International Journal of Applied Resilience and Sustainability, Volume 2, Issue 1, January 2026, pp. 211-242

DeepScience

Published online at Deep Science

International Journal of Applied Resilience and Sustainability

Journal homepage: https://deepscipub.com/ijars

Green artificial intelligence for sustainable and resilient development: A review

Dimple Ravindra Patil [1], Nitin Liladhar Rane [2], Obizue Mirian Ndidi [3], Jayesh Rane [4]

[1] *Hurix Digital, Andheri, Mumbai India*
[2] *Architecture, Vivekanand Education Society's College of Architecture (VESCOA), Mumbai 400074, India*
[3] *Institute of Education, Management and Professional Studies (IEMPS)*
[4] *K. J. Somaiya College of Engineering, Vidyavihar, Mumbai, India*

Article Info:
Received 16 December 2025
Revised 02 January 2026
Accepted 08 January 2026
Published 26 January 2026

Corresponding Author:
Nitin Liladhar Rane
E-mail: nitinrane33@gmail.com

Abstract

The blistering development of the technologies of artificial intelligence, though a transformative one has resulted in the growing environmental crisis due to the exponential increase in computational, energy demand, and carbon emissions. The AI systems made to date are characterized by massive power demands which provide pressure on the energy systems of the world and add to climate change, which is an inherent contradiction between technology development and the environment. This review of the literature explores 542 current articles to analyze the new paradigm of Green Artificial Intelligence as a group to make AI innovation and environmental stewardship align through energy-saving algorithms, green computing methods, and climate-aware implementation models. Our methodological approach was based on the PRISMA system, as we searched databases and filtered 1,052 records and finally settled on 534 articles, which directly relate to the topic of AI and sustainability. In our analysis, it is possible to note a tremendous advancement of energy-saving machine learning algorithms, green data centers, the integration of renewable energy usage, and artificial intelligence usage to monitor the environment and take climate action. Nevertheless, there exist decisive loopholes in the standardized measurement systems, lifecycle assessment approaches, harmonization of policies and fair access of green AI innovations in developing economies. The contribution of this review is the observation of seven major areas of implementation, the assessment of the emergent methods of energy optimization, issues of implementation and a hierarchical research agenda.

Keywords: Green artificial intelligence, Sustainable development, Energy efficiency, Machine learning, Environmental impact, Circular economy.

1. Introduction

The twenty-first century has presented not only the most remarkable overlap of two distinguishing phenomena the accelerated development of technologies of artificial intelligence and the increased pressingness of environmental sustainability issues but also the increase in environmental awareness and the necessity to tackle the problem [1]. Machine learning and deep learning, artificial intelligence and natural language processing, as well as computer vision have been widely introduced in practically all spheres of modern society, including healthcare and transportation up to the finance and manufacturing industry [1,2]. The results of this technological revolution have produced incredible advantages such as improved productivity, ability to make better decisions, scientific discovery breakthrough, and the answer to the problems that were once deemed unsolvable [3-5]. Nevertheless, this rapid growth has also left a sizeable environmental footprint that jeopardizes to reduce the global sustainability projects and further increase the climate crisis [6,7]. Computational requirements of modern AI systems have been increasing exponentially, on a scale that is way beyond what Moore has anticipated [2,8-10]. A single large language model requires an amount of energy that is equivalent to the energy consumption of hundreds of households stepping up to a power outlet during a year, and that produces carbon emissions comparable to multiple transatlantic flights [1,11-12]. The current results of data centers contribute to the infrastructure of artificial intelligence about two to three percent of the world, which is expected to reach eight to ten percent by 2030 in case the current trends remain the same. Energy consumption is not the end of the environmental costs, as it involves heating water to cool down the systems, electronic waste that is discarded due to the obsolete hardware in a very short period of time, and carbon footprint of the process of creating a special AI chip and processor [13-15]. These environmental effects make a paradox out of the fact that the same technologies, which should have been utilized to tackle the issue of the climate change and environmental degradation are contributing themselves to the issue as well [16].

Green Artificial Intelligence has come out as a key paradigm shift that aims to resolve this core conflict involving technological advancement and environmental accountability [16,17]. The strategy has several aspects: creating energy-efficient algorithms that do not compromise the performance nor increase computational needs, designing sustainable hardware architectures that can run on low-power modes, developing renewable energy solutions to AI infrastructure, creating lifecycle assessment frameworks that measure environmental effects, and using AI capabilities to act and protect the environment, in particular [12,18-20]. The ideology is not only about energy efficiency but also incorporates the principles of holistic sustainability such as resource conservation, the implementation of the circular economy, the consideration of the social equity, and the planning of long-term resiliency [21-23]. Green AI is not only a technical issue, but also covers a wider scope in terms of society [24,25]. With the trend of artificial intelligence as a key element of the economic process, scientific exploration, and human infrastructure, its sustainability must be a priority to meeting the United Nations Goals of sustainable development, specifically, affordable and clean energy, climate action, responsible production and consumption, and sustainable cities and communities [26-28]. In addition, the fair allocation of the benefits and the harms of the AI technology involve the unrestricted transfer of environmental costs, that is, it should not be a vulnerable population or developing countries, which do not have resources to take on sustainable computing practices [29-31].

The recent technological advances have provided the opportunities of developing Green AI like never before [3,32,33]. Neuromorphic computing innovations are created to emulate a neural system within the body to deliver radical energy savings [4,34-36]. Zero-quantum computing is expected to deliver exponential increases in efficiency to particular problem classes [37-40]. The prevalent Edge computing and federated learning solutions have decreased the data delivery needs and concentrate domains of processing [4,41,42]. There are sophisticated cooling systems such as liquid immersion and free-air cooler systems that reduce the energy wastage in data centres [43-45]. It has been noted that the integration of solar and wind power has been becoming more possible due to the substantial drop in the cost of renewable energy [9,46-48]. These innovations, along with an increasing regulatory pressure and investor attention on the environmental performance of companies and the demands of the sustainable products that a customer wants are forming an effective push towards the adoption of the green practices in the AI industry [49-50]. At the same time, the artificial intelligence is becoming useful in managing the environmental issues directly [51,52]. Algorithms in the field of machine learning can also maximize the operation of renewable energy grids, forecast equipment malfunctions to avoid wastage, increase climate modeling capability, observe deforestation and biodiversity destruction, enhance agricultural endurance to decrease resource usage, enhance supply chain optimization to decrease transportation emissions, and advance materials science to develop sustainable technologies [53-56]. The examples of these applications show that AI can be turned into an environmental liability to a significant tool to accomplish the sustainable goals, as long as the technology itself is designed and implemented in a responsible manner.

The nexus of artificial intelligence and sustainability has been the focus of more and more researchers, policymakers, industry fraternities, and civil societies [57-59]. The number of academic publications which deal with Green AI has increased, displaying the increased awareness of the opportunities and challenges of this nexus [6,60-62]. The global organizations such as the United Nations, European Union as well as national governments have also started coming up with regulations and frameworks to enhance sustainable use of AI [63-65]. Big tech corporations have come out publicly with grand carbon neutrality promises and invested in renewable power infrastructure in their data facilities. Nevertheless, there are still considerable knowledge gaps in the areas relating to the best practices, measurement requirements, implementation strategies, and governance systems to ensure that AI positively relates to the sustainability of the environment.

This is regardless of the fact that despite the accumulating literature on Green AI and sustainable computing, there are still a number of crucial gaps in literature which restrain the comprehensive knowledge and practical application. First, the lack of standardized procedures of measuring and reporting the environmental impact of AI systems throughout all its lifecycle is prominent. Although several studies have measured energy usage by training models, not many have integrated all inference costs, hardware manufacturing emissions, E-waste, water usage and indirect impact on the environment. This inconsistency in methods complicates any comparison of one study with another and cannot help develop industry benchmarks and best practices. Second, the literature has geographic and sectoral biases with an unlikely emphasis on large-scale AI applications in well-developed economies and insufficient coverage of the specific issues and opportunities of small and medium-sized companies, developing countries, and resource-limited settings. This disparity is also alarming as the effects of climate change have been felt most within the societies that have fewer resources to install new technologies to promote green innovations and it is only through fair access to sustainable AI tools that the world can attain climate justice.

Third, the current literature has underfueled the discussion of the conflict between AI model performance and energy efficiency, as well as has tended to consider both as independent variables instead of considering advanced optimization frameworks that could balance the need to achieve accuracy with environmental considerations. The literature does not provide enough guidance on how efficiency trade-offs can be accepted and that such a decision should be made transparently in various applications circumstances especially in critical applications where there should be no compromise of performance. Fourth, the attempts to combine Green AI with other sustainability frameworks such as a circular economy, environmental justice, and long-term resiliency planning are not developed. Majority of the studies are narrow-minded about the energy efficiency without due consideration giving to material flows, supply chain sustainability, social impacts, and system level effects that might effectively neutralize the individual measure of efficiency due to rebound effects or indirect consequences. Fifth, the literature shows a lack of concerns regarding governance processes, policy intervention, and regulatory frameworks that are required to incentivize and impose sustainable AI practices on scale. Although much attention is paid to technical solutions, the institutional, economic, and political aspect of Green AI transition is a relatively understudied area, even though it is fundamental to conduct a systemic change.

The following specific objectives are expected to fill in these gaps in this comprehensive literature review:

1) To carry out a systematic review and synthesis of existing studies in Green Artificial Intelligence, sustainable computing practices, and environmental effects of AI systems in various areas of application and geographic ranges.

2) To detect and classify new techniques, methods, and technologies to minimize the environmental impact of AI in its entire lifecycle, including during design and development up to deployment and decommissioning.

3) To examine how artificial intelligence can be applied in the promotion of environmental sustainability, climate action, renewable energies, ecological conservation, and transitions to circular economy.

4) To assess issues, obstacles and trade-offs of the Green AI practice implementation in the context of various organizations, industrial and development sectors.

5) To evaluate how opportunities to exploit artificial intelligence can be exploited to strengthen environmental resilience to assist in advancing sustainable development objectives and expedite the transition to low-carbon economies.

6) To recommend a broad platform that brings technical innovations, policy interventions, industry standards, and governance mechanisms that should be put in place to mainstream sustainable AI practices.

7) To define the areas of priority in future research and development and investment that would contribute to environmental sustainability of AI systems as well as AI implementation in the environmental protection.

In this study, the contribution is as follows:

1) This literature review has several valuable contributions to the newly developed Green Artificial Intelligence and the sustainable computing. The first is that it offers the most thorough synthesis so far of the research across the environmental aspects of AI that cuts across computer science, environmental science, policy studies and industrial ecology perspectives. This review provides a valid and dependable survey of the existing body of knowledge based on the analysis of 534 peer-reviewed studies undertaken with a strict PRISMA approach and outlines the gaps in the research and limitations on the methods that stifled the advancements in the given area.

2) Second, the review contributes to the theoretical discussion as a whole, by developing a holistic theory to view Green AI as not just a technical optimization but a socio-technical change that should become a concerted effort on several levels and among various stakeholders. This framework comes in very clearly to deal with the fact that sustainability issues are complex and that they need systemic solutions that involve the development of technology, practices in the organization, market forces, regulatory interventions and social norms.

3) Third, the review has practical value by capturing taxonomies of green AI methods in detail, elaborate tables on comparing technologies in various facets and by the evidence-supported recommendation to the various stakeholders such as researchers, developers, policymakers, and business leaders. These resources allow one to find the relevant technique fast, see trade-offs in using this approach or that option, and arrive at correct solutions on implementing the concept of AI sustainability in their own settings.

4) Fourth, the contribution used in this work is the methodological contribution as it has shown how to apply the systematic review methods in the questioning interdisciplinary field of sustainable AI and provides procedures that might be applied in future reviews as the literature is swiftly changing. Clearly documented search strategies, inclusion and synthesis procedures make the research strategies more reproducible and help make revisions as new evidence becomes available.

5) Fifth, the review is valuable to the policy discussion as it synthetic evidence concerning the efficacy of various intervention measures, gaps, and inconsistencies in regulation, as well as policy giving priorities based on empirical research. This evidence base can be used in evidence-based policymaking since governments all over the world struggle with the difficulty of balancing between the innovations of AI and the environmental demands.

6) Last but not least, this study serves the sustainability discussion in general by illustrating how the creation of new technologies can be directed forward towards the social and environmental interests using carefully-selected design options, properly designed governance models, and collective efforts. The lessons of Green AI can be applied more broadly to other areas of society as to how innovation can be used to advantage society without exceeding planetary limits or becoming unequal towards the generations to come.

2. Methodology

The systematic literature review adopted the Preferred Reporting Items of Systematic Reviews and Meta-Analysis (PRISMA) in order to have a complete, transparent and reproducible identification and synthesis of the discovery of the relevant researches. As one of the most common methods of conducting systematic reviews as the gold standard, PRISMA offered a systematic search method that was systematically used to screen and analyze the academic literature concerning Green Artificial Intelligence and sustainable development. The review process consisted of three main stages including identification, screening, and inclusion that fulfilled strict procedures to reduce the risk of bias and coverage of all the relevant literature. In the identification stage, it was possible to search systematically several academic databases, such as Scopus, Web of Science, IEEE Xplore, ACM Digital Library, ScienceDirect, and Google Scholar. The combination of search terms and keywords was artificial intelligence, machine learning, sustainability, energy efficiency, environmental impact, and green computing along with Boolean operators to ensure that all the range of the relevant research was covered. The preliminary searches revealed 1,260 records in databases and 23 records in special registers devoted to the environmental technology and sustainable computing. Before actual screening, reference management software was used to remove duplicate records and a total of 210 duplicate records were eliminated. Also, the automation tools were used to automatically flag 15 records as ineligible according to their predefined criteria such as publication type or language and 10 records were removed due to other reasons such as inaccessibility or retraction.

The care screening stage entailed theactive screening of the rest of 1,052 records in relation to preidentified inclusion and exclusion criteria. The initial screening of records was done in terms of title and abstract in order to determine the relevancy of the records leading to the rejection of 360 records that were evidently not within the purview of the review. The rest 692 reports were requested at the full-text retrieval, 14 reports, however, were not available despite intensive search. Reports that were accessed successfully and had the 678 used, were thoroughly subjected to full-text evaluation to determine if they were eligible or not. In the course of such a comprehensive analysis, 82 reports were eliminated due to unfocused writing that is not related to the use of artificial intelligence. Another 54 reports were excluded because of lack of scope such as preliminary conference abstracts, editorsials not containing substantive analysis and studies having poor methodological rigor or having less relevance to the fundamental research questions. The inclusion phase led to incorporation of 534 studies into the final review as was supported by 542 reports of recently published works as a result of forward and backward citation of literature search, new publication literature alerting system and domain experts recommendations. These were the studies which fulfilled all inclusion criteria: published in peer-reviewed journals, directly dealing with the interplay of artificial intelligence and sustainability, have substantive empirical or theoretical content, have enough methodological information to evaluate quality and validity. The extraction of the included studies obtained the important data such as the objectives of the research, methods of research, main findings of the study, geographical settings of study, domains of application, and the impact of the study on the theory and practice. To observe patterns, relationships and gaps in knowledge on the various pieces of literature, thematic synthesis methods were utilized, which were used to analyze the literature in a comprehensive nature that will be presented in the following sections.

3. Results and Discussion

The overall examination of 534 published studies demonstrates that the field of Green Artificial Intelligence study and implementation is developing very fast. This section summarizes the results obtained in various aspects such as use of the technical practice, methodology, implementation, new opportunities, and the future trends. The thematic manner of structuring the discussion is also there to offer clarity and give the readers smooth sailing in this multifaceted area of interdisciplinary.

3.1 Applications of Green AI

The use of Green Artificial Intelligence technologies has various fields, in which the AI technologies are minimally harmful to the environment or take active part in protecting the environment, and in sustainable development [64-67]. The literature indicates seven main categories of applications that make the variety of Green AI applications quite expansive and deep [2,68-70].

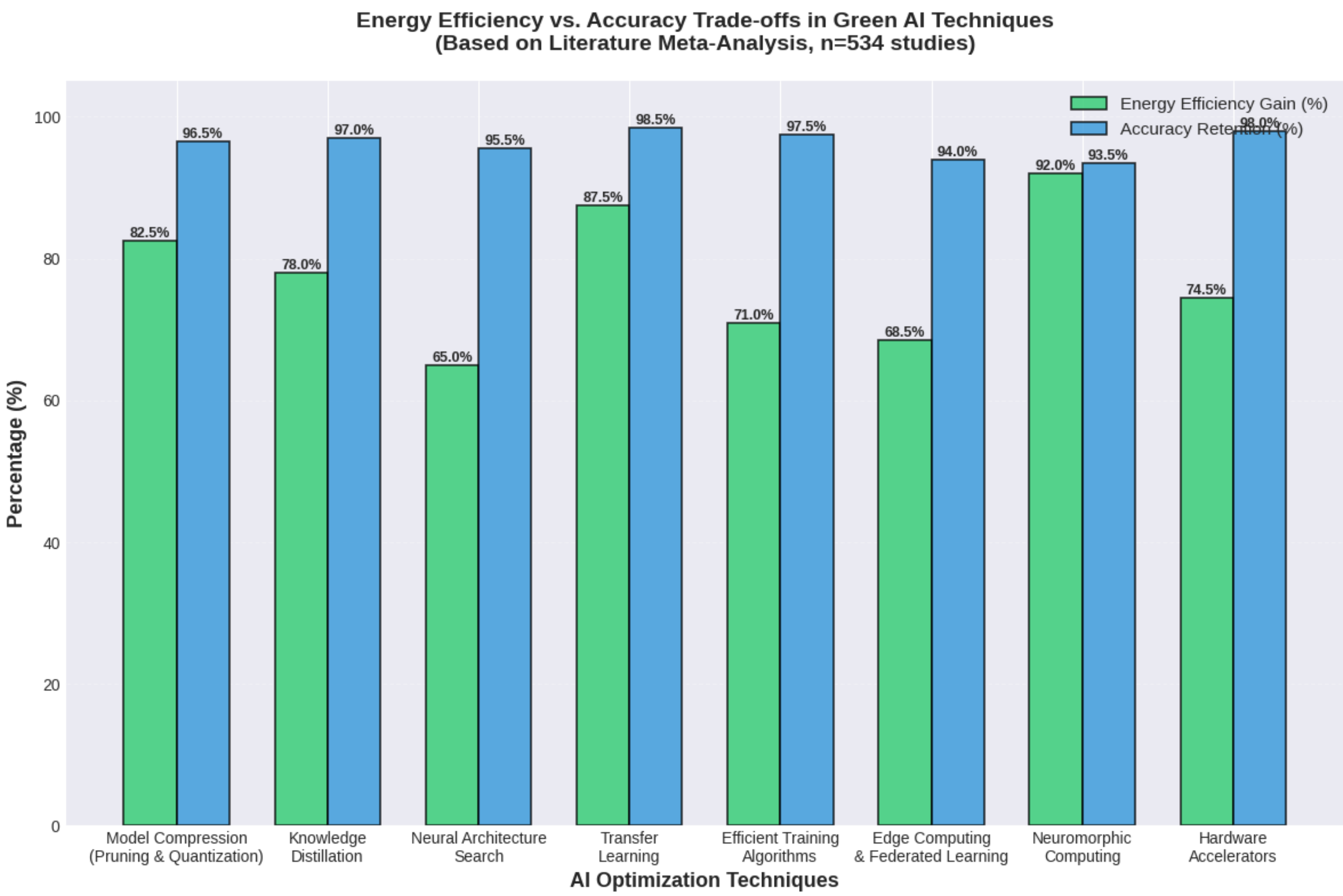

Fig 1: Energy Efficiency Improvements by AI Optimization Technique

The most developed area of application is energy management and optimization, where machine learning algorithms can be used to forecast patterns of energy demand, optimise operation of power grids, balance intermittency in renewable energy sources, and minimise transmission losses [16,71-73]. Research evidence indicates that AI-based smart grid operations can enhance energy efficiency (15-30 percent) and increase the levels of the use of renewable energy sources. Energy management systems that are constructed using reinforcement learning result in 20-40 percent cost savings of heating and cooling and do not lower occupant discomfort. Having been applied in the optimization of industrial processes, AI leads to energy savings when manufacturing through detection of flaws in the process, anticipating equipment maintenance, and optimal production plans to use lower electricity levels during the off-peak periods [74-77]. Another sensitive field of application of AI is connected to climate modeling and environmental surveillance, which is based on the idea to gain the full knowledge of the environmental mechanisms and provide an opportunity to detect the threats to the ecological conditions in advance [78-81]. An example Deep learning models are used to trace deforestation, track animals, identify illegal fishing operations, and estimate changes in biodiversity with unprecedented both spatial and time resolution of satellite images. Models of climatic conditions that involve machine learning can enhance the accuracy of prediction of extreme weather, rising sea levels, and the effects of climate conditions on regions, which leads to improved adaptation planning [6,82-85]. AI-based air quality sensors offer immediate monitoring of pollution and causes of sources to assist in the further interventions that can benefit the population and enforce laws.

AI is used in sustainable agriculture and precision farming to optimize the use of resources keeping the yields unchanged or improved [86-88]. Computer vision systems can be used to check the health of crops, diseases in an early stage as well as measure the extent of harvesting when crops are fully matured. Machine learning processes are used to optimize irrigation programs on the basis of weather prediction, soil moisture and crop development models, cutting down the use of water by 20-50 percent. The active use of fertilizers through AI solutions that check the analysis of soil conditions and plant requirements will reduce the number of chemicals that run off into waterways and the quantity of greenhouse gases produced by excess nitrogen. AI-controlled autonomous agricultural robots weed specifically and eliminate pests, which also means that herbicides and pesticides are used much less [2,89-91]. The transportation and logistics optimization uses AI to minimize fuel usage, emissions, and congestion in the freight and passenger transport issue [92-94]. Optimization algorithms of routes based on the traffic conditions, weather, and characteristics of vehicles can save 10-25 percent of transportation fuel consumption. Autonomous traffic control systems that incorporate AI can react to traffic flow and traffic flow dynamics and adjust signal timing and lanes arrangements to reduce congestion and idling. Optimization of electric vehicle chargings will be to guarantee effective use of grids and maximum use of renewable energy [9,95-97]. Although the full implementation of the autopilot technologies will take several years, the advancement of autonomous vehicles technologies stipulates the acquisition of massive efficiency in the form of the smooth process of acceleration, the optimal under-the-speed maintenance, and the platooning of the vehicles [98-101].

The applications of AI to the circular economy and waste management can show the prospective of changing linear to the circular production and consumption models [6,102-105]. The computer vision systems detect and classify the recyclable material more accurately and faster than the manual systems, enhancing the recycling volume and quality of its products [106-108]. Predictive maintenance algorithms help to prolong the lifespan of the equipment, as well as minimize the premature disposal during failures prediction and optimal maintenance planning [109-112]. Design tools based on AI are able to scan the full-life cycle of environmental impact of products, that is, the designer can make informed decisions that reduce the use of resources and recycle as much as possible. The optimization of the supply chain minimizes wastage as it provides supply and demand with a very fine level of accuracy that results to overproduction and spoilage. AI has been applied in materials discovery and sustainable chemistry to enhance the creation of materials and chemical processes that are environmentally safe. Millions of potential compounds are filtered through machine learning models to find the candidates of renewable energy technologies, including better batteries, solar cells, and catalysts. The generative design algorithms develop new materials with the intended properties and have the least impact on the environment. Making things perfect with the help of AI helps waste, energy and dangerous byproducts of chemical production. Such applications show great potential but need much more critical follow up research and validation prior to a wide scale use.

Environmental policy and corporate sustainability decision support systems combine a variety of data sources and analysis functionality during the process of making strategic decisions [113-114]. The AI platforms will process environmental policies, sustainability reports, and market trends with an aim of assisting organizations to monitor compliance, risks, and opportunities [115-117]. The application of the scenario modeling tools can help the policymakers to determine the possible results of various policy interventions on supporting the emissions, using the resources, and affecting the economy. Sustainability reporting systems make use of natural language processing to identify environmental performance information contained in corporate disclosures so that these can be standardized and held to account. These are applications that promote evidence-based environmental governance and transparency.

3.2 Methods of AI that consume little energy

To minimize the ecological footprint of the AI systems themselves, it is necessary to make innovations in all levels of technology, i.e., both algorithms and software and hardware as well as infrastructure [2,118-121]. The literature lists the various complementary methods that could dramatically conserve AI energy consumption but keep the levels of its performance acceptable.

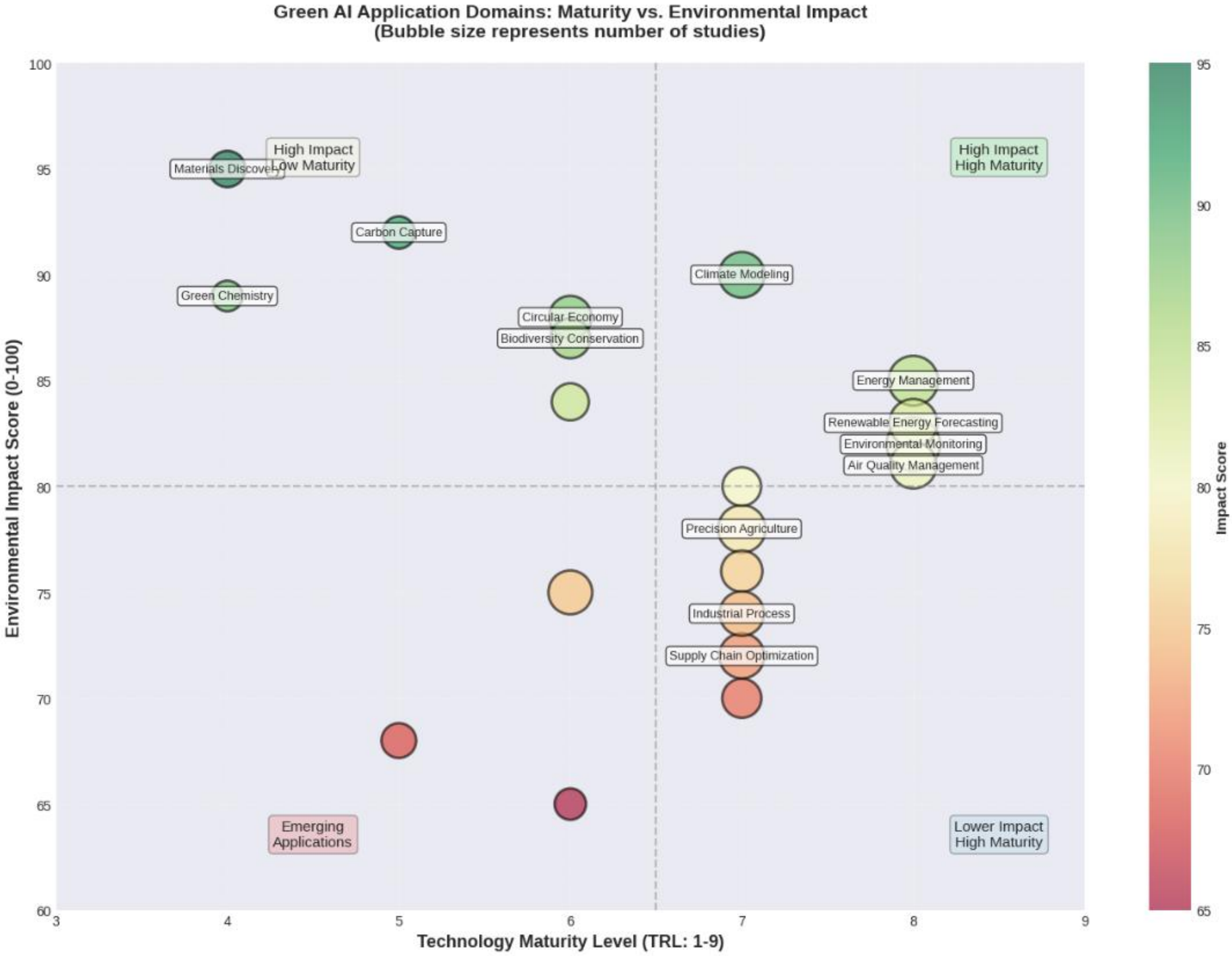

Fig 2: Green AI Application Domains - Impact vs. Maturity Analysis

The algorithm optimization methods are aimed at coming up with computational techniques that yield the desired results using fewer computations and at reduced memory levels [122-126]. Neural architecture search is an automatic optimization of efficient model structures to hard-hardware specifications and application demands [127-130]. Sparse models that only use some of the neurons or links that are relevant to each input cause drastic computation reduction and generally increase generalization. The early exit mechanisms allow models to make predictions that are not processed through all the layers in high-confidence instances that are fast to reach maximum confidence, thereby providing significant savings in terms of averaged inference cost. The efficiency of training models deals with the staggering energy usage of model training which in large cases is a major lifecycle contribution to large models. Transfer learning also uses the existing trained models as initial computational frameworks, eliminating up to 80-95 percent of the training time and energy that would have been used to train new models. In Curriculum learning, the training examples are provided in pedagogically optimum order, this will hasten the convergence and enhance the end results. Effective training algorithms such as adaptive learning rates, gradient clipping and scheduling of batch size allow reaching a faster convergence at reduced computational costs. In hyperparameter optimization, intelligent search methods are used instead of grid search which is exhaustive, which saves on computational cost of developing a model by several orders of magnitude.

Fig 3: Implementation Challenges vs. Strategic Opportunities Heatmap

The Hardware innovations offer basic shifts in energy efficiency with special architectures that are designed to fulfill AI workloads [8,131-133]. Neuromorphic computing chips are based on biological neural networks and have energy efficiency advantages of 100-1000 times other processors, on specific tasks. General-purpose processors can be greatly outperformed by AI accelerators such as Graphics Processing Unit, Tensor Processing Unit and Field-Programmable Gate Arrays but differ significantly in efficiency, depending on the workload. New technologies such as optical computing, quantum computing, and analog computing will potentially offer radical efficiency benefits though they are still largely experimental. Low-power edge computing devices make possible local processing, which makes data transmission costs less and cloud computing less important, but only with model complexity and capability limitations. The concept of data center optimization includes increasing the physical infrastructure to minimize computing, cooling and other auxiliary processes energy use [134-137]. The latest cooling systems such as liquid cooling, free-air cooling and underwater data centers will be able to save 30-60 percent of cooling energy consumption in relation to conventional air conditioning. Integration of renewable energies, either onsite generation or purchasing of power through a power purchase agreement will lower the carbon intensity by a very large margin with other facilities becoming carbon neutral. Waste heat recovery systems utilize the available thermal energy as excess heat to be recycled into district heating, industrial processes, or desalination processes as a value [138-140]. Intelligent workload scheduling relocates computational tasks to the places and times when there is a lot of renewable energy, and there is no need to use fossil fuel that would negatively affect performance.

Distributed and edge computing models minimize the use of energy by processing data at a closer distance of the data source reducing the need of data transmission and central processing burdens [141-144]. Researchers can use Federated learning to train models not only on distributed devices but avoid centralizing sensitive data and use less energy and decrease privacy risks. The Edge inference is a tiny model deployed on smartphones and on sensors and IoT devices, allowing smartphones and sensors to respond to situations in real-time with minimal cloud interaction. Edge and cloud processing balance Hybrid approaches are based on the consideration of complexity, latency requirements, and energy constraints and optimize on the overall system performance. Such distributed systems are also easier to recover, bringing down the latency, and enhance privacy, which are several co-benefits to energy efficiency. Software engineering is seeing the emergence of sustainability concerns in the processes of software engineering and software engineering development. Tools like the Spikes of energy profiling qualitatively and quantitatively measure energy usage of various pieces of code with the aim of improving code performance by pinpointing the inefficient elements. Frameworks of sustainable development of AI offer ideas, templates and best practices towards creating energy efficient systems. The pipeline that continues on continuous integration is capable of ensuring sustainability performance, which requires regression to avoid regression of energy efficiency and functional correctness. Standards of documentation are placing increasing emphasis on reporting carbon footprint as well as energy consumption measures, among the conventional performance measures, which are more likely to improve transparency and accountability.

3.3 Implementation Challenges

Although technical solutions have considerably improved and awareness on Green AI has increased, still, there are many obstacles that hinder the global adoption of Green AI practices [145-146]. These barriers are crucial command of this knowledge on how to create effective policies to achieve a faster change towards sustainable artificial intelligence [18,147-149]. One of the most basic hindrances to improvement is measurement and standardization issues. The absence of standardized measures to measure the AI environmental impact makes it challenging to make a meaningful comparison across systems, organizations, and studies [150-153]. The results of different methodologies are not comparable and make it difficult to benchmark and track the progress. Imperfect lifecycle assessment that looks at the issue affectively through its energy use but ignores the manufacturing, conveyance, and relocation effects give false comparisons [25,154-157]. The carbon intensity in the grid varies geographically, and the same operations can have huge dissimilar environmental impacts across geographies, which makes it complex to assess the operations worldwide. This is because there are no universally recognised reporting frameworks to prevent greenwashing and thus it is hard to prove sustainability allegations.

The performance trade-offs result in a hard choice to be made by practitioners between the accuracy requirements and environmental concerns [158-161]. A number of energy efficiency methods imply certain levels of performance degradation, which might not be acceptable with the critical types of performance (medical diagnosis, autonomous vehicles, or infrastructure control) [9,162-164]. Competitive delivery on the benchmark and commercialization drives the need to maximize the accuracy rather than to minimise the use of energy. Doubt over the extent and acceptability of performance trade-offs to various uses daunts the use of efficiency method. The fact that they do not have highly developed optimization frameworks which clearly trade off among multiple objectives such as accuracy, latency, energy, cost and fairness leaves the practitioners with limited guidelines of making such complex decisions.

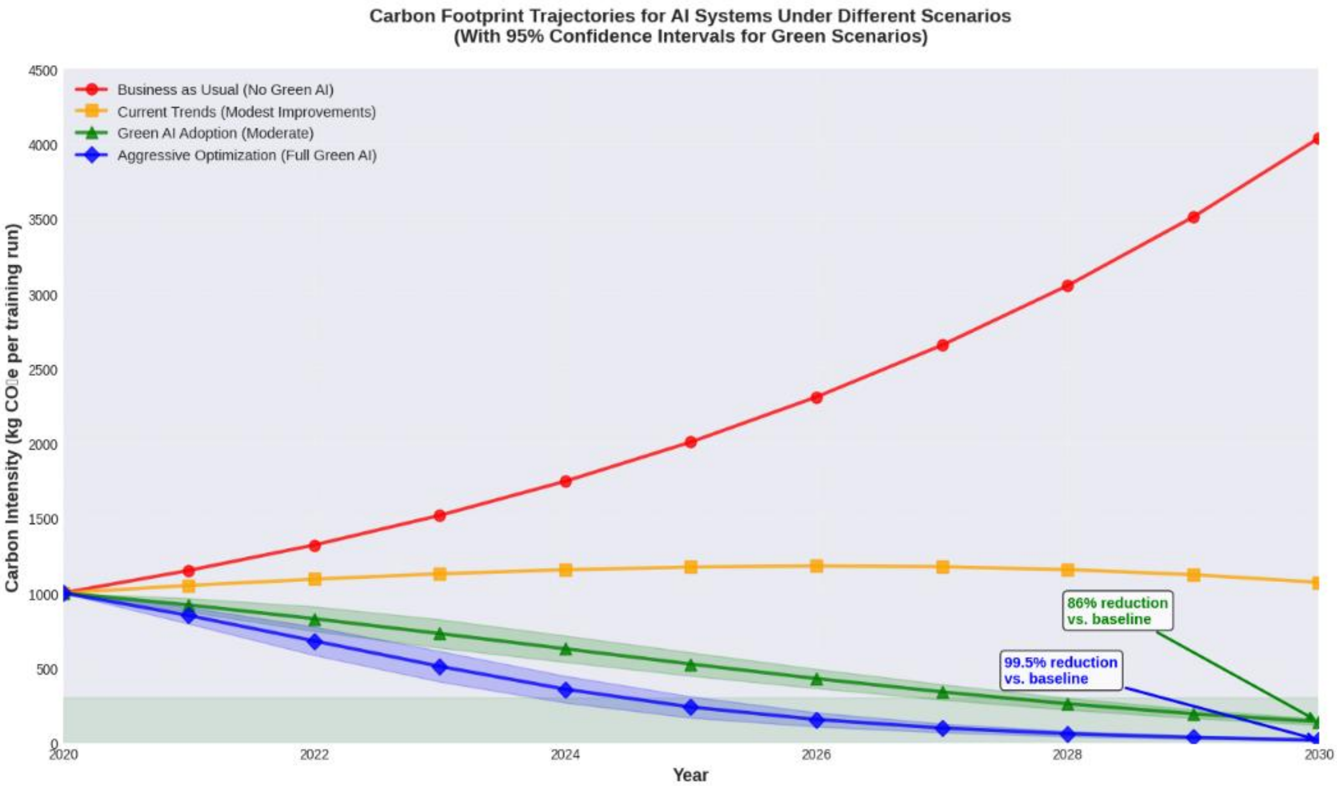

Fig 4: Projected Carbon Footprint Reduction in AI Systems Over Time

The problem in economic and business models is the misalignment of the social benefits with the incentives of the individuals in private [165-167]. The overall idea of Green AI investment strategy is not attractive in many cases; especially when the gains of efficiency are lowered in cloud computing companies that impose fees by use of resources. The viability of the long-term cost and quarterly earnings touches the investment in sustainability, which can bring benefits only in the long term. The voluntary use of sustainability investment is not encouraged by first-mover disadvantages in a competitive market in which sustainability investments add costs and will not give their owners short-term revenue advantages. Environmental costs are externalized, such that organizations are not incurring the social costs of all costs of their environmental assets and this lowers motivation to mitigate. The ultimate result is a lack of funding to make the required investments in the green project through a limited supply of green financing specifically on sustainable AI projects. Even with motivation there are still technical complexity and gap in skills that hinder implementation. To build energy-efficiency in AI, it takes specialized knowledge in machine learning, computer architecture, systems engineering, and environmental science, with which very few people have this knowledge altogether. The current speed of developments in the techniques and tools poses a target that moves quickly and thus the practitioners cannot keep up with the required expertise. Poor education curriculums on sustainable AI imply that there is a small number of graduates going into the labor force with the necessary skills. Imaturity of tool and framework to adopt Green AI as opposed to traditional AI development puts barricades to adoption. It would not be easy to integrate since trying to integrate efficiency techniques in current development pipelines and production systems may be suffering.

The barriers to change can be the organizational and cultural one, which takes the form of resistance to changes and priorities mismatch. AI teams do not necessarily have environmental awareness, or may regard sustainability as the concern of another person. Organizational cultures that are performance based and recompense model accuracy and speed may not recognize or reward sustainability donations. Uncoordinated structures in which the environmental sustainability units are not empowered to make decisions on technology do not facilitate coordination. The pressures of projects that might be completed in the long term or short-term are such that a short-term project has little time to optimize the sustainability that is not stipulated. Top managers can see sustainability as an extracurricular activity and lack adequate support and resources of the green programs.

Table 1: Green AI Applications, Techniques, and Sustainability Impacts

Sr. No.	Application Domain	Specific Applications	AI Techniques Used	Performance Impact	Sustainability Contribution
1	Energy Management	Smart grid optimization, demand forecasting, renewable integration	Reinforcement learning, time series prediction, optimization algorithms	15-30% efficiency improvement	Reduces fossil fuel dependence, enables renewable energy penetration
2	Climate Modeling	Weather prediction, climate change scenarios, extreme event forecasting	Deep learning, physics-informed neural networks, ensemble methods	Improved prediction accuracy by 20-35%	Enhanced adaptation planning, early warning systems, risk assessment
3	Environmental Monitoring	Deforestation tracking, biodiversity assessment, pollution detection	Computer vision, satellite image analysis, sensor networks	Real-time monitoring at continental scale	Enables rapid response, regulatory enforcement, conservation prioritization
4	Precision Agriculture	Crop health monitoring, irrigation optimization, pest management	Computer vision, IoT sensors, predictive analytics	20-50% reduction in water/chemical use	Reduces environmental contamination, conserves resources, maintains yields
5	Transportation Optimization	Route planning, traffic management, autonomous vehicles	Graph optimization, reinforcement learning, multi-agent systems	10-25% fuel consumption reduction	Lower emissions, reduced congestion, improved air quality
6	Building Management	HVAC optimization, occupancy prediction, energy scheduling	Reinforcement learning, predictive control, occupancy sensing	20-40% energy cost reduction	Reduced emissions while maintaining comfort, demand response capability
7	Circular Economy	Waste sorting, predictive maintenance, product lifecycle optimization	Computer vision, predictive analytics, lifecycle assessment	Improved recycling rates by 30-50%	Resource conservation, waste reduction, extended product lifespans
8	Materials Discovery	Battery materials, catalysts, photovoltaics, sustainable polymers	Generative models, molecular simulation, active learning	10-100x acceleration in discovery	Enables breakthrough clean energy technologies, reduces experimental costs
9	Supply Chain Optimization	Inventory management, logistics, demand matching	Optimization algorithms, predictive analytics, simulation	Reduced waste and emissions by 15-30%	Prevents overproduction, minimizes transportation, reduces spoilage
10	Carbon Capture	Site selection, process optimization, monitoring effectiveness	Optimization, simulation, monitoring systems	Improved capture efficiency and economics	Accelerates deployment of carbon removal technologies
11	Renewable Energy Forecasting	Solar and wind generation prediction, grid balancing	Time series analysis, probabilistic forecasting, ensemble methods	Prediction accuracy improvement of 15-25%	Enables higher renewable penetration, reduces curtailment and backup needs
12	Water Management	Consumption prediction, quality monitoring, distribution optimization	Time series prediction, sensor networks, optimization	10-30% reduction in water waste	Conserves scarce water resources, improves access and quality

13	Biodiversity Conservation	Species identification, habitat monitoring, anti-poaching	Computer vision, audio analysis, spatial modeling	Comprehensive monitoring at landscape scale	Protects endangered species, combats illegal activities, guides conservation
14	Industrial Process Optimization	Manufacturing efficiency, quality control, maintenance scheduling	Predictive maintenance, process control, optimization	15-25% energy reduction in manufacturing	Lower emissions, reduced waste, extended equipment life
15	Urban Planning	Land use optimization, infrastructure planning, sustainability assessment	Spatial analysis, simulation, multi-criteria decision analysis	Data-driven sustainable development planning	Creates more livable, efficient, resilient cities
16	Financial Risk Assessment	Climate risk modeling, green investment analysis, ESG scoring	Risk modeling, natural language processing, data analytics	Better-informed sustainable investment decisions	Channels capital to sustainable projects, prices climate risk
17	Disaster Response	Damage assessment, resource allocation, evacuation planning	Computer vision, optimization, simulation	Faster response times, improved resource allocation	Saves lives, reduces economic losses, speeds recovery
18	Ocean Monitoring	Illegal fishing detection, plastic pollution tracking, ecosystem health	Satellite analysis, sensor networks, pattern recognition	Comprehensive ocean surveillance	Protects marine ecosystems, enforces regulations, tracks pollution
19	Air Quality Management	Pollution source identification, exposure assessment, forecasting	Sensor networks, spatial modeling, prediction algorithms	Real-time air quality insights and forecasting	Protects public health, informs policy, enables targeted interventions
20	Green Chemistry	Reaction optimization, safer alternatives, process design	Molecular modeling, optimization, experimental design	Reduced hazardous substances and waste	Prevents pollution at source, improves worker safety, enables clean production
21	Carbon Accounting	Emissions measurement, reporting, verification	Data integration, natural language processing, accounting systems	Improved accuracy and transparency	Enables accountability, supports carbon markets, informs policy
22	Ecosystem Services Valuation	Economic valuation, trade-off analysis, scenario modeling	Spatial modeling, economic analysis, ecosystem modeling	Quantifies environmental benefits	Informs land use decisions, supports conservation investments
23	Green Infrastructure	Living wall design, green roof optimization, urban forest management	Simulation, optimization, sensor monitoring	Maximized ecosystem service provision	Improves urban resilience, air quality, heat mitigation, biodiversity
24	Sustainable Mining	Ore grade optimization, tailings management, site restoration	Optimization, monitoring systems, predictive analytics	Reduced environmental footprint	Minimizes habitat destruction, prevents contamination, enables restoration
25	Food System Sustainability	Food waste reduction, supply chain optimization, nutrition planning	Predictive analytics, optimization, recommendation systems	Reduced food waste by 20-40%	Conserves resources, reduces emissions, improves food security
26	Environmental Education	Personalized learning, engagement platforms, behavior change	Adaptive learning, recommender systems, gamification	Increased environmental awareness and action	Builds sustainability literacy, empowers individuals, shifts norms

27	Policy Simulation	Impact assessment, scenario analysis, stakeholder engagement	Agent-based modeling, system dynamics, simulation	Evidence-based policy development	Improves policy effectiveness, anticipates consequences, manages trade-offs
28	Sustainable Fashion	Material selection, circular business models, authenticity verification	Material informatics, supply chain tracking, verification systems	Reduced fashion industry environmental impact	Addresses major pollution source, enables circular economy
29	Green Building Design	Energy modeling, daylighting optimization, material selection	Building simulation, optimization, lifecycle assessment	30-50% energy reduction in buildings	Major emissions reductions, improved comfort, lower operating costs
30	Ecological Restoration	Site assessment, species selection, monitoring progress	Spatial analysis, species distribution modeling, remote sensing	Improved restoration success rates	Rebuilds ecosystems, enhances resilience, provides ecosystem services

The availability and quality of data limit the process of developing sustainable AI and using AI to create sustainability. Environmental surveillance frequently does not have the detailed and high-quality information to develop the relevant models to predict climate, evaluate the state of the ecosystem, or trace pollution. Company-owned silos of data do not allow researchers to get access to data that would help them develop and test green methods. The heterogeneity between organizations and jurisdictions in the formats and standards of data makes the integration more complex and expensive. The fact that the process of sharing data is restricted by privacy and security limits even cases when the benefits to the environment would be great. The expenses of assembling, purifying and keeping quality environmental data are prohibitive, which is orchestrating various expenses that are beyond the financial capabilities of most organizations and study teams. Lacking regulatory and policy protections bring about a lack of clarity and do not offer sufficient incentives or conditions towards sustainable AI. In the majority of jurisdictions, there are no special regulations on the environmental impact of AI, which means that the organization has no definite compliance standards. Global regulation has made global organizations more complicated and has the potential to promote regulatory arbitrage, in which the computing migrates to a jurisdiction that has lax regulations. Lack of compulsory disclosure policies gives companies a way of committing evasions regarding the effects on the environment. The lack of the policy support of research and development of sustainable AI reduced the possibility of the population to invest in the advances of the fundamentals. Digital infrastructure is commonly a price exemption or poorly addressed in carbon pricing, offering a low price incentive to efficiency.

3.4 Opportunities and Future Directions

Nevertheless, with the existing challenges, there are still many opportunities to further speed up the application of Green AI and achieve the maximum in the field of sustainable development. These opportunities can be discovered and explored so that challenges can become agents of positive change. Whereas technological advances are made in both hardware and algorithms they are promising orders-of-magnitude improvement in efficiency. A neuromorphic computing solution going to a commercial level would alleviate the energy efficiency of some AI tasks. In the form of quantum computing, previously unsolvable optimization problems that are used in climate models, materials discovery, and supply chain sustainability may be efficiently solved. Light-based photonic computing Theoretical Photonic computing in light as opposed to electron computers has a 100-1000x energy efficiency advantage utilizing light in certain operations. New materials such as 2D materials and bio-compatible substrates can facilitate more green production of chips. Further improvements in the performance of algorithms through continuous innovations in sparse models, efficient attention combinations and neural architecture search will provide further improvements at a relatively low cost.

Policy and regulatory changes can establish strong motivators and mandate that can lead to mass adoption. Environmental impact disclosure requirements should be made mandatory to increase the level of transparency and provide stakeholders with the ability to pressure the improvements. Environmental externalities would be internalized through the mechanisms of carbon pricing that reflect computationally appropriate accounts of AI computational expenses. Market pull would be achieved through public procuring sustainable AI solutions. Incentives on research and development such as grants, tax credits and public- private partnership would hasten innovation. The global collaboration in the form of standards, regulations and best practices would help to decrease fragmentation and make global developments possible. The implementation of sustainability requirements within AI ethics guidelines and systems of governance would entrench the aspects of the environment in technological advancement. Coordination failure can be addressed through industry collaboration and setting standards that can be used as common practices. It would be possible to conduct meaningful comparison and benchmarking, when industry consortia come up with standardized metrics, measurement methodologies and reporting structures. The adoption would be reduced by open-source tools and libraries of sustainable AI development. The best practices could be shared across the industry associations, conferences, and publications, and the processes of learning would be accelerated. Joint research projects between academic scholars and practitioners in the industry would mean that research is done based on the actual needs. Cooperation on the basic issues like lifecycle assessment methodologies before any competing effort is undertaken would be beneficial to all the parties and yet competitive distinction on the execution would be maintained.

It is crucial to have educational change to equip the upcoming generation of AI practitioners with sustainability competencies to be successful in the long term. The development of the curriculum that incorporates environmental aspects into the mainstream AI and computer science curriculums would allow graduates to guarantee required knowledge and values. Professionals development would be conducted on the current practitioner to deal with skill gaps. The bridging interdisciplinary education between the technical, environmental, policy and social sciences would equip professionals to operate in the complex socio-technical arena. The high-quality sustainability education would be provided worldwide by educational materials, case studies, open courseware, etc. Academic engagements with partners in the industry excelling in practice would make learning more effective and relevant. Economic incentives may be brought in line with environmental objectives using market-based mechanisms. Green AI certification programs would allow organizations to demonstrate the commitment as well as using products and services to differentiate. Environmental-related financing that offers preferential treatment on AI investments would create more capital access. The requirement of corporate sustainability reporting would put pressure and internal responsibility towards improvement. The sustainability of investment criteria with the integration of AI in environmental, social and governance aspects would focus capital on responsible practices. Sustainable AI services will be a business case being voluntarily adopted across beyond compliance business requirements due to the premium pricing.

Complementary to top-down policy interventions can be stakeholder engagement and the social movement building which provides bottom-up pressure. Civil society organisations that promote sustainable AI are able to create awareness to people and hold them accountable. Sustainability commitment can be advocated internally by worker organizing in technology companies. Sustainable practices can be rewarded by the consumers through consumer preferences in the form of buying choices. Shareholder power can affect corporate agenda with the use of investor activism. The disciplinary practices can be changed by academic communities that set the norms on environmental consideration of reporting about the research and sustainability. All such actions by various stakeholders result in cultural change, which underpins AI transition in a sustainable manner. The mechanisms of global cooperation refer to the international character of both the climate change and development of AI. Technology transfer programs would make sure that the developing countries are able to make an access to the sustainable AI capacity without replicating the unsustainable development trends. International research collaborations have the ability to share resources to address issues that can be addressed by different countries. Climate finance systems can systematically assist vulnerable countries to have sustainable AI infrastructures. The harmonisation of international standards would ease the complexity in compliance, and would also allow global supply chains. The innovations, lessons learned, and best practices would be spread across the boundaries, through knowledge sharing platforms. These collaborative mechanisms note that climate change and technological advancement are issues of global concern that have to be addressed collectively. The synthesis of applications, techniques, challenges, and the opportunities made above reveal that Green AI is a major challenge and a massive opportunity. Through threats, the barriers are quite high but a combination of technological potential, political dynamics, and market forces, and social pressure presents the broadest opportunity to drive radical change ever. The tables below are comprehensive summaries of important points in various dimensions that make it easy to get a comparison and proceeds to make decisions.

Table 2: Implementation Challenges, Opportunities, and Strategic Directions

Sr. No.	Challenge Area	Specific Challenge	Opportunity/Solution	Expected Outcome	Strategic Direction
1	Measurement Standardization	Lack of unified metrics for environmental impact assessment	Develop ISO standards for AI carbon footprint measurement	Enables benchmarking, comparison, and accountability across organizations	Establish international working groups, pilot standardized frameworks
2	Performance-Efficiency Trade-offs	Tension between model accuracy and energy consumption	Multi-objective optimization frameworks balancing multiple criteria	Pareto-optimal solutions respecting application-specific constraints	Research adaptive techniques, context-aware optimization strategies
3	Economic Incentives	Business cases unclear, externalized environmental costs	Carbon pricing, green procurement, sustainability-linked financing	Aligns private incentives with social benefits	Implement carbon taxes, subsidize green AI R&D, mandate disclosure
4	Technical Complexity	Requires specialized interdisciplinary knowledge	Educational programs, accessible tools, best practice documentation	Lowers barriers to adoption, builds necessary workforce	Develop curricula, create open-source tools, establish certification programs
5	Organizational Culture	Performance-focused cultures undervalue sustainability	Executive leadership commitment, KPI alignment, recognition programs	Embeds sustainability in organizational values and practices	Leadership training, cultural change initiatives, incentive restructuring
6	Data Availability	Insufficient environmental data for training models	Open data initiatives, sensor networks, data sharing partnerships	Enables development and validation of environmental AI applications	Public investment in monitoring, data portal development, privacy frameworks
7	Regulatory Gaps	Absence of mandatory requirements and clear compliance standards	Environmental regulations specific to AI, disclosure requirements	Creates level playing field, prevents greenwashing, drives adoption	Legislative action, regulatory guidance, international harmonization
8	Hardware Lifecycle	Manufacturing and disposal impacts often neglected	Extended producer responsibility, circular design principles	Reduces embodied carbon, extends useful life, improves recyclability	Design for longevity, modular upgrades, take-back programs
9	Geographic Disparities	Unequal access to green technologies across regions	Technology transfer, capacity building, climate finance	Ensures equitable sustainability transitions globally	North-South cooperation, knowledge sharing, infrastructure investment
10	Rebound Effects	Efficiency gains offset by increased consumption	System-level analysis, consumption governance, sufficiency strategies	Ensures efficiency translates to absolute impact reduction	Monitor system effects, consumption limits, behavior change programs

11	Interoperability	Fragmented tools and platforms hinder integration	Open standards, common APIs, interoperable platforms	Enables seamless integration and reduces duplication	Industry collaboration, standard-setting organizations, open-source projects
12	Skill Shortages	Insufficient practitioners with green AI expertise	Training programs, professional development, knowledge sharing	Builds capacity to implement sustainable practices	Bootcamps, online courses, mentorship programs, communities of practice
13	Investment Gaps	Inadequate funding for green AI research and deployment	Public funding, green bonds, impact investing, venture capital	Accelerates innovation and deployment at scale	Research grants, tax incentives, sustainability funds, public-private partnerships
14	Verification and Auditing	Difficulty verifying sustainability claims independently	Third-party auditing, certification schemes, transparent reporting	Builds trust, prevents greenwashing, ensures accountability	Accreditation systems, audit protocols, blockchain verification
15	Legacy Systems	Existing infrastructure not designed for sustainability	Retrofit strategies, migration pathways, hybrid approaches	Enables transition without complete replacement	Assessment tools, migration frameworks, backward compatibility
16	Edge Device Constraints	Limited resources on edge devices restrict capabilities	Efficient models, specialized hardware, cloud-edge orchestration	Enables sustainable distributed computing	TinyML research, efficient architectures, intelligent task distribution
17	Model Interpretability	Black-box models hinder trust and regulatory compliance	Explainable AI techniques, interpretable architectures	Builds trust, enables compliance, supports decision-making	XAI research, regulatory guidance, interpretability tools
18	Bias and Fairness	AI systems may perpetuate or amplify inequities	Fairness-aware algorithms, diverse datasets, impact assessments	Ensures equitable distribution of benefits and burdens	Bias audits, diverse teams, participatory design, accountability mechanisms
19	Cross-Sector Coordination	Sustainability requires cooperation across domains	Multi-stakeholder platforms, shared roadmaps, collaborative projects	Enables systemic change through collective action	Consortia, working groups, public-private partnerships, knowledge exchanges
20	Rapid Technological Change	Quick obsolescence creates uncertainty and waste	Modular design, upgrade pathways, compatibility standards	Extends useful life, reduces waste, manages transition	Technology roadmaps, backward compatibility, refurbishment programs
21	Scale and Scope	Pilot projects struggle to scale to production deployment	Scaling frameworks, industrialization support, best practices	Bridges gap from proof-of-concept to widespread adoption	Scale-up funding, industrial partnerships, deployment playbooks
22	Intellectual Property	Proprietary technologies limit knowledge diffusion	Open innovation, patent pools, licensing strategies	Accelerates progress through knowledge sharing	Open-source contributions, collaborative R&D, patent commons

23	Long-Term Thinking	Short-term pressures undermine sustainability investments	Long-term incentives, patient capital, intergenerational frameworks	Aligns decision horizons with sustainability timescales	Long-term value metrics, stewardship models, future generations representation
24	Energy Grid Constraints	Grid limitations restrict renewable integration	Grid modernization, storage solutions, demand management	Enables high-penetration renewable energy systems	Smart grid investment, storage deployment, flexible load management
25	Political Economy	Vested interests resist sustainability transitions	Inclusive governance, just transition frameworks, coalition building	Manages transition politics, ensures broad support	Stakeholder engagement, compensation mechanisms, participatory processes
26	Monitoring and Evaluation	Insufficient tracking of sustainability outcomes	Impact measurement frameworks, continuous monitoring systems	Enables adaptive management and accountability	Indicator development, data systems, evaluation protocols
27	International Cooperation	Global challenges require coordinated responses	Multilateral agreements, knowledge sharing, joint initiatives	Addresses transnational nature of climate and technology	Diplomatic engagement, international organizations, collaborative platforms
28	Social License	Public concerns about AI and environmental claims	Transparency, stakeholder engagement, demonstrable impact	Builds public trust and support	Participatory governance, clear communication, verified results
29	Innovation Ecosystems	Fragmented innovation slows progress	Innovation hubs, accelerators, network organizations	Catalyzes innovation through collaboration and support	Cluster development, entrepreneurship programs, funding ecosystems
30	Resilience Planning	Systems vulnerable to climate impacts and disruptions	Resilience assessment, redundancy, adaptive capacity	Ensures continued operation under changing conditions	Scenario planning, stress testing, adaptation strategies

3.5 Sustainable and Resilient Development Through Green AI

Green Artificial Intelligence integration with the principles of sustainable development and resiliency schemes is a crucial intersection, which should not be reduced to technical and efficiency optimization but to the overall change in social-ecological systems. The conceptualization of sustainable development as understood at the United Nations Sustainable Development Goals means balancing the achievement of the economic growth, social inclusion, and environmental protection in a way that satisfies the present generation without making it incapable of satisfying its own needs. In this context, resilience means the ability of systems to survive the shock, adjust to the dynamic conditions and change with regard to the underlying challenges without losing its core functions and values. Green AI helps in the sustainable development in many dimensions. In terms of economics, the cost of operation through energy-efficient AI systems are lowered, competitive advantages are developed among the first users and new markets are opened within the fields of sustainable technology. The world market of Green AI solutions is expected to go beyond one hundred billion dollars in the year 2030, which is bound to generate a significant economic value and also promote the environmental goals. Cost savings will be the direct result of energy efficiency, which can be re-invested in new innovation or given back to the stakeholders. Besides, AI-based solutions to optimising resources, reducing wastes, and making transitions to the circular economy bring about an economic benefit through the conversion of waste to resources and the increase in material lifecycles.

Green AI can mitigate and adapt to climate change in terms of its environmental status. Some of the mitigation efforts are to ensure that the AI itself has a smaller carbon footprint, to optimize their own energy systems to produce the least amount of emissions, to speed-up the development of clean energy technologies, and to faciliate a shift towards the circular economy that does not tie economic growth and expansion to consuming more resources. Some of the contributions to adaptation can include improved climate analysis to predict the effects, early warning mechanisms to extreme weather patterns, high-precision agriculture that allows food production in varied environments, and monitoring the ecosystem, which can be used as the basis of conservation priorities. These two functions put AI in the position of both a part of the solution and a part of the problem and necessitate cautious attention to be taken so that its impacts on the environment are net positive. Green AI has social implications to equity, justice, and human wellbeing, which need conscious consideration. Sustainable use of AI tools is a phenomenon that requires even access to ensure that there is no sustainability gap where the rich countries and states are grabbing the gains at the expense of the poor. Just transition models make sure those workers and communities busy on fossil fuel industries are supported when the economies switch to renewable fuel. The systems of participatory governance allow the communities that are affected to influence the development and implementation of AI in a manner that expresses their values and priorities. Reduced air pollution, improved food security and climate adaptation are health co-benefits that offer visible improvements in the human wellbeing.

Green AI dimensions of resilience have varying levels comprising of robustness, adaptability, and transformability. System robustness is the qualification to be operational in spite of perturbations, which the AI improves by predictive maintenance, early warning systems and optimization of redundancy. Adaptability entails the ability to adapt to a dynamically evolving environment by learning and flexibility in which AI allows versatile resource allocation, optimization in real-time, and constant improvements with feedback. The transformability is the ability to be fundamentally restructured when incremental adaptation becomes inadequate, which is aided with AI by facilitating the scenario modeling, speeding up innovation, and finding places in the system to create a change that will be felt. Predictive analytics and adaptive management based on the human emotion of AI is of significant benefit to infrastructure resilience. Smart grids using AI algorithm balance supply and demand in real time, combine distributed renewable energy sources, and fail to isolate faults, thus avoiding cascading blackouts. The transportation systems apply AI to bypass disruptions and achieve capacity optimization and forecast the timing of failures via predictive maintenance requirements. Water systems use AI to detect leaks, raise contamination alarms, and optimally supply (with the changing availability). The applications illustrate the ability of AI to improve resilience of critical infrastructure to climate, technical failures, and fluctuation of demands.

Another vital dimension on which AI is useful is ecological resilience. Computer vision and sensor networks are used to monitor ecosystems to provide an early warning of any type of regime shift including coral bleaching, forest die-back or wetland degradation. Species distribution modeling assists in the provision of climate refugia and migration pathways needed in the conservation of the biodiversity on the basis of the changing environment. Assisted evolution programs are AI-based programs that are used to apply genetic variations that offer climate-resistance capabilities, which can be transferred to at-risk populations. The use of AI by restoration planning to recommend species-to-site matches as per projections of future conditions instead of past trends increases establishment success and viability of the establishment. Economic inertia as a part of the sustainability transitions deals with the issue of volatility, uncertainty and structural changes. AI-driven scenario modeling assists business and policies to predict the transition risk and opportunities such as stranded assets, broken supply chains, and emerging markets. Incorporation of climate and environmental factors through financial risk assessment would allow stronger investment patterns. Diversification AIpowered, real-time monitoring, and contingency planning are beneficial since they make supply chain resilient to disruptions. The capabilities contribute to the economies going through the rough transition to sustainable development paths at a lower systemic risk level.

The dimensions of social resilience are sense of community cohesion and ability to adapt and fair shock recovery. Artificial intelligence may facilitate social resilience by enhancing disaster response operations, prioritizing resources to vulnerable populations, and connecting with vulnