Review Article

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Ethical, Social, and Environmental Impacts of Generative Artificial Intelligence in Engineering: A Systematic Review*

Impactos éticos, sociales y ambientales de la inteligencia artificial generativa en ingeniería: una revisión sistemática

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Abstract

This paper presents a review and critical analysis of the multidimensional impacts of Generative Artificial Intelligence in the field of engineering, particularly the ethical, social, and environmental implications arising from its accelerated implementation. Its main purpose is to map the challenges and opportunities associated with sustainable development and innovation. To this end, a systematic approach based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology was employed to select relevant publications from the Scopus database, focusing on articles published between 2021 and 2025. Initially, a heuristic phase was conducted, during which 54 documents were selected according to the following categories of analysis: technology ethics, social aspects, and environmental issues. Subsequently, a hermeneutic phase was carried out to interpret the collected information. The results show an urgent need to develop a legislative framework, improve the transparency of algorithmic systems, and adopt a more proactive approach to addressing the ecological effects of these technologies. Finally, the analysis concludes that it is important to integrate robust ethical principles into technological development, strengthen engineering education, and establish comprehensive environmental assessment processes that support the development and deployment of all Generative Artificial Intelligence tools. In this way, shared responsibility among developers, users, and regulators can be fostered, thereby ensuring inclusive and sustainable technological advancement.

Keywords: environmental impact, generative artificial intelligence, sustainable development, sustainable engineering, technology ethics.

How to Cite

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Resumen

Se presenta una revisión y un análisis crítico de los impactos multidimensionales de la inteligencia artificial generativa en el campo de la ingeniería, particularmente de los aspectos éticos, sociales y ambientales que surgen de su implementación acelerada. El objetivo del estudio es mapear los desafíos y las oportunidades en el desarrollo sostenible y la innovación. Al respecto, se implementó un enfoque sistemático, según la metodología PRISMA, para seleccionar información publicada en la base de datos Scopus, mediante la indagación de artículos publicados entre 2021 y 2025. Inicialmente se desarrolló la fase heurística y se seleccionaron 54 documentos según las categorías de análisis: ética tecnológica, aspectos sociales y ambientales, y posteriormente se procedió con la fase hermenéutica para la interpretación de información. Los resultados muestran una necesidad urgente de desarrollar un sistema legislativo, mejorar la transparencia de los sistemas algorítmicos y centrarse de manera proactiva en los efectos ecológicos de estas tecnologías. Finalmente, se concluye que es importante integrar principios éticos estables en el desarrollo tecnológico, fortalecer la educación en ingeniería y establecer amplios procesos de evaluación ambiental que acompañen el desarrollo e implementación de todas las herramientas generativas de inteligencia artificial promoviendo la responsabilidad compartida entre desarrolladores, usuarios y reguladores para garantizar un avance tecnológico inclusivo y sostenible.

Palabras clave: impacto ambiental, inteligencia artificial generativa, desarrollo sostenible, ingeniería sostenible, ética tecnológica.

INTRODUCTION

The emergence of tools capable of generating content automatically has sparked intense debate around issues of innovation, ethics, and sustainability. In particular, attention has been paid to Generative Artificial Intelligence (GenAI), which has expanded rapidly in recent years. Systems that were once designed to process large volumes of information have since evolved into tools that can create new content autonomously, carrying implications across a wide range of fields. In factory automation, product design, the simulation of complex scenarios, the construction of predictive models, and strategic business decision-making, for instance, substantial changes are already being observed as a result of these technologies (Mikołajewska et al., 2025). Even so, several authors have raised concerns about the challenges posed by such rapid adoption. Questions regarding the ethical implications, societal effects, and environmental repercussions of GenAI remain open, and in-depth, context-specific research is still needed to address them (Cañavate et al., 2025).

Given this situation, clear regulatory frameworks and well-defined ethical principles are urgently called for. Only in this way can technological advancement be reconciled with respect for fundamental human rights and environmental stewardship. At the same time, collaboration among different stakeholders—governments, private companies, and research institutions—can facilitate the development of policies that promote transparency, equity, and accountability in how data-driven technologies are implemented (Prather et al., 2025).

For these reasons, it is essential that universities and workplaces assume a more active role in shaping how these platforms are used. Establishing training environments in which ethical values and social responsibility remain a constant priority is especially important. Doing so not only strengthens the technical preparation of future professionals but also enhances their ability to critically reflect on the consequences of their decisions (Honig et al., 2025).

This review made it possible to trace meaningful connections among the various theoretical and methodological approaches that researchers have adopted to address these issues. It also allowed for the identification of strategies that have proven effective in a range of contexts and settings, while underscoring the need to integrate perspectives from multiple disciplines in order to fully grasp the complexity of these challenges.

METHODOLOGY

To conduct this study, a systematic literature review was performed, as this method enables the identification, examination, and integration of scientific evidence in an organized and replicable manner. Through this approach, a critical analysis could be made of current knowledge regarding the social, environmental, and ethical implications of GenAI when applied to engineering, while also ensuring rigor in the selection and analysis of data (Onatayo et al., 2024). The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol was followed, given its relevance to research dealing with issues of ethics, technology, and emerging developments, as well as the clear guidelines it provides for selecting and analyzing available information (Page et al., 2021). The methodology comprised the following two phases:

Heuristic Phase

Relevant publications were first identified through systematic searches. An initial screening was then carried out based on predefined inclusion and exclusion criteria in order to address questions concerning the ethical, social, and environmental dimensions of GenAI use in engineering.

Sources of Information

The Scopus database was searched to retrieve research-related information. The search was restricted to scientific articles published between 2021 and 2025, with the aim of identifying evidence regarding the ethical, social, and environmental impacts of GenAI in engineering.

Search Strategy

The search criteria required that the title, abstract, or keywords simultaneously contain terms related to GenAI, its ethical implications, environmental sustainability, and engineering applications. Accordingly, the search strategy was structured around three main components, which together allowed for a comprehensive capture of the relevant literature.

The search was conducted using the following Boolean formula:

TITLE-ABS-KEY: ("IA Generativa" *OR* "Modelos de IA" *OR* "Inteligencia Artificial Generativa") *AND* ("Impacto Ambiental" *OR* "Sostenibilidad" *OR* "Ingeniería Verde") *AND* ("Educación en Ingeniería" *OR* "Ingeniería Sostenible" *OR* "Plan de Estudios de Ingeniería" *OR* "Educación para la Sostenibilidad").

Inclusion and Exclusion Criteria

These criteria (see Table 1) were established to ensure methodological rigor and thematic relevance in the selection of articles, so that the set of publications under review could be narrowed down and focused specifically on the ethical, environmental, and social sustainability impacts of GenAI.

Table 1. Inclusion and exclusion criteria applied in the systematic review

Inclusion Criteria	**Exclusion Criteria**
Publications between 2021 and 2025	Publications prior to 2021
Articles written in English or Spanish	Publications in other languages
Full text available	Restricted access
Studies published in indexed journals	Book chapters or conference papers
Research focused on ethics, sustainability, or innovation in engineering	Studies outside the thematic focus (e.g., unrelated to GenAI)

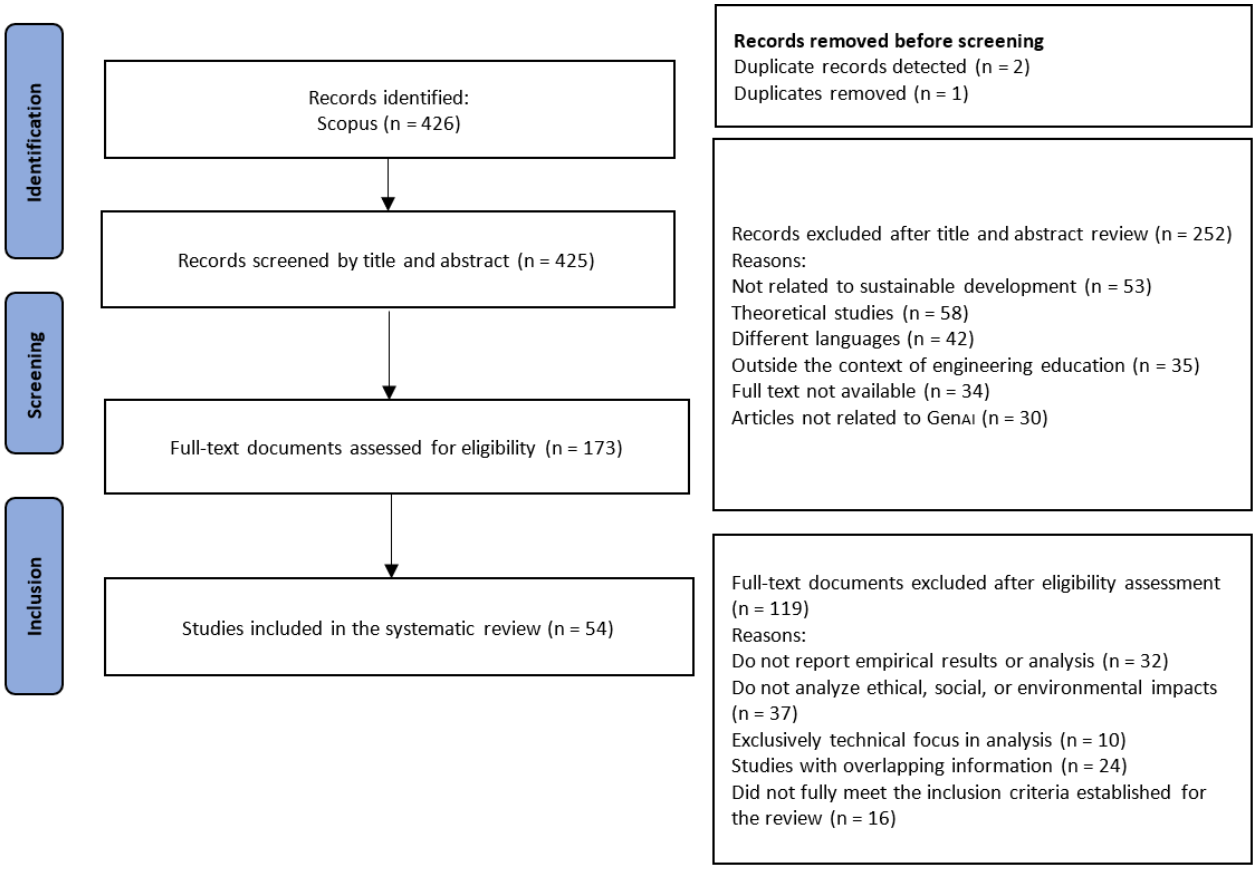
Source: Authors' own work.

By applying these criteria, it was possible to refine the initial set of retrieved articles and ensure that the evidence analyzed was directly aligned with the study's purpose. Therefore, publications on GenAI that did not address its ethical, social, or environmental implications in the context of engineering were excluded, as were those for which the full text could not be accessed.

Data Collection and Analysis

Rayyan software was employed to manage the systematic review process in accordance with the PRISMA 2020 protocol (Page et al., 2021). Initially, 426 records were identified in the Scopus database. Once two potential duplicates were detected and one was removed, 425 records remained for the screening process. As shown in Figure 1, 252 records were excluded after titles and abstracts were reviewed; the remaining 173 full-text documents were then assessed for eligibility, of which 54 studies ultimately met the inclusion criteria and were retained for the final analysis.

Figure 1. Flowchart of study selection according to the PRISMA 2020 protocol



Source: Adapted from Bazán Linares et al. (2023).

The screening process, carried out using the Rayyan tool, spanned 15 sessions and took more than six hours in total. Two independent reviewers oversaw the process, reaching an agreement rate of 87% on inclusion and exclusion decisions. Cases of disagreement (13%) were resolved through joint discussion until consensus was reached.

Hermeneutic Phase

The 54 selected articles were examined using an Excel spreadsheet designed to categorize key information such as author, year of publication, language, and methodological approach. Of the studies reviewed, 90% were published in English and the remaining 10% in Spanish; all were open access and included a Digital Object Identifier (DOI). The most recurrent themes concerned the use of GenAI in technology, ethics, and sustainability, which made it possible to trace trends, approaches, and gaps within the current literature. On this basis, the following research questions were formulated: What are the relevant concepts associated with GenAI? What methodologies are used to investigate the ethics and sustainability of GenAI? What ethical impacts and mitigation

strategies can be identified from an engineering perspective? And what are the associated social and environmental impacts, and what mitigation strategies have been proposed?

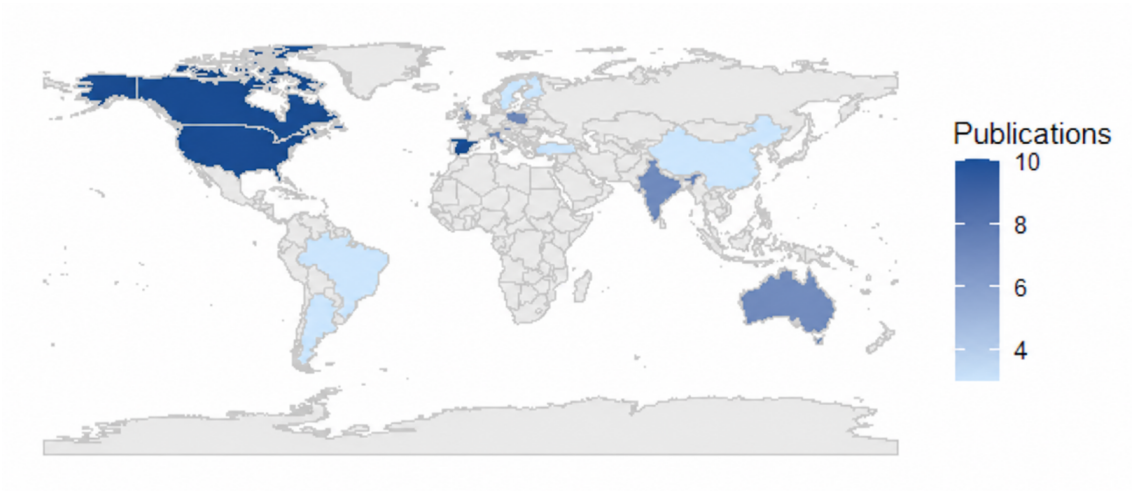
RESULTS AND DISCUSSION

The systematic review of the 54 articles published between 2021 and 2025 provided answers to the four research questions posed, bringing to light significant findings regarding the multidimensional impacts of GenAI on engineering. Among the most relevant results, the field emerges as one dominated by research from developed countries, particularly Spain, the United States, and Canada. The predominant methodologies are theoretical and systematic, with limited empirical validation. Additionally, the main ethical concerns center on algorithmic bias, transparency, and accountability, whereas the environmental impacts resulting from energy consumption remain insufficiently addressed.

Geographic Distribution of Research on GenAI

As shown in Figures 2 and 3, the geographic distribution of the selected publications was examined first, so as to situate the origin of the evidence analyzed. Through this bibliometric analysis, clear patterns of geographic concentration became evident in scientific output on GenAI in engineering.

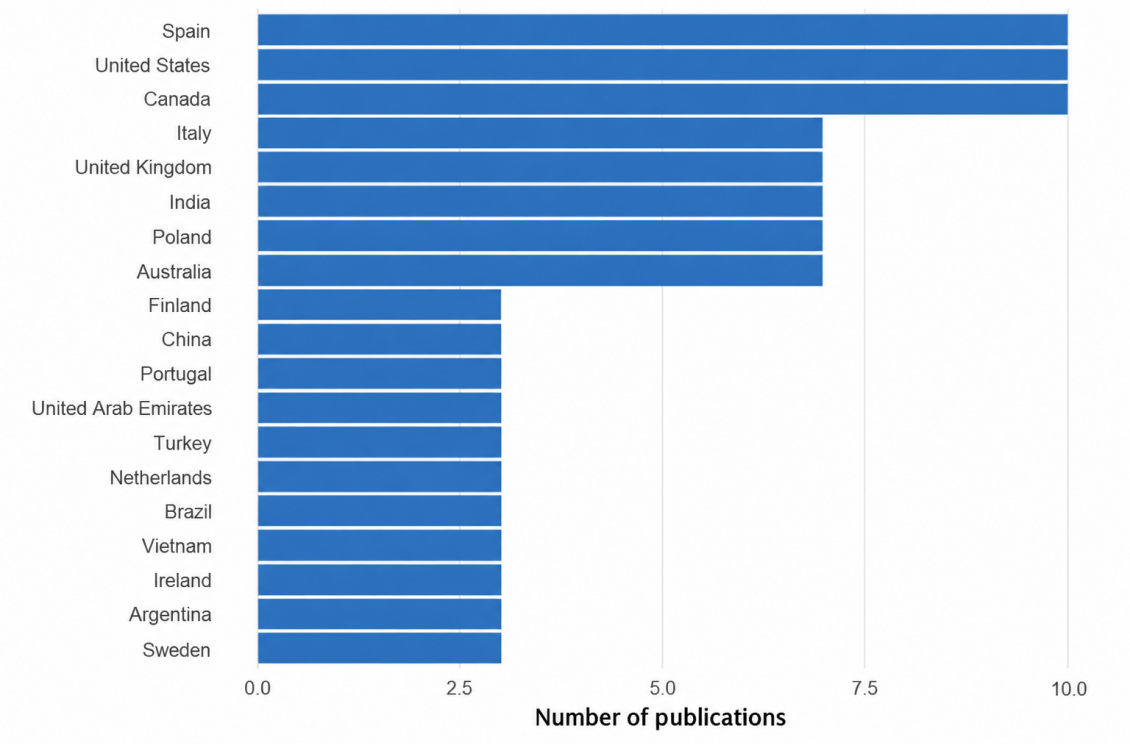
Figure 2. Geographic distribution of publications on GenAI in engineering



Source: Authors' own work, based on the bibliometric analysis conducted in Bibliometrix (2025).

Note. The map shows the distribution of the analyzed publications by country of origin. Color intensity represents the number of publications.

Figure 3. Number of publications by country



Source: Authors' own work, based on the bibliometric analysis conducted in Bibliometrix (2025).

Note. Due to international co-authorship, a single article may be affiliated with more than one country. Consequently, the total number of publications by country exceeds the total number of studies included in the review.

According to the study, the countries with the highest number of publications addressing the ethical, social, and environmental impacts of GenAI are Spain, the United States, and Canada, each with 10 publications. Together, these countries account for more than 55% of the scientific output examined. Notable research interest was also found in countries such as Italy, the United Kingdom, India, Poland, and Australia, each contributing seven publications.

This concentration in developed countries suggests potential biases within the academic literature on GenAI, where perspectives from the Global South and emerging economies remain underrepresented. Given such an asymmetrical distribution, questions arise as to the universality of the conclusions drawn and the applicability of ethical and regulatory frameworks across diverse socioeconomic, cultural, and technological contexts. In particular, the predominance of English-language and European research may thus fail to capture the specific challenges faced by regions with different development priorities, technological capacities, and regulatory frameworks.

What stands out, nonetheless, is that this topic is both current and cross-cutting, generating considerable interest worldwide, as reflected in the fact that the publications reviewed originate from countries across several continents, including Europe, the Americas, Asia, and Oceania. Although still

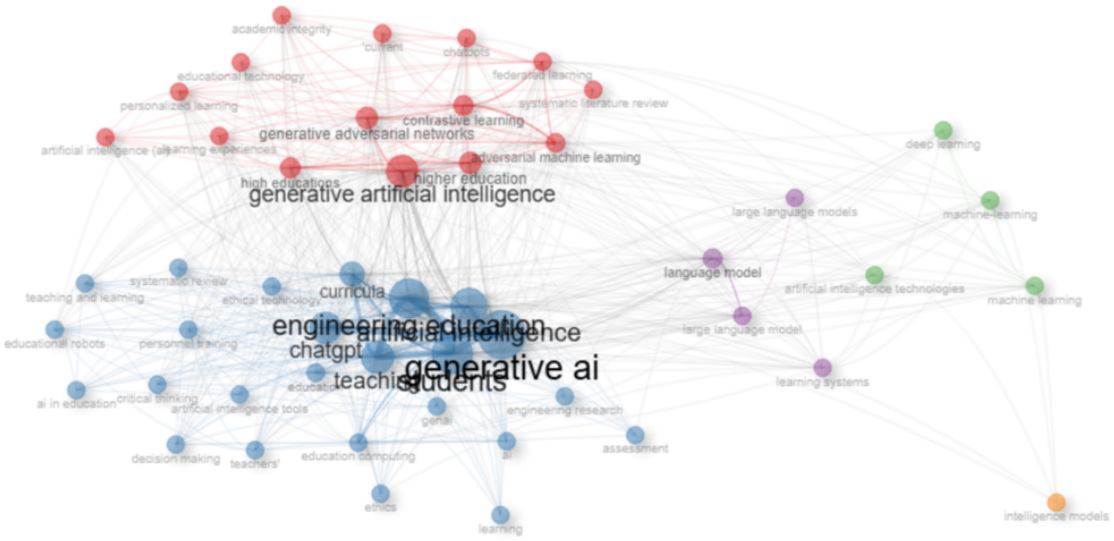
limited, this geographic diversity points to growing recognition of GenAI as a disruptive technology, one that calls for multidimensional analysis from ethical, social, and environmental perspectives.

These findings are discussed below in relation to each of the research questions formulated.

What are the relevant concepts associated with GenAI?

The co-occurrence network (Figure 4) shows that the terms most frequently associated with GenAI in engineering are "students," "engineering education," "artificial intelligence," "ethics," and "critical thinking," revealing a strong educational and ethical focus within current research. From this conceptual framework, four distinct thematic clusters emerge: engineering education and ethics (blue), advanced AI (red), machine learning and deep learning (green), and language models and machine learning (purple).

Figure 4. Co-occurrence network of key terms in the literature on GenAI in engineering



Source: Authors' own work using metadata from Bibliometrix (2025).

Note. Node size represents the frequency of occurrence of each term, while connections indicate their co-occurrence within the same documents. Colors group thematically related terms.

This finding is consistent with Cañavate et al. (2025), who similarly confirm the predominance of ethical and educational concerns in current academic discourse, though it contrasts partially with Mikołajewska et al. (2025), whose report prioritizes the industrial applications of GenAI in design, simulation, and automation. The disparity between its technical and industrial potential (Byrne et al., 2025) and the educational-ethical focus that dominates the literature suggests an asymmetrical pattern of development, in which academia takes on a largely reflective role, whereas industry moves ahead with practical implementation.

Based on the identified thematic groupings, both the interdisciplinary nature of GenAI and a certain degree of conceptual fragmentation become apparent (Heilala et al., 2025). No unified conceptual framework yet exists capable of integrating the technical, ethical, and social dimensions of GenAI, and this in turn hinders the development of coherent policies and systematic implementation strategies. Therefore, greater conceptual integration is needed so that engineers can build a holistic understanding of GenAI as a technology, an educational tool, and a social phenomenon all at once.

What methodologies are used to investigate the ethics and sustainability of GenAI?

The methodological analysis showed that the discipline remains at a stage of conceptual development that precedes practical implementation (Leão et al., 2024), with the body of work characterized primarily by systematic literature reviews and theoretical approaches. Although understandable, given that the subject of study is still an emerging technology, this methodological bias raises concerns about the external validity of the findings and about the field's capacity to propose practices grounded in empirical evidence.

Despite being limited in number, the empirical studies identified do offer useful insights. For instance, the systematic comparison of different chatbots (ChatGPT, Bing, Bard) conducted by Akpan et al. (2025) and Naser et al. (2024) reveals technical differences and cognitive limitations that affect their effectiveness in workplace and educational settings. Similarly, Taktak (2025) implemented remote laboratories incorporating GenAI tools to foster educational innovation. Together, these studies demonstrate that it is possible to measure the performance of such tools systematically in real-world situations, providing valuable information for engineers and educators.

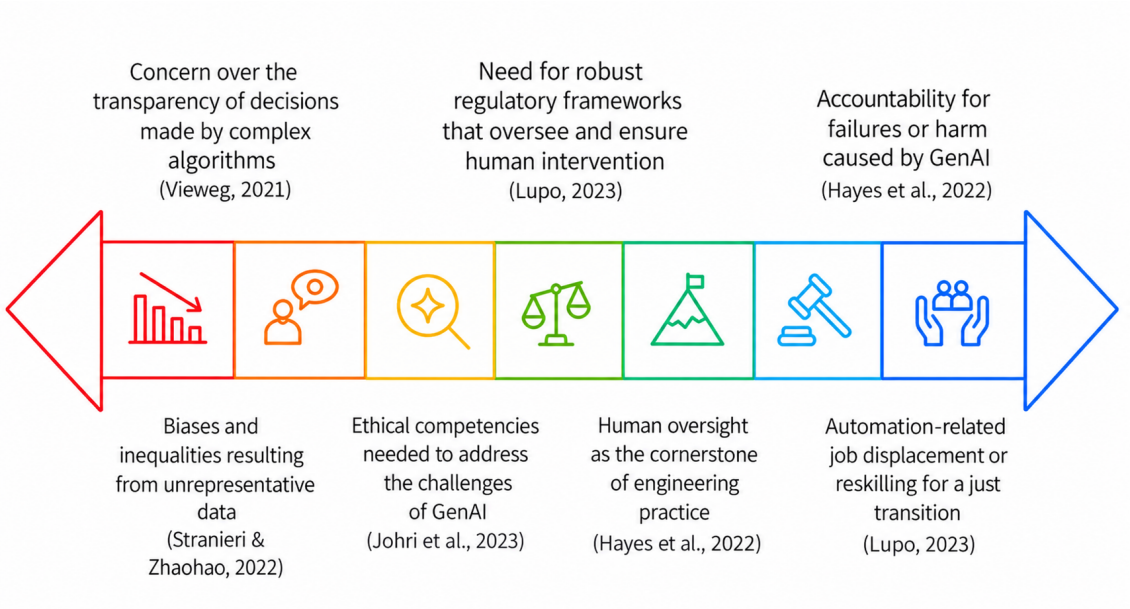
In a systematic review by Padovano and Cardamone (2024), the Delphi method was employed to adapt engineering education to the demands of Industry 5.0, offering a particularly promising practical approach. This participatory method allows experts to reach consensus on controversial or emerging issues, thus overcoming the limitations inherent to purely documentary reviews. Meanwhile, research examining the causal effects of GenAI on specific variables—including the development of technical skills, academic performance, or the effectiveness of technical design processes—remains scarce, if not virtually nonexistent.

Given the predominance of theoretical approaches, there is a pressing need to train engineers capable of critical thinking and of addressing ethical issues across fields such as industry, education, and social management. This emphasis, however, must be balanced with rigorous empirical research able to confirm or refute emerging theoretical claims. As suggested by Saihi et al. (2024), mixed-methods designs—combining the conceptual depth of qualitative approaches with the generalizability of quantitative methods—should be a priority.

What ethical impacts and mitigation strategies can be identified from an engineering perspective?

The results of this study confirm that the ethical challenges associated with GenAI—including transparency, algorithmic bias, accountability, and data protection—are widely recognized in the literature (Johri et al., 2023; Stahl & Eke, 2024). Figure 5 summarizes these ethical impacts and mitigation strategies, outlining a conceptual framework that moves from problem recognition toward the proposal of systemic solutions.

Figure 5. Ethical impacts of GenAI and mitigation strategies from an engineering perspective



Source: Authors' own work.

It is important to highlight the existence of a critical gap between the numerous ethical frameworks that have been proposed and their effective institutional implementation; ethical recommendations, in other words, remain disconnected from the regulatory system. For this reason, initiatives such as the AI-systems engineering approach (Pfrommer et al., 2022) or proposals aimed at designing systems grounded in ethical principles have yet to be translated into specific institutional policies that are measurable and replicable in real-world settings (Bertossi et al., 2024). As demonstrated by Lupo (2023) and Yoo and Jo (2023), this disconnect stands out as one of the most problematic findings in the literature.

While several studies propose ethical principles—academic integrity (Gallent-Torres et al., 2023), human oversight (More, 2024), and responsible design (Bucolo et al., 2022)—few are backed by concrete mechanisms for implementation, evaluation, and accountability. This contrasts sharply with fields such as biotechnology or nuclear engineering, where decades of development have produced specific operational ethics protocols and regulatory frameworks. Adding to this gap are

the limitations of current regulatory frameworks and the absence of clear policies governing the use of GenAI in engineering, particularly within educational, industrial, and governmental contexts (White & Lidskog, 2022).

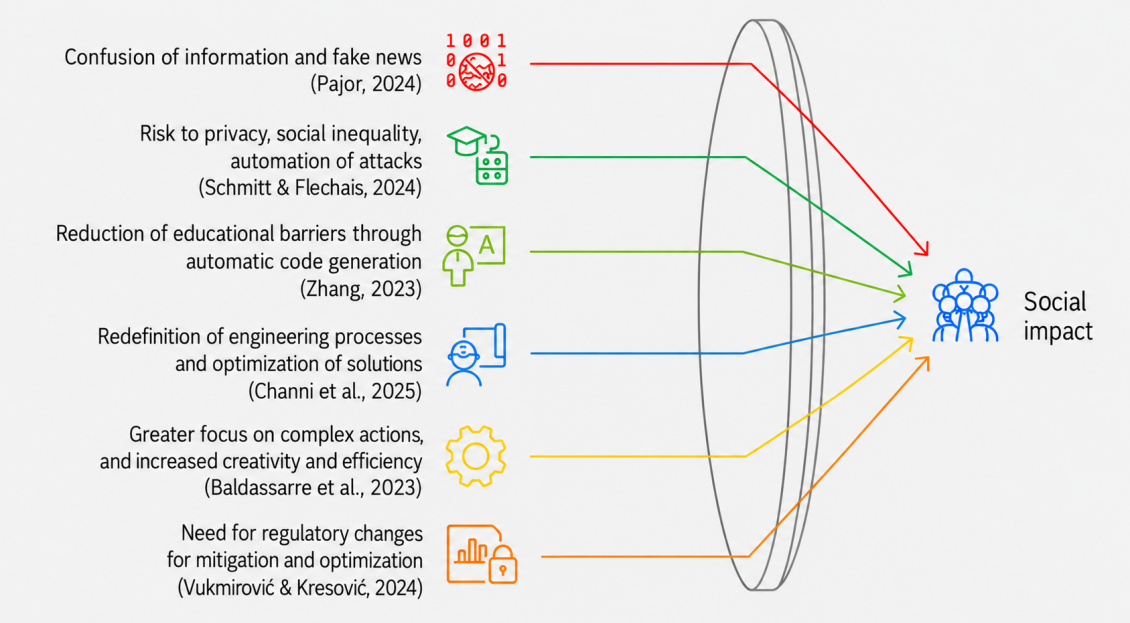
Some promising proposals, however, point toward more inclusive and legitimate forms of regulation by encouraging the creation of ethical standards that involve end users such as students, teachers, and local communities (Akpan et al., 2025; Cutillas, 2025; Liu, 2025). Likewise, integrating social responsibility from the earliest stages of technological design (Assadi et al., 2022; Vistorte et al., 2024) represents a conceptual approach that engineering methods should incorporate. Meanwhile, the SQUARE method applied to autonomous ships (Yoo & Jo, 2023) illustrates how cybersecurity requirements can be refined systematically, helping to prevent attacks linked to the use of GenAI.

Strengthening the theoretical-practical balance of GenAI also calls for specialized negotiation models—such as BioinspiredLLM (Luu & Buehler, 2024)—that build ethical considerations directly into their core structure. Within the broader debate on the balance between human autonomy and automation, some authors stress the benefits that GenAI can bring (Kuhail et al., 2024), while others warn of the risks that come with excessive reliance on the technology (Lönngren, 2021; Tepsa et al., 2024). At the heart of this debate lies a central question: how can the opportunities offered by GenAI be harnessed without compromising critical thinking and professional autonomy? In this respect, metacognitive knowledge is essential because it allows specialists to treat GenAI as a complementary tool for engineering assessment, rather than as a substitute within engineering education.

What are the associated social and environmental impacts, and what mitigation strategies have been proposed?

The analysis revealed a range of distinct environmental and social effects, each requiring specific management strategies. Figure 6 summarizes the social effects identified in this study and highlights the opportunities and risks tied to implementing GenAI in an engineering context. These social impacts include the development of digital skills, interdisciplinary collaboration, and greater personalization of learning, alongside risks such as the erosion of essential skills, digital exclusion, and excessive dependence on technology.

Figure 6. Social impacts of GenAI in engineering



Source: Authors' own work.

The results point to a positive social impact of GenAI, since it personalizes learning by giving students access to content and resources tailored to their pace and needs. It can also foster interdisciplinary collaboration and the development of advanced digital skills, which are essential for addressing the challenges posed by Industry 5.0. Moreover, GenAI can support the use of augmented reality in creative processes to drive product innovation, particularly within industrial contexts that embrace Industry 5.0 principles (Grech et al., 2023). This, in turn, calls for an understanding not only of the advantages of these technologies but also of their environmental, social, and ethical implications (Pajor, 2024; Schmitt & Flechais, 2024).

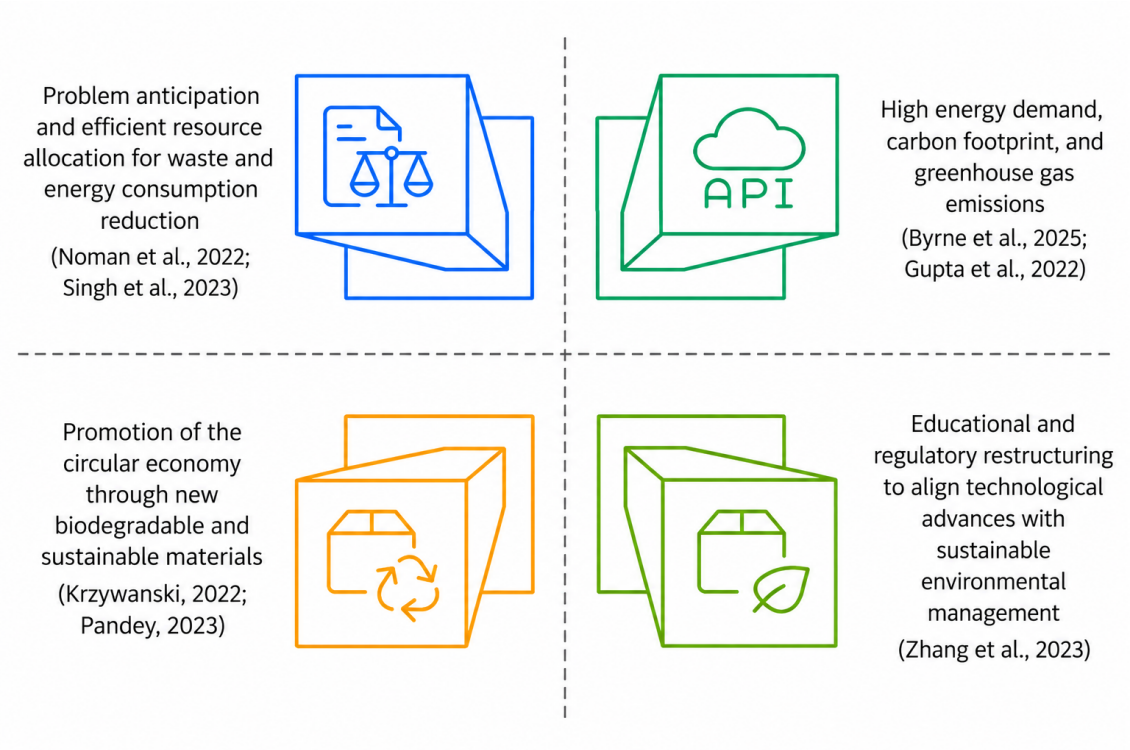
It should be noted, nevertheless, that alongside these potential benefits lie well-documented risks: technological dependence, digital exclusion, and the erosion of fundamental skills. As this ambivalence suggests, the social impact of GenAI varies according to context and therefore demands active management rather than uncritical acceptance. The accuracy of AI-generated information (Kuhail et al., 2024) can be preserved through human validation, a step that proves crucial for improving information quality and reducing the automated biases that may hinder learning.

In this regard, research on natural language processing and on the practical application of chatbots such as DCHATBOT underscores the need for genuine evaluation, teacher involvement, and careful use of GenAI tools. Technology, then, emerges as both a tool and a socially constructed cultural phenomenon (Alves et al., 2025; Liu, 2025). Striking a balance between technological advancement and human oversight is therefore essential to prevent automated errors. Furthermore, critical thinking and digital competencies should be fostered among students and teachers, so that they

may draw the greatest possible benefit from the opportunities offered by GenAI without becoming dependent on it.

Turning to environmental impacts, Figure 7 summarizes the most significant ecological concerns associated with GenAI, together with the mitigation strategies identified in the literature. These include the high energy consumption involved in model training, the associated carbon emissions, and the generation of electronic waste. The mitigation strategies proposed, in turn, center on improving computational efficiency, adopting renewable energy sources, and conducting life-cycle assessments.

Figure 7. Environmental impacts of GenAI and mitigation strategies



Source: Authors' own work.

A major concern emerging from this study is that the engineering literature has yet to give sufficient attention to the environmental impacts of GenAI. While some studies, such as that of Gupta et al. (2022), demonstrate that training these generative models leaves a substantial carbon footprint, few go on to propose concrete engineering strategies for tackling the problem. This is particularly striking given that many institutions claim to uphold the principles of sustainable engineering and pursue the Sustainable Development Goals.

Even so, the findings of this study suggest that GenAI could become a powerful tool for sustainability, provided it is accompanied by appropriate education and the necessary ethical and technical frameworks. Predictive maintenance, for instance, is already being implemented in the energy industry

through AI, yielding gains in both operational efficiency and targeted, sustainable use (Hernandez-Betancur et al., 2022; Mikołajewska et al., 2025; Noman et al., 2022; Yahaya et al., 2023). However, applications of this kind that contribute positively to sustainability remain the exception rather than the rule.

What seems to be missing is a systemic perspective that regards GenAI both as a tool with the potential to promote sustainability and as a significant source of environmental impact. Accordingly, it is imperative that the engineering field develop evaluation indicators capable of capturing the environmental benefits and costs across the entire life cycle of GenAI systems. As proposed by Lesage et al. (2024), robust environmental assessments need to be incorporated into the development of these systems. Likewise, specific engineering standards—comparable to those already established in chemical or process engineering—must be put in place to quantify and reduce their environmental footprint.

Engineering is also called upon to promote reliability and sustainability as key principles that contribute to cybersecurity (Mustapha, 2025), thereby strengthening the technical security of systems while reducing long-term operational risks. Disciplines such as AI-systems engineering (Pfrommer et al., 2022) have proven effective in structuring the processes, technical standards, and ethical principles required to integrate GenAI into institutional settings. Likewise, technological developments should align with international regulations such as ISO standards in order to meet sustainable management guidelines that foster responsible and reliable use.

The literature agrees that disruptive innovation must be grounded not only in ethical and regulatory frameworks that ensure safe implementation, but also, more fundamentally, in human values—so that GenAI drives change that is ethical, sustainable, and inclusive (Nelke et al., 2024). Within this integrated vision, engineers are called on to do more than lead the technical development of GenAI systems: they must also help formulate the regulatory frameworks, environmental standards, and educational models that ensure these technologies make a genuine contribution to human well-being and to the sustainability of the planet.

Other studies further examine the social, educational, and regulatory dimensions of GenAI and related technologies, providing nuanced insight into their potential and their risks across a range of engineering and educational contexts (Baldassarre et al., 2023; Bazán Linares, 2023; Binani, 2022; Channi et al., 2025; Cutillas, 2025; Dinh & Tran, 2023; Hayes et al., 2022; Krzywanski, 2022; Onatayo et al., 2024; Pandey, 2023; Prather et al., 2025; Singh et al., 2023; Stranieri & Zhaohao, 2022; Tafferner et al., 2023; Vieweg, 2021; Vukmirović & Kresović, 2024; Zhang et al., 2023; Zhang, 2023).

Study Limitations and Future Research

To properly contextualize the findings of this systematic review, several limitations should be acknowledged. First, studies published in languages other than English and Spanish were excluded, and the search was restricted to a single database (Scopus). Second, given that the analysis period (2021–2025) covers a rapidly evolving technology, the results may become outdated relatively quickly. Third, because theoretical research predominates in the reviewed literature, conclusions regarding the practical effectiveness of specific interventions remain limited. Fourth, the 87%

agreement rate among reviewers indicates that 13% of decisions required further discussion, suggesting a certain degree of subjectivity in the final selection of studies.

Looking ahead, future research should prioritize the following: (1) empirical longitudinal studies evaluating the real-world impact of GenAI across both engineering education and professional practice; (2) the development and validation of specific regulatory frameworks for GenAI in engineering, including mechanisms for accountability and performance assessment; (3) interdisciplinary research integrating technical, ethical, social, and environmental perspectives; (4) comparative analyses across different cultural and geographic contexts, aimed to identifying factors that facilitate or hinder the responsible implementation of GenAI; and (5) comprehensive research into the full environmental life cycle of GenAI systems, leading toward specific mitigation strategies for engineering applications.

Additionally, it is essential to examine participatory management models that involve end users—affected communities, practicing engineers, and students—in the design of GenAI systems. Finally, within today's engineering education, promoting prompt engineering competencies (Gibreel & Arpaci, 2025) and critical literacy in GenAI becomes critical, so that future generations of engineers not only use these technologies effectively but also develop and manage them responsibly.

CONCLUSIONS

Drawing on the most recent scientific literature from 2021 to 2025, this study enabled a systematic analysis of the social, ethical, and environmental dimensions associated with the implementation of GenAI in engineering. The findings show that, despite the significant opportunities GenAI offers for innovation and sustainability, its development continues to be hampered by institutional and regulatory challenges, as well as by structural challenges within the engineering field.

Within engineering, approaches to GenAI remain predominantly educational and ethical in orientation, whereas direct industrial applications have received comparatively less attention. The central concerns identified in the literature include critical thinking development, student education, and ethical considerations. These issues can, in turn, be grouped into four main thematic areas: automated deep learning, language models, advanced AI, and ethics in engineering.

Most methodologies used to study GenAI-related sustainability and ethics in engineering are systematic and theoretical in nature, and empirical research remains scarce. Conceptual analyses, literature reviews, and qualitative studies dominate the field, which suggests that the discipline is currently oriented more toward conceptualization than toward practical validation. Although valuable progress has been made through approaches such as the Delphi method and certain applied studies—for example, those involving remote laboratories or chatbot comparisons—these efforts are still not enough to firmly establish evidence on the effectiveness of specific interventions.

Among the ethical impacts of GenAI in engineering are algorithmic bias, a lack of transparency in automated systems, accountability gaps in automated decision-making, and threats to personal data protection. These challenges have been widely recognized in the literature, prompting the proposal of various ethical frameworks and principles; even so, a considerable gap persists between

declarative ethical statements and their effective implementation within institutions. Indeed, most of the identified mitigation strategies—such as critical thinking training, individual monitoring, participatory planning, and the incorporation of ethical principles from the outset—still lack operational mechanisms for implementation, evaluation, and accountability.

At the same time, the societal benefits of GenAI, including personalized learning, interdisciplinary collaboration, and digital skills development, stand in contrast to substantial risks such as technological dependence, digital exclusion, and the erosion of fundamental competencies. These impacts are context-dependent, and they call for active management through human validation, critical education, and ongoing evaluation. As for environmental impacts, the technical literature has yet to adequately address issues related to electronic waste generated by GenAI infrastructure, high energy consumption, and the carbon emissions associated with model training.

Ultimately, GenAI represents both a transformative opportunity for contemporary engineering and a complex challenge to navigate. Its responsible integration will require bridging the gap between declarative ethical principles and actual institutional practice, moving beyond theoretical approaches toward systematic empirical validation, developing operational regulatory frameworks with clear accountability mechanisms, and incorporating rigorous environmental assessment as a core component of technological progress. In the end, it is crucial to train engineers who are both technically competent and ethically aware to ensure that GenAI contributes effectively to inclusive and sustainable development.

CONFLICTS OF INTEREST

The authors declare that they have no financial, personal, or professional conflicts of interest that could have unduly influenced the conclusions or interpretations presented in this manuscript.

AUTHORS' CONTRIBUTIONS

All authors contributed equally to every stage of the work, including the conceptualization of the research, methodological design, data collection and analysis, synthesis of results, discussion, drafting of the manuscript, and its revision and final approval. No individuals who did not meet the criteria for substantial contribution were included as authors, thereby avoiding honorary or ghost authorship.

ARTIFICIAL INTELLIGENCE USE STATEMENT

The authors used AI tools—specifically ChatGPT (OpenAI), Claude (Anthropic), and Perplexity AI—along with the Rayyan platform, solely as technical support during the development of the manuscript. ChatGPT and Claude were employed for proofreading and style adaptation, for checking the coherence of the argumentation, and for assisting with content organization and concept clarification. Perplexity AI, for its part, served as a support tool for initial research and the review of academic literature, while Rayyan was used to support study selection and organization during the systematic literature review,

following the PRISMA protocol. None of these GenAI or digital support tools generated the data, research results, or original scientific content, nor did they at any point replace the authors' critical analysis. All results were manually reviewed, edited, and approved by the authors, who assume full responsibility for the content of the manuscript.

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