a potential hindrance to sustainable development goals (Vinuesa et al., 2020; Rolnick et al., 2022). This in turn calls for responsible and ethical development of AI, also leveraging multi-stakeholder governance frameworks able to promote equity and transparency (Truby, 2020). While AI offers innovative solutions to long-standing global challenges, it simultaneously introduces new problems that can make AI adoption paths non-linear. Against this backdrop, this study seeks to map the contributions of AI to sustainable development goals, providing critical insights into the dynamics of innovation and emerging paths that support sustainable growth.

3. Data and methods

This section outlines the overall approach of the analytical process we adopted for unveiling the interconnections between AI solutions and the landscape of sustainable development, by leveraging the semantic content of AI patents. The complete methodological workflow is shown in Fig. 1.

Even though patents are not an exclusive outcome of innovation of firms, as not all AI invention are patented (Lankinen, 2020) and young firms may not be at the stage of patenting (Van Roy et al., 2020), they allow tracking and analyze the widespread diffusion of AI technology across time and spaces (Mühlroth and Grottke, 2020), regardless of industry types. Following previous studies (e.g., Cockburn et al., 2018; Abadi and Pecht, 2020; Van Roy et al., 2020) and the methodology in Baruffaldi et al. (2020) for AI patents selection, this paper employs a systematic approach combining a keyword-based search with IPC (International Patent Classification) codes. This combined research strategy effectively enables us to overcome the difficulties associated with the quantitative profiling of patenting in an emerging technology field, while ensuring accuracy and precision. More specifically, we identified AI patents as those featuring in their English abstracts or claims at least one of the AI-related keywords and assigned at least to one of the IPC AI-related codes derived by Baruffaldi et al. (2020), .[1] Data was collected from Questel-Orbit worldwide patent database, covering more than 60 patent authorities, including the European Patent Office, the US Patent and Trademark Office, and national patent offices worldwide. Further, employing patent families, that group together patent applications covering identical technical content, help minimize redundancy and prevent double counting.

The final AI-patents database consists of two fields: (1) basic information, and (2) technical ones. First, the basic information includes publication numbers, earlier publication dates, latest available assignee and main technological domain. Second, the technical content refers to titles, abstracts and claims.

To reconnect AI-related advancements with the broader idea of sustainable development, we adopted the Sustainable Development Goals (SDGs) as a functional proxy, that provide a clear structure for understanding sustainability-related AI innovations. Even though formally adopted in 2015, their structure provides a useful lens through which retrospectively reframe technological contributions to the global challenge of sustainability. For this purpose, among several available SDG keyword dictionaries, we specifically chose relying on the Auckland Approach (Wang et al., 2023), which provides a comprehensive list of 2321 SDG-associated keywords.[2]

Against this backdrop, the central element of our analytical framework is the use of the improved Term Frequency- Inverse Document Frequency (TF-IDF) bigrams weighted Word2Vec as text modeling strategies on the textual content of AI-patents. This method has been shown to be effective in overcoming limitations of simple occurrence counts, addressing issues of zero-inflation and document length bias (Lilleberg et al., 2015; Ramadhani and Wibawa, 2022; Appio et al., 2024). Therefore, it provides a more robust exploration of the semantic relationships among words and constructs to better represent the technical content of recent AI-patented development and to consequently assess the implications of the new trajectories for achieving SDGs.

3.1. Data preprocessing

At the initial stage of analysis, the textual content in AI patents was preprocessed to clean, harmonize and tokenize all the input text. This preprocessing phase transformed unstructured patent data into structured ones, through a comprehensive text normalization process that filters out unnecessary or confounding data. Following establishing methods (Lee et al., 2020; Hajikhani and Suominen, 2022) the process included lowercasing, removing blanks, stop words (like articles, prepositions and conjunctions), extra whitespaces, and special characters,

[1] In their contribution, Baruffaldi et al. (2020) addressed the challenges occurring in delineating the boundaries of AI-related development, by providing a comprehensive approach to identifying and measuring developments in AI. The authors defined an exhaustive list of 214 AI-related keywords-spanning from action recognition to xgboost- and of 63 CPC codes. The complete list can be assessed through the following link: https://www.oecd-ilibrary.org/docserver/5f65ff7e-en.pdf?expires=1725901325&id=id&accname=guest&checksum=0DCD6504DC66E5FB687D9C756F51953B.

[2] The full list of SDG-associated keywords is fully available at the link https://www.sdgmapping.auckland.ac.nz/. The list includes keywords associated to all the SDGs except for SDG17.

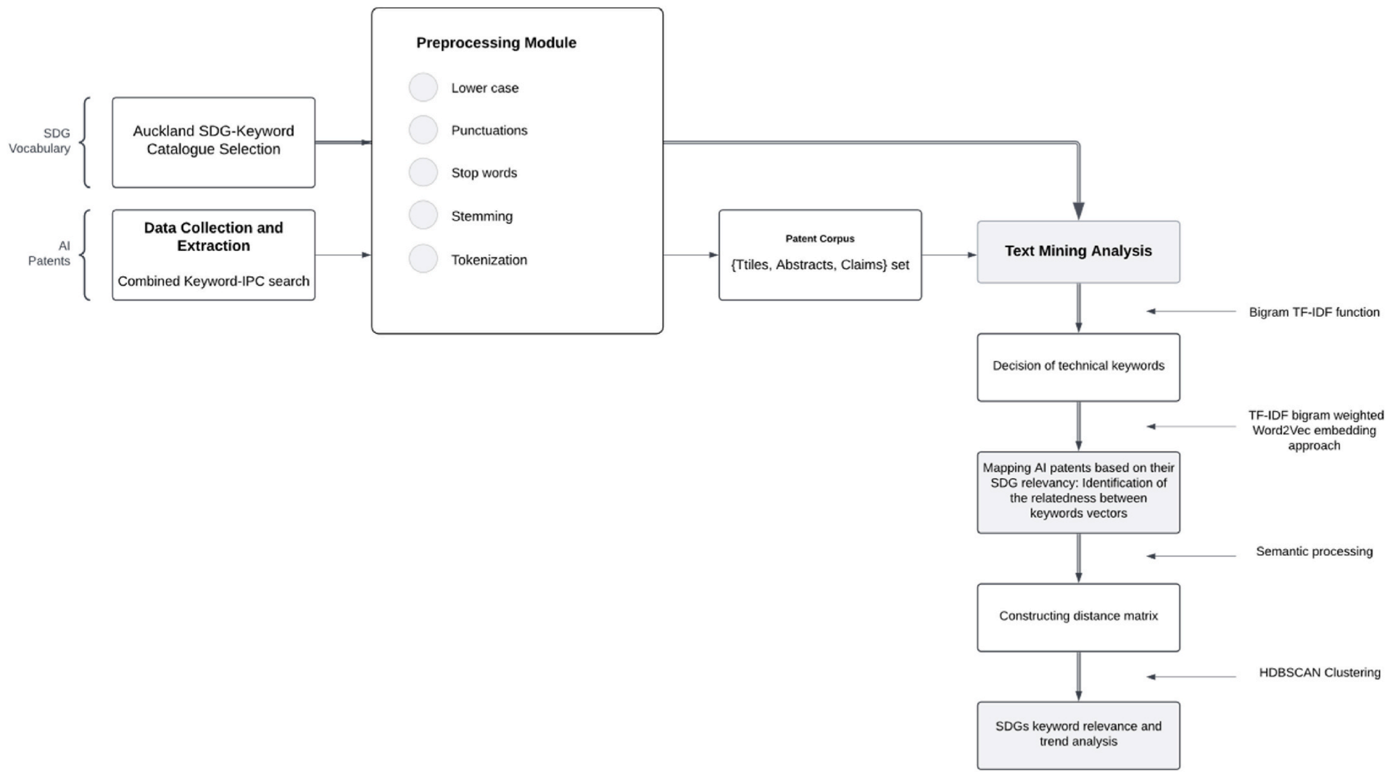

Fig. 1. Workflow for Sustainable Development Goals (SDGs) mapping of AI-Patents.
Source: Authors' personal elaboration

followed by lemmatization and tokenization for improved natural language processing (NLP) analysis.

3.2. Word embedding for AI-patented ideas

To numerically represent the high-specific technical content of AI patents, among various word embedding techniques, we rely on Word2Vec with TF-IDF-based n-gram filtering. Introduced by Mikolov (2013), Word2Vec maps words into vector space using a neural network model, based on a large text corporus. Two different approaches have been proposed: the continuous bag-of-words (CBOW) and the continuous skip-gram. While the former predicts the current word based on its surrounding words, the skip-gram uses the current word to predict the surrounding window of words (Mikolov, 2013). Although slower, this study adopts the skip-gram method, as it outperforms CBOW (Goldberg and Levy, 2014) and other embedding models, like fastText (Kang and Yang, 2020), and Glove (Dharma et al., 2022) in handling less frequent words. Following Lilleberg et al. (2015) and Schmidt (2019), we assume adding a weighting approach within documents in Word2Vec can enhance performances in text analysis, particularly in some domain-specific contexts like AI. Using bigram TF-IDF weighting further reduces noise, enhancing the accuracy of AI patent representations and better reflecting the underlying semantic and syntactic structures specific to AI patented technologies. Formally, this method computes bigram weights through the inverse proportion of frequency of a phrase in a document text to the percentage of documents where the bigram appears:

$$w_{jk} = tf_{jk} * log\left(\frac{n}{df_j}\right)$$

with tf_{jk} the number of times bigram j occurring in document k; n is the total number of documents in the document set; df_j is the total number of documents containing the bigram j.

3.3. Identifying the relatedness between AI-patents and SDGs

Following word embedding, the relatedness between each AI-patent and SDG keyword was measured using cosine similarity, where higher cosine values indicated greater similarity between the corresponding vectors. Cosine similarity was computed as:

$$Cosine\ Similarity\left(v_{AIpatent}, v_{SDGKeyowrd}\right) = \frac{v_{AIpatent} {}^{*} v_{SDGKeyword}}{\| v_{AIPatent} \| \| v_{SDGKeyword} \|}$$

where $v_{AIpatent}$ and $v_{SDGKeyowrd}$ are the respective vector representations, $v_{AIpatent} {}^{*} v_{SDGKeyword}$ denotes their dot product, and $\| v_{AIPatent} \| \| v_{SDGKeyword} \|$ represents the product of their magnitudes.

Once the cosine was computed, to deeply explore the broader alignment between AI-patents and SDGs, we aggregated cosine similarity scores at the SDG level, by calculating the mean of all the cosine similarity values for the keywords associated with each SDG, as follows:

$$\overline{Cosine\ Similarity}_{SDG_i} = \frac{1}{|K_{SDG_i}|} \sum_{k \in K_{SDG_i}} Cosine\ Similarity\left(v_{AIpatent}, v_{SDGKeyowrd}\right)$$

Where K_{SDG_i} is the set of keywords linked to SDG_i. This approach provides a more comprehensive measure of how each AI-patent aligns with specific SDGs, thus highlighting the technological advancements effectively contributing to sustainable development goals.

3.4. Clustering analysis

One way to cluster the information to identify new AI advancements that align with SDGs is to follow unsupervised machine learning techniques. Following previous studies (Campello et al., 2013; Liu et al., 2023) we applied Hierarchical Density-Based Spatial Clustering of Application with Noise (HDBSCAN), that has been found to adaptively cluster data while naturally distinguishing noise and outliers. Compared with other popular clustering algorithms, HDBSCAN has shown promising results in patent landscaping (Appio et al., 2024; Lin et al., 2024; Park and Lee, 2024), as it allows to automatically find the optimal number of clusters, only specifying *min samples* and *min cluster size* (Hu et al., 2020), while handling irregular shapes and non-uniform distribution of data points.

4. Results

The described approach designed to assess the relatedness of AI-patents to SDGs was implemented in RStudio software. Using the combined keyword-based search with IPC codes of Baruffaldi et al. (2020), we identified 23.444 AI patent families, encompassing both applications and granted patents. The analysis covered a timespan from 1979 to 2023, capturing the evolution of AI solutions from their early development stages to the most recent ones across various industries. Notably, patent filings have significantly increased in recent years, peaking at 2701 in 2020. In terms of technological domains, computer technology dominates with 20.927 findings, followed by telecommunications (6.442), IT methods for management (4.402), medical technology (4.234) and control systems (3.811), thus underscoring the pervasive role of digital transformation across sectors. The sample encompasses 6.486 AI assignees - entities holding patent rights - indicating a strong concentration of patents among few major players. Table 1 presents AI patent filings per year (panel A) and by their technological domains (panel B). After noise removal from patents' corpus (titles, abstracts and claims), we applied a bigram-based TF-IDF filtering approach to convert documents into numerical representations. A skip-gram Word2Vec, trained on the filtered text, resulted in the extraction of 9.253 keywords, forming the vocabulary for AI patent vectorization. To map AI-patented developments to the SDGs, we applied the same pre-text cleaning to SDG-related keywords, representing them in the same vector space, using the trained Word2Vec model. Cosine similarity was computed to compare AI patent vector with SDG keywords vector, assigning patents to the most similar SDG(s) based on contextual meaning rather than simply keyword matching.

Table 2 summarizes the SDG assignment distribution of AI patents based on their relevance to one or more SDGs, as determined through the cosine similarity. Of the 23444 AI patents, 22196 (94.7 %) were exclusively assigned to a single SDG.

Among the single-SDG assignments, SDG 11 (Sustainable Cities and

Table 1
AI Patents' Filling per year and Technological Domains.

Panel A.			*Panel B.*		
AI Patents' Filings per year			AI Patents' Technological Domains		
Year	**Number**	**Perc. Variation**	**Technological Domain**	**Number**	**Percentage**
1970	1		Computer technology	20927	36.23 %
1979	7	600.00 %	Telecommunications	6442	11.15 %
1980	8	14.29 %	IT methods for management	4402	7.62 %
1981	25	212.50 %	Medical technology	4234	7.33 %
1982	26	4.00 %	Control	3811	6.60 %
1983	20	−23.08 %	Measurement	3457	5.98 %
1984	32	60.00 %	Audio-visual technology	3179	5.50 %
1985	32	0.00 %	Digital communication	2913	5.04 %
1986	39	21.88 %	Transport	1730	2,99 %
1987	51	30.77 %	Handling	1092	1,89 %
1988	76	49.02 %	Optics	998	1.73 %
1989	110	44.74 %	Biotechnology	662	1.15 %
1990	116	5.45 %	Analysis of biological materials	570	0.99 %
1991	127	9.48 %	Furniture, games	465	0.80 %
1992	114	−10.24 %	Other special machines	367	0.64 %
1993	123	7.89 %	Electrical machinery, apparatus, energy	364	0.63 %
1994	126	2.44 %	Other consumer goods	262	0.45 %
1995	112	−11.11 %	Textile and paper machines	223	0.39 %
1996	128	14.29 %	Machine tools	211	0.37 %
1997	184	43.,75 %	Semiconductors	187	0.32 %
1998	211	14.67 %	Basic communication processes	187	0.32 %
1999	321	52.13 %	Chemical engineering	177	0.31 %
2000	377	17.45 %	Civil engineering	176	0.30 %
2001	369	−2.12 %	Environmental technology	133	0.23 %
2002	396	7.32 %	Pharmaceuticals	101	0.17 %
2003	428	8.08 %	Engines, pumps, turbines	99	0.17 %
2004	381	−10.98 %	Thermal processes and apparatus	74	0.13 %
2005	445	16.80 %	Organic fine chemistry	71	0.12 %
2006	388	−12.81 %	Mechanical elements	63	0.11 %
2007	404	4.12 %	Materials, metallurgy	54	0.09 %
2008	408	0.99 %	Surface technology, coating	40	0.07 %
2009	438	7.35 %	Food chemistry	39	0.07 %
2010	467	6.62 %	Basic materials chemistry	26	0.05 %
2011	544	16.49 %	Micro-structure and nano-technology	24	0.04 %
2012	648	19.12 %	Macromolecular chemistry, polymers	8	0.01 %
2013	684	5.56 %			
2014	782	14.33 %			
2015	971	24.17 %			
2016	1220	25.64 %			
2017	1716	40.66 %			
2018	2254	31.35 %			
2019	2507	11.22 %			
2020	2701	7.74 %			
2021	2158	−20.10 %			
2022	683	−68.35 %			
2023	86	−87.41 %			

Table 2
Distribution of AI patents by SDG assignment type.

SDG Assignment Type	Number of Patents
Single SDG Assignments	22196
Dual SDG Assignments	769
Three SDG Assignments	431
Four SDG Assignments	40
More than Four SDG Assignments	8
Total AI-patents	23444

Communities) accounted for the highest number of patents (2868), thus indicating a strong orientation of AI innovations toward urban infrastructure, efficient transport systems and sustainable urban planning. This is followed by SDG 3 (Good Health and Well-Being) with 2466 patents, emphasizing the growing adoption of AI solutions in healthcare domains, like diagnosis, treatment optimization, and patients monitoring. SDG 4 (Quality Education) received 2259 AI patents, reflecting the role of AI in enhancing educational access, personalization, and increasing the quality of pedagogical innovation. SDG 9 (Industry, Innovation, and Infrastructure) accounted for 2022 AI patents, emphasizing the role of AI solutions in supporting industrial transformation and technological innovation, particularly within manufacturing industries. Additionally, AI patents linked to SDG 13 (Climate Action), SDG 12 (Responsible Consumption and Production) and SDG 10 (Reduced Inequality), with 1970, 1773 and 1463 patents respectively, show the significance of AI in addressing environmental and social sustainability challenges. In the environmental domain, SDG 14 (Life Below Water) stands out with 1441 patents, SDG 7 (Affordable and Clean Energy) collects 1349 patents, while SDG 15 (Life on Land) and SDG 6 (Clean Water and Sanitation) have fewer assignments (710 and 431, respectively). On the other hand, AI's role in addressing poverty and hunger is clearly visible in SDG 1 (No poverty) with 923 patents and SDG 2 (Zero Hunger) with 695 patents. Emerging contributions are also observed for SDG 5 (Gender Equality) and SDG 16 (Peace, Justice and Strong Institutions), with 498 and 644 patents respectively, pointing to an increasing interest in leveraging AI for social inclusion.

However, in line with evolving complexity of challenges that AI is being called to address, our findings underscore the ability of AI to contribute to multiple SDGs simultaneously. In particular, 769 AI-patents were simultaneously associated with two SDGs, 431 patents with three SDGs, and 40 patents were linked to four SDGs. A residual group of patents (8 in total) were assigned to more than four SDGs. These cases represent highly integrated AI solutions designed to address an interconnected set of sustainability challenges.

To deepen the understanding of AI's role in advancing SDGs, Fig. 2 presents the distribution of AI patents according to their aggregate cosine similarity scores, ranked from highest to lowest relevance per SDGs. The results show that the highest share of AI-patents (14.9 %) is heavily focused on urban infrastructure (SDG 11), thus underscoring a strong focus on AI solutions that contribute to smarter and more efficient cities. It follows the 11.7 % of AI-patents linked with Health and Well-Being (SDG 3), with an increasing number of technologies enhancing patient management and treatment. Additionally, SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) are also prominent, representing 11.26 % and 10.66 % respectively. This demonstrates that AI-patented innovations are significantly contributing to environmental sustainability, particularly through the progressive adoption of even more digital-based technologies that enhance industrial efficiency, reduce waste, and boost the adoption of circular management approaches. The prominence of these two SDGs suggests that industries are adopting technologies to redefine their value chains and address both consumption and production challenges, while simultaneously targeting climate-related issues. Conversely, one interesting observation is the relatively lower focus on other critical areas, such as clean water (SDG 6), gender equality (SDG 5), and zero hunger (SDG 2), signaling that there remain unexplored opportunities for AI to drive progress in basic human needs and social equity.

Finally, to illustrate the semantic proximity between AI patents and the various SDGs, the resulting cosine similarity matrix was visualized as a heat map (Fig. 3). This helped us to quickly identify which SDGs are most frequently associated with AI patents and detect patterns of how AI solutions are spread across different sustainability goals. In this representation, darker areas indicate a higher degree of similarity between AI-patents and a specific SDG, whereas lighter areas represent lower similarity scores.

Building on these preliminary insights, we delved into the analysis of the seven resulting clusters, each shedding light on distinct innovation trajectories across sustainability. This more granular exploration allowed us to better understand how AI solutions are being applied in diverse domains.

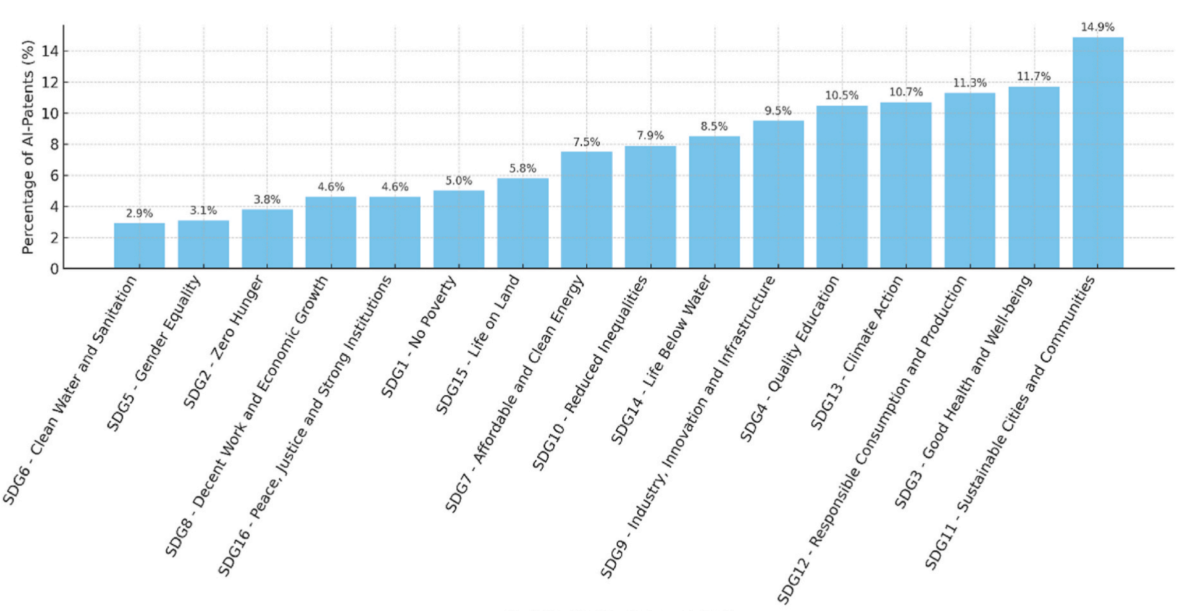

Fig. 2. AI Patents distribution across Sustainable Development Goals (SDGs).
Source: Authors' personal elaboration

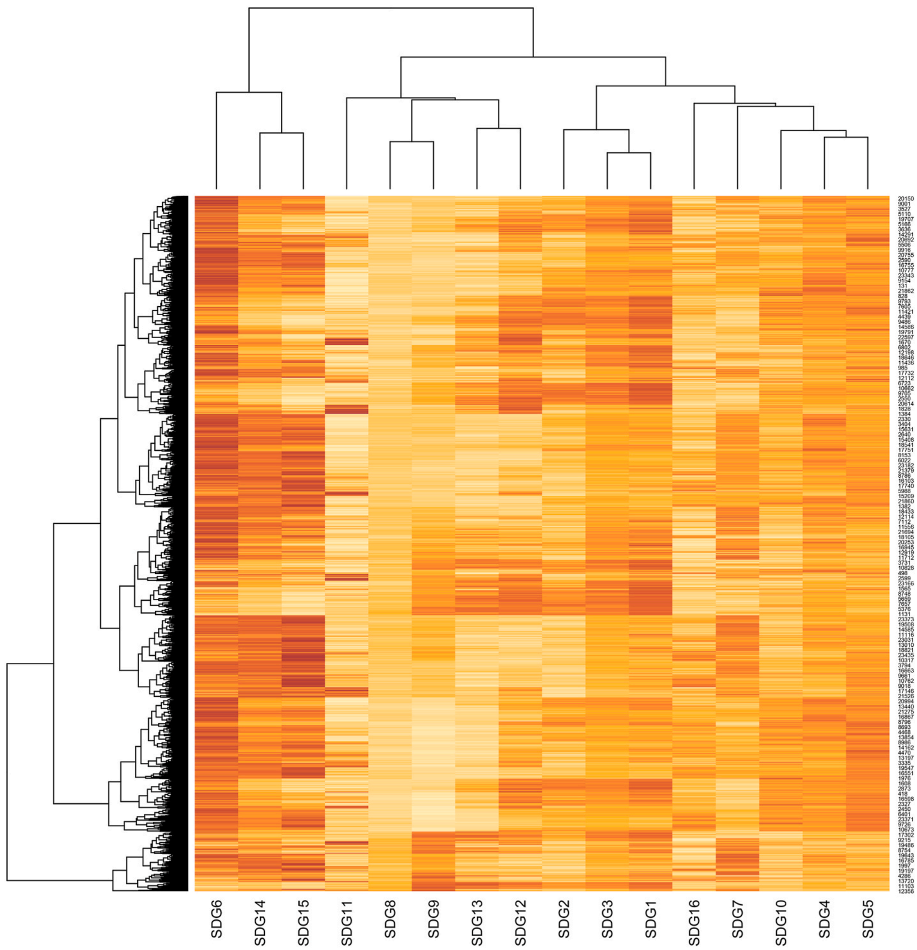

Fig. 3. Heatmap of AI-Patent similarity across SDGs.
Source: Authors' personal elaboration

The first cluster includes patents focused on AI technologies related to visual data processing and interpretation. Specifically, these innovations include systems able to handle both static and dynamic images, based on high-dimensional visual and sensory data. As underlined by words like "image", "processing", "pixel", "medical", "color", a significant share of these AI patents is oriented toward AI-driven image analysis for medical purposes, especially in radiology and dermatology, where AI supports diagnostic scanning through X-rays and MRIs. Terms like "image", "imaging", "search", "facial", "device" and "body", or "video", "digital", "patterns", "physical", "tissue" also underscore an increasing attention to technological applications for biometric monitoring, telemedicine and real-time patient assessment, to timely detect diseases and anomalies. In the same direction, the presence of words like "object", "detection", "control", "sensor", "mobile" point to the development of sensor-based technologies and automated detection algorithms, often embedded in wearable health devices or mobile diagnostic tools. Finally, from the technical viewpoint, terms such as "network", "neural", "training", "feature", "model" and "topic" reflect the complexity of these AI learning architectures needed for visual data processing.

Cluster 2 centers on the integration of AI technologies into industrial manufacturing, aiming at redefining value creation processes to enhance efficiency and industrial automation through AI-based control, sensing and decision-making support systems. As stressed by the prevalence of words like "sensor", "measurement", "processing", and "device", AI technologies in this cluster heavily refer to real-time monitoring and predictive analytics. The cluster also includes patents focusing on mobile sensor technologies used for spatial positioning and tracking in manufacturing processes (as indicated by words like "feature", "image", "vector", "map", "motion" and "recognition"). Further, the presence of words like "vehicle", "robot", "mobile", "control", "autonomous" and "road" highlight AI's role in advancing logistic automation and intelligence transport systems. Similarly, terms like "information", "target", "processing", "node", and "position" suggest the progressive adoption of AI technologies in dynamic warehouse settings, reshaping the entire logistic value chain.

Cluster 3 brings together AI patents aimed at supporting the public sector and improving services accessibility, through those AI systems capable of analyzing administrative data and guiding quasi-automatic decision-making processes. Terms such as "time", "process", "evaluation" and "reference" underscore the potential of AI-driven applications in policy simulation and risk assessment in strategic planning, helping manage the complexity of administrative workflows. Additionally, the occurrence of terms such as "information," "control", "target," "system," and "virtual" suggests the usefulness of AI-driven solutions for the development and the updating of public platforms, based on the principles of transparency and data openness. Meanwhile, another portion of AI patents in this cluster reflects AI applications aimed at improving facilities accessibility for citizens.

Differently, Cluster 4 includes AI technologies that support environmental innovation within industrial settings. These technologies refer to smart solutions that improve efficiency and enable environmental monitoring, often leveraging AI for resource management and environmental performance optimization. This cluster also includes patents for real-time control systems, as remarked by words like "sensor", "vehicle", "control" and "frame", which rely on continuous feedback loops to minimize both environmental and economic impacts of manufacturing. For instance, such systems are specifically designed to monitor gas emissions and energy consumption, assisting industries in making greener production decisions. Further, several patents focus on AI-based architectures, reflected by terms like “network”, “neural”, “training” and “model”, that could enhance operational performance while enabling learning mechanisms for real-time processes’ adjustments in response to environmental data. Finally, many of these AI technologies are designed to remotely work on devices like sensors and mobile equipment, capable of handling and processing data locally without external connectivity, thus making AI a key enabler of more scalable green innovation.

Cluster 5, the largest in terms of patents count, encompasses a broad set of AI technologies applied to smart mobility. Its size reflects the growing strategic importance of this domain, where AI is concretely leveraged to enhance transportation efficiency, safety, and sustainability. Specifically, words like “vehicle”, “robot”, “autonomous”, “motion” and “control” highlight the central role of AI solutions for traffic management control, smart logistic and self-driving vehicles, able to spur sustainability within the mobility industry, often through the integration of energy-efficient infrastructures. Moreover, this cluster includes AI solutions that combine image processing with sensor data, thereby increasing accuracy and timely object recognition, with the goal of enhancing safety and efficiency in transport, especially in urban environments. In the same direction, closely linked to this are AI-related patents supporting user interactions, enabling forms of “speech”, “voice”, “text” and “acoustic” recognition and conversion, confirming the increasing use of voice-controlled systems in both autonomous and semi-autonomous vehicles.

Unlike previous clusters, Cluster 6 covers patented AI technologies aimed at enhancing digital accessibility and smart communication, without a specific focus on a single domain. As remarked by words like “video”, “content”, “query”, “language”, this cluster includes technologies that make digital interfaces more natural, intuitive and accessible for a wider range of users, thereby contributing to the deployment and increasing adoption of assistive tools, particularly in public, healthcare and educational settings. That is, patents in this cluster focus on systems combining multiple data sources to extract and deliver information, frequently leveraging virtual or augmented reality (VR/AR) to support AI-assisted services and automated customer support. Further, this cluster includes technologies supporting computer vision and gesture recognition, as highlighted by words like “object”, “detection”, “gesture”, “motion”, “target” and “bounding”. In particular, these technologies unlock the potential of touchless navigation and environmental perception in smart public spaces, making public environments more responsive and adaptable to diverse user needs, and ultimately impacting on inclusivity.

Finally, Cluster 7 encompasses AI technologies designed to improve cybersecurity and ensure data privacy across digital services and infrastructures. Words like “user”, “device”, “electronic”, “text”, “content”, “language” and “search” suggest the development of tools that secure digital interactions while implementing automatic filtering of online content, to prevent privacy violations and uncontrolled data compromises. This often requires the adoption of deep learning models and neural networks able to detect data flows anomalies, suspicious links and prevent intrusion attempts through adapting cybersecurity protocols, as reflected in terms like “network”, “neural”, “vector”, “data”, “classification”, and “output”. Moreover, terms like “information”, “target”, “processing”, “unit” and “candidate” emphasize the focus of AI technologies on access management, supporting the deployment of risk scoring and data labelling systems while minimizing data leakage.

Table 3 provides an overview of the seven identified AI patent clusters, highlighting their dominant SDGs and the associated top ten keywords.

Table 3
Dominant SDGs and top ten keywords of the clusters.

Cluster	No. Patents	Dominant SDGs	Keywords
1	1971	SDG 3, SDG 9	image, processing, pixel, medical, color, facial, body, physical, tissue
2	2909	SDG 9, SDG 12	sensor, measurement, processing, device, robot, autonomous, control, node, vector, motion
3	3057	SDG 16, SDG 4	time, process, evaluation, reference, information, virtual, target, system, control, human
4	2816	SDG 12, SDG 13	sensor, vehicle, control, frame, network, neural, training, model, prediction, detection
5	8117	SDG 11, SDG 7	vehicle, robot, autonomous, motion, control, speech, voice, text, acoustic, sensor
6	2269	SDG 10, SDG 16	video, content, query, language, object, detection, gesture, motion, target, bounding
7	2305	SDG 16, SDG 9	user, target, electronic, text, content, language, search, data, classification, candidate

5. Discussion

This study systematically maps the landscape of AI-related patents with respect to their contribution to sustainable development, leveraging a novel semantic methodology. Our findings provide significant insights into the role of AI in promoting sustainable development and offer evaluable implications for academics, managers and policymakers.

6. AI and SDGs: a dualistic relationship

Our results demonstrate the rapidly growing role of AI as a critical tool in sustainability transitions, with notable concentrations in industrial applications that deliver environmental and social value. By identifying seven thematic clusters of AI-patented technologies, our findings not only illustrate how AI is being operationalized across various domains, but also show the breadth of AI’s role and its effectiveness in reshaping socio-technical and cultural systems. In particular, deepening the analysis of AI-related patents in each cluster, this study confirms the dualistic relationship between AI and sustainability: even if AI patents can drive industrial adoption, promote resource efficiency, decarbonization and foster sustainable innovations that align with SDG targets (Kulkov et al., 2024), the extent to which AI patents effectively translate into actionable outcomes depends on the breadth of its potential drawbacks.

Cluster 1 groups AI-related patents in the areas of diagnostic imaging, biometric analysis and clinical decision-making, aiming to enhance diagnostic precision, build trust and promote transparency in reasoning (Crumbly et al., 2025; Fong et al., 2025). For instance, patent 8458 refers to “*a computer-based diagnostic system […] to classify organ regions of diseased functional tissue […] as belonging to a set of abnormal image patterns*”, reflecting a clear use of AI for predictive processes. Similarly, patent 16696 addresses anatomical estimation of “*a chest well shape*” through optical scan data and machine learning, while patent 795 proposes a detection system for “*biological conditions based on fluorescence imaging*”, providing support for the use of AI-enhanced real-time disease monitoring. Patent 2555 goes further proposing a system for “*determining a body language state*” based on contextual attributes like culture, race, age, mental and physical health conditions-useful to interpret non-verbal behavior, thereby enhancing patient monitoring and broadly aligning with SDG 3 (Good Health and Well-being).

While these solutions offer clear value, they also raise ethical and practical concerns. AI systems that heavily rely on sensitive biological or behavioral data (e.g., patents 2555, 8458) raise significant privacy concerns, particularly for vulnerable individuals (Murdoch, 2021). In addition, clinicians may exhibit automation bias: as remarked by WHO (2021), physicians should not ignore their own competencies and judgment in favor of AI recommendations, which can pose several risks to both patient safety and healthcare quality. Further, many AI inferential models, especially those based on pattern recognition (e.g., patent 16696), may replicate societal bias and discrimination, exacerbating disparities in health care particularly in highly decentralized systems (Aminizadeh et al., 2024). Cluster 2, on the other hand, gathers AI-related patents in industrial settings, emphasizing how real-time sensing, control systems and automated decision-making tools are redefining value creation. For example, patents 13088, 21456, and 22428 perfectly capture this industrial logic. The former claims a "*method for automatically detecting a malfunction of a device into food and beverage industry*", while patents 21456 and 22428 refer to "*a control managing transport of vehicles*" and "*a logistics facility management system*" respectively, exemplifying AI's contributions to predictive maintenance in production chains and intra-logistics coordination in smart warehouses, thereby supporting SDG 9 (Industry, Innovation and Infrastructure). Complementing this, patent 20781 proposes a method for "*automatically generating AR landmarks [..] while performing maintenance operations in a device*", suggesting a progressive shift toward error-minimizing and increased efficiency (Agrawal et al., 2023). Differently, patents 17173 and 19269 underscore the impact of AI technologies for energy optimization, through "*a concentrating type of hybrid photovoltaic system*" and "*an image processing system […] for adaptive energy settings*" respectively, supporting carbon footprint reduction (SDGs 13- Climate Action, and 12- Responsible Consumption and Production). Yet, this cluster also reveals some constraints. Data quality dependencies and operational complexity (patents 13088, 17173, 20781) may hinder reliability and scalability, especially in dynamic and resource-constrained conditions. Beyond these operational constraints, broader systemic concerns are related to job displacement (Rawashdeh, 2025), with an estimated labour-market churn of 152 million jobs (23 % of 673 million employees) across countries and sectors between 2023 and 2027 (World Economic Forum, 2023, pp. 28–36). These transformations are obviously accompanied by reskilling strategies, thus potentially undermining SDG 8 (Decent Work and Economic Growth) and SDG 1 (No Poverty). Furthermore, the same AI-driven systems that optimize industrial supply and value chains may also intensify unsustainable consumption patterns by stimulating overproduction (Belanche et al., 2024). Those feedback loops between AI advancements and product system responsiveness could ultimately amplify environmental and societal pressures, ultimately hindering the achievement of SDGs 12 (Responsible consumption and production), 13 (Climate action), 14 (Life below water) and 15 (Life on land).

Cluster 3 reflects the growing implementation of AI technologies aimed at improving public administration and decision-making (Kulal et al., 2024; Anshari et al., 2025), and service accessibility. Patent 14128 introduces "*a policy evaluation device",* confirming how AI tools can be leveraged for policy forecasting and assessment, helping administrators optimize interventions. This rationalization of administrative processes also resonates in patent 114, which introduces an "*automated document extraction and classification [method]*" directly supporting digital workflows and accelerating public service delivery. Similarly, patent 79 enhances public efficiency through "*an optimization framework for optical character recognition of low-resolution […] documents*". Differently, patent 11818 focuses on service accessibility, through "*a method for real-time object recognition for […] visually impaired individuals*" based on context-aware voice guidance and sensor data. Complementing this, patent 3306 claims "*a system for improving disordered speech recognition*", contributing to facilitating public interactions, while patent 1295 focuses on "*text-to speech navigation and multimedia navigation*". Similarly, patent 935 claims a "*method for asynchronous multi-mode messaging*", allowing flexible communication through multiple interfaces. Taken together, these patents disclose the inclusive potential of AI to reduce barriers to services, directly aligning with SDG 10 (Reduced Inequality) and SDG 4 (Quality Education), through accessible digital infrastructures and inclusive information systems. However, the effectiveness of these innovations is constrained by technical and ethical limitations. Several technologies rely on the availability of structured and clean data (patents 79, 114, 14128), implicitly confirming that excessive data noise and heterogeneity can compromise automation efficiency. Additionally, as reported in the AI Now Institute Report (2025, p. 51), AI algorithms systematically encode biases, "*from predictive policing systems that replicate historical patterns of "dirty" policing […] to algorithmic discrimination […].*" These biases can effectively lead to biased decision-making processes (Costanza-Chock, 2020) and discriminatory outcomes in service provision and resource allocation, ultimately impacting the achievement of SDG 16 (Peace, Justice and Strong Institution). Furthermore, overreliance on AI-generated outputs also raises critical issues, including AI hallucinations that can propagate errors across digital workflows, with severe consequences in both institutional and legal contexts (Taeihagh, 2025). These issues are compounded by the progressive erosion of citizen trust (Grimmelikhuijsen, 2023; Berman et al., 2024). Furthermore, the extensive integration of AI-assisting technologies into human daily routines, even if enhancing service accessibility, has led to cognitive offloading (Gerlich, 2025) while progressively increasing digital dependence (Rojas et al., 2024; Aghaziarati and Rahimi, 2025). This is even more true for individuals with lower baseline cognitive abilities, potentially reinforcing negative educational and social disparities (Aagaard and Vanhaverbeke, 2024; Roldán-Monés, 2024), thus conflicting with the goals of SDG 4 (Quality Education) and SDG 10 (Reduce Inequalities).

Concerning Cluster 4, the results highlight the potential of AI solutions in reducing the environmental impact of industrial and manufacturing processes. For instance, patent 9992 proposes a "*method for processing environmental data of an environment of a vehicle*", confirming the role of AI in enabling real-time monitoring through mobile sensing technologies. Patent 20679 discloses a "*method for determining the amount of pollutant emissions […] by a vehicle"*, demonstrating how AI solutions can support environmental public strategic planning. Similarly, patent 22588 proposed a "*method for online monitoring and optimization* […] *for mining and mineral processing operations*" specifically aimed at improving key performance, such as "*cost of operations, energy consumption […]*". Nonetheless, the same patent cluster presents certain limitations. Patent 15556 claims a method for "*reducing power consumption […] during generation and transmission of machine learning interfaces*", explicitly acknowledging the energy footprint of AI-systems (Bojic et al., 2024; Durmus Senyapar and Bayindi, 2025). This ultimately affects the achievement of SDG 12 (Responsible consumption and production) and 13 (Climate action). Furthermore, as emphasized by the patent 18530 claiming for a "*system […] for managing environmental, social, and governance perception of entities and industries*", there has been a shift toward reputation management over tangible sustainability practices, raising concerns about the risks of algorithmic greenwashing (Zhou and Li, 2025). Finally, the adoption of AI-complex monitoring systems (e.g., patent 12588) can be infrastructure and resource-intensive, especially for small and medium-sized companies in low and middle-income countries (Jamwal et al., 2025), thus reinforcing rather than reducing inequalities among firms, industries and countries (SDG 10 – Reduced inequalities).

In the context of smart mobility (Cluster 5), AI technologies are reshaping the mobility landscape, fostering real-time responsiveness and autonomous vehicle safety. Patents 30 and 7762 propose a "*vehicle-to-pedestrian collision avoidance system*" using a deep neural network and camera sensors to enhance object detection and prevent road accidents. Patents like 22 and 2103 introduce methods for controlling vehicles and autonomous vehicles by acquiring road images and through a traffic signal recognition model, respectively. In the same direction, patents 194, 2206, 7226 focus on environmental sensing and object detection for "*predicting three-dimensional features*", "*objects […] through sensor* *data, including images*" and "*obstacles in real-time*" to refine autonomous navigation in complex and dynamic scenarios. Yet, the same patents (22, 30, 103) warn about the heavy dependence on continuous network communication and data flows with potential vulnerability in low-connectivity environments, which can limit the scalability of smart mobility solutions in underserved areas (OECD, 2019, p. 52) and hinder the achievement of SDG 10 (Reduced Inequalities). Additionally, systems such as the one in patents 75 and 1948, focusing on "*textual emotion detection*" and "*human face detection model[s]*" respectively, implicitly highlight the risks of biased interpretation when AI systems mediate human interaction and behavior, raising ethical concerns especially when implemented in public settings (OECD, 2019). Finally, these issues intersect with broader debates on algorithmic transparency and privacy risks (Luusua et al., 2023; Sanchez et al., 2025).

In parallel, Cluster 6 expands to AI solutions that enhance digital accessibility and user experiences (Almufareh et al., 2024; Chemnad and Othman, 2024), aiming to make interfaces more intuitive and inclusive, especially in public contexts. Patents like 6550 and 8826 focus on improved accessibility in healthcare and assistive environments, through "*automatized medical screening and triage*" and a system for "*collecting first data associated with users […] including historical health data and set of [health-monitoring] sensor data*", respectively. Others, such as patents 6163, 8616, 10246 and 2333 expand the scope of accessibility by enabling integrated and multimodal data collection to provide "*customized experience for [a] user*" (patent 10246) and evaluable information and records "*preferably trained by supervised machine learning*" (patent 8626). These innovations directly contribute to the promotion of SDG 10 (Reduced Inequalities), SDG 3 (Good Health and Well-being), and SDG 9 (Industry, Innovation and Infrastructure), as they foster more responsive digital ecosystems. Furthermore, patents like 4118, and 21604 extend the development of gesture-based interfaces, supporting natural and contactless interactions. Patent 4118 claims "*a voice-controlled user interface […] through image acquisition modules*", while patent 21604 discloses "*a speech recognizer [and translator] system*", suggesting how such technologies support the assistive and inclusive nature of public environments, reducing barriers across populations with physical, linguistic or cognitive needs. In turn, these solutions support the pursuit of SDG 16 (Peace, Justice and Strong Institutions) by promoting equal access to information, communication, and institutional services. Despite these advancements, several drawbacks persist. Many of these technologies require systemic challenges in integration and resource allocations (e.g., patents 6550 and 8826). Additionally, patents like 6163, 8616, 10246, and 2333 implicitly acknowledge the risks of result inaccuracy due to data incompleteness and poor quality. Similarly, the development of gesture-based solutions often requires high investments and efficient digital infrastructures, potentially exacerbating disparities across developed and developing countries and negatively affecting SDG 10 (Reduced Inequalities). Lastly, the heavy dependence of these solutions on visual and sensory data may raise privacy concerns while also lowering trust in AI (Gomstyn and Jonker, 2025).

Finally, within Cluster 7, patents specifically claim new solutions "*enhancing cybersecurity and operational monitoring*" (e.g., patent 15742) while "*preserving the privacy of user[s]*" (e.g., patent 17064). Patent 12527, for instance, introduces a "*privacy-preserving voiceprint authentication apparatus and method*", which enables secure user identification without exposing raw voice data. Similarly, patent 13526 introduces a system for "*for layered masking of data*", allowing for the deletion of personally identifiable information, while patent 17527 specifically focuses on "*reducing visibility of [personal] images*". Yet, the same patents (such as patents 12527 and 17527) warn about the risk of biometric tracking and unauthorized access, profiling (Luusua et al., 2023; Sanchez et al., 2025), especially when coupled with users' limited or misleading understanding of the implications of data leakage (ENISA, 2022). If left unaddressed, these concerns may undermine the potential of AI to contribute to SDG 16 (Peace, Justice and Strong Institutions) and SDG 9 (Industry, Innovation and Infrastructure) by eroding public trust and transparency.

Table 4 summarizes the positive contributions and potential risks associated with each of the seven identified clusters.

7. AI for addressing grand challenges: a systemic perspective

Our findings shed light on how AI-related technologies can be leveraged to support sustainable innovations at organizational, industrial and institutional levels (European Commission, 2021), capitalizing on the well-acknowledged interactions between technological development and sustainability (Appio et al., 2024; Mancuso et al., 2025). A cross-cutting interpretation of the identified clusters reveals that AI is being deployed in domains crucial to the long-term resilience of society, intersecting with systemic transitions in labor markets, environmental sustainability, and societal challenges. At the same time, our study reveals that to fully exploit their potential while minimizing possible negative drawbacks, AI-related (patented) technologies must be both integrated into complex systemic solutions and governed by clear societal approaches.

In a broader context, the systemic perspective aligns with leading global sustainability frameworks and long-term development trajectories. The United Nations' 2030 Agenda positions AI as a strategic catalyst across all 17 Sustainable Development Goals; however, growing evidence indicates that AI can simultaneously enable and constrain progress toward these objectives. Similarly, the Planetary Boundaries framework (Steffen et al., 2015) underscores the urgency of respecting ecological thresholds, thereby reinforcing emerging calls for an "Earth-aligned AI" agenda – one oriented toward mitigating greenhouse

Table 4
AI patent clusters benefits and potential drawbacks.

Cluster	Benefits	Potential drawbacks
1	[SDG 3] *In healthcare*: Enhanced image analysis, telemedicine and real-time patient assessment	[SDG 3] - Privacy concerns from biometric tracking and informed consent - Challenges in integrated AI in distributed health systems
2	[SDG 9] *In industrial settings*: Improved productivity, predictive maintenance automated logistics and energy optimization	[SDGs 1, 8, 12, 13, 14, 15] - Job displacement risks and labor force resistance - Modification of individual preferences and consumption choices towards polluting products
3	[SDGs 4, 16] *In public services and administrative activities*: - Improved public decision-making and service delivery - Enhanced administrative efficiency and accessibility	[SDGs 4, 10,16] Overreliance on AI-driven algorithms may increase opacity and lower citizen trust
4	[SDGs 12, 13] Greener manufacturing and real-time environmental monitoring	[SDGs 10, 12, 13] - High energy demand - Increased inequalities among adopters and non-adopters of AI solutions
5	[SDGs 7, 11] Advanced smart mobility solutions, traffic optimization and energy-efficient infrastructures	[SDGs 9, 10, 11] - Privacy concerns, ethical challenges in autonomous navigation and urban planning - Infrastructure gaps and economic viability constraints
6	[SDGs 3, 9, 10, 16] Improved digital accessibility, inclusive user interfaces and assistive technologies, especially for public and educational sectors	[SDG 10] Technological exclusion, due to the high cost of technologies and increased dependence on digital connectivity
7	[SDGs 9, 16] Enhanced cybersecurity and data privacy protection	[SDGs 9, 16] Potential false positives and overreliance on intersectionally biased algorithms

gas emissions, preserving biodiversity, and promoting just and inclusive access to sustainability-oriented technological advances. Complementary paradigms focused on Grand Societal Challenges and global megatrends – including climate disruption, demographic transitions, rapid urbanization, digital proliferation, and systemic inequality – further recognize that AI's transformative role is co-evolving with broader economic and institutional dynamics. As such, fully realizing AI's potential in addressing grand societal challenges necessitates a deliberate integration of technological innovation with normative governance frameworks. This integration should be firmly grounded in ethical principles, anticipatory regulatory practices, and multi-stakeholder collaboration, as underscored by prominent international initiatives such as the OECD AI Principles and UNESCO's Recommendations on the Ethics of Artificial Intelligence. Such governance approaches are crucial for effectively guiding AI trajectories toward outcomes aligned with societal well-being and the Sustainable Development Goals.

This implies that AI is not merely a technological tool, but a pivotal force in reconfiguring how the mechanisms through which economies grow, institutional architectures change, entrepreneurial business models evolve, and societies engage with global challenges. The clustering of AI patents across multiple SDGs highlights how AI is not merely an enabler of progress, but a general-purpose infrastructure, functioning as a strategic vector, whose directionality is shaped by regulatory frameworks, institutional settings and governance choices (European Commission, 2023).

Governance choices are crucial in finding the right balance between the benefits and drawbacks arising from the application of AI solutions. For instance, AI technologies in healthcare and public governance (clusters 1, 3 and 6) reveal the role of AI in democratizing access to goods and services, reshaping rights and responsibilities, recalibrating welfare delivery, and enabling more adaptive and data-driven decision-making. Nevertheless, such solutions introduce new dependencies on data quality and digital infrastructures. Moreover, as shown in clusters 2 and 4, related to environmental and industrial applications, AI empowers digital sustainability (Bello et al., 2024) while simultaneously raising concerns about the rebound effects of green technologies (Nishant et al., 2020; Inclezan and Prádanos, 2023). The key aspect is that AI-related applications are not neutral in their consequences: they tend to centralize decision-making while also fostering a transnational convergence of policy regimes (Filgueiras, 2022). In this sense, AI has become a tool for industrial and policy harmonization, which must be embedded within democratic, inclusive and more equitable economic, environmental, and social infrastructures. Similar dynamics can be observed in smart mobility and cybersecurity clusters (clusters 5 and 7), where AI solutions heavily rely on interconnected platforms and are increasingly dependent on algorithmic advancements. While such systems enhance predictive capabilities and operational efficiency, they also exacerbate privacy concerns and algorithmic opacity. This demands robust governance mechanisms to ensure traceability and explainability (Henman, 2020), aligning with calls from international institutions (OECD, 2024).

Ultimately, adopting this systemic, governance-mediated perspective implies moving beyond entrepreneurial dynamics to critically assess whether and how the evolving AI applications can reconcile with the broader SDGs. Building on this, our findings suggest that firms should increasingly integrate AI technologies into their business operations but also reveal tangible pathways to redefining their R&D structures operationally to better match sustainable development trajectories, ultimately fostering a culture of sustainability through organizational practices and open innovation strategies. This necessitates the development of anticipatory regulatory frameworks, that can align AI innovation with long-term societal goals and mitigate systemic risks (OECD, 2024). In this perspective, the integration of AI into daily lives must be understood not as a merely advanced process of digitalization, but as a shared project shaping progress across societies.

Furthermore, fostering broad-based AI literacy and public awareness remains essential to cultivating informed public engagement and facilitating democratic deliberation around AI's role in society.

From a systemic perspective, integrating AI into domains associated with grand societal challenges should be conceptualized as part of a broader socio-technical transformation, rather than merely as a technological solution. In the absence of clear policy guidance and rigorous governance structures, the proliferation of AI applications risks undermining climate goals, increasing existing socio-economic disparities, and affecting public trust and democratic institutions. Conversely, aligning AI development proactively with long-term societal and environmental goals can significantly improve the transition toward a low-carbon, more inclusive, and resilient global citizenship. Consequently, the extent to which AI contributes positively to sustainable development is essentially dependent upon collective governance decisions and institutional capacity. Realizing AI's transformative potential thus constitutes a crucial political-economic challenge, necessitating anticipatory regulatory frameworks, strong international collaboration, and a collective commitment to direct AI innovation toward outcomes aligned with the broader public interest.

8. Contribution to existing literature

By mapping the dynamics of AI patents in sustainable domains, our study provides several theoretical contributions. First, it responds to the call by George et al. (2021) on the instrumental role of digital innovations in tackling grand challenges while also identifying multiple paths for AI technological development. In doing so, it aligns with the European Commission's emphasis on digital technologies to support the achievement of the European Green Deal's goals (Gailhofer et al., 2021). Moreover, it confirms the strategic role of AI-related technologies in fostering new forms of digitally sustainable entrepreneurship (Di Vaio et al., 2020), unlocking new avenues for sustainable competitive advantage while benefiting from intentionally and better controllable spillover effects (Wang et al., 2023).

More broadly, by adopting the SDG framework, our study contributes to a better understanding of the diverse development paths pursued at both business and societal levels, to manage the twin transition. Our findings offer empirical evidence to the stream of literature that considers AI - at least when applied to sustainability - as a generally-purpose technology (Ballestar et al., 2020; Chen et al., 2023; Kopka and Fornahl, 2024) capable of driving paradigm shifts not only across business models and production systems but also within governance, infrastructure, and societal behavior, rather than simply applying AI to a specific technological domain for addressing isolated problems (Gebhardt, 2017; Guandalini, 2022).

While many AI-related patents are assigned to a single SDG, a non-negligible share of patents are simultaneously assigned to two or more SDGs, thus revealing how a single AI-related solution can address several (and potentially unrelated) application contexts. This suggests that the full realization of AI's potential for sustainability requires a parallel transformation of organizational structures, innovation ecosystems, institutional capacities, and even public policies. Finally, from a methodological point of view, this study introduces a comprehensive and nuanced approach for assessing the often-subtle connections between AI technologies and sustainability goals through patent data. Compared to traditional methods based on keyword frequency, which are often constrained by specialized and domain-specific language, our improved TF-IDF bigrams weighted Word2Vec approach provides a more robust framework for exploring and disentangling semantic relationships across these domains. This solution enables a more detailed assessment of how and to what extent AI technologies contribute to Sustainable Development Goals, thereby supporting a more analytical integration of digital and sustainability imperatives.

9. Conclusions and future research areas

This study provides empirical evidence of how AI-related patents intersect with and contribute to the Sustainable Development Goals. By uncovering the semantic alignment between AI solutions and SDGs, our findings underscore the dual role of AI as an enabler of sustainable transition and a vector of new societal challenges that require adaptive and proactive industrial and governance frameworks. As such, leveraging AI for sustainability requires not only technological advancement, but also adaptive and proactive governance, innovation infrastructures and inclusive policymaking. Embedding AI systems within equitable, transparent and mission-oriented frameworks that contribute to shared societal value will be essential to maximizing AI's potential as a driver of sustainable economic growth.

Despite its evaluable contributions, our study is not without limitations. First, the analysis is based exclusively on patented AI solutions, which may not encompass all the relevant AI innovations contributing to sustainability. Closely linked, while our semantic approach offers a more granular mapping of the interconnections between AI patents and sustainable goals, it is dependent on the accuracy of the chosen SDG keyword dictionary (Auckland approach). Third, even if recognizing the advantages of using the improved TF-IDF bigrams weighed Word2Vec method associated with the cosine similarity and HDBSCAN clustering approaches to assess the relatedness between AI patents and SDGs, future studies could benefit from future comparisons with alternative embedding techniques (e.g., BERT and SAO) to further validate the findings. Similarly, redefining the clustering based on innovation typologies, application purposes and organizational impact areas may provide deeper insights into the differentiated roles of AI. Furthermore, this study does not distinguish between different typologies of AI technologies-most notably, between generative AI (Gen-AI) and non-generative AI (non-Gen-AI) which are increasingly diverging in terms of applications, business models and sustainable impacts (Rafiq et al., 2025). Given the acceleration of Gen-AI tools, future studies should investigate their specific contributions and potentially trade-offs compared to more traditional AI applications, enabling a more differentiated understanding of how various AI typologies support or hinder the pursuit of different sustainability goals, and whether they generate distinct ethical, environmental and societal challenges, with concrete implications for both managers and policymakers. Additionally, our study does not employ classifiers to predict future AI patent assignments to specific SDGs, leaving space for future research to leverage predictive models in forecasting AI patent trends and their alignment with sustainability goals. Finally, further validation of our findings would benefit from sector-specific investigations to better uncover heterogeneous dynamics and development patterns of AI technologies, thereby more precisely assessing how AI technologies contribute to the achievement of SDGs in some technological domains (like healthcare, education, mobility), while also accounting for longitudinal differences in technological evolution and adoption over time (Valeriya et al., 2024).

Despite these limitations, our study provides a comprehensive overview of the potential of AI technologies to drive sustainable development, while also paving the way for broader interdisciplinary reflections, ranging from strategic business planning to the reconfiguration of innovation policy frameworks in light of digital and sustainable imperatives.

CRediT authorship contribution statement

Alessandra Costa: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Antonio Crupi:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Fabrizio Cesaroni:** Writing – review & editing, Writing – original draft, Validation. **Tindara Abbate:** Writing – review & editing, Writing – original draft.

Data availability

Data will be made available on request.

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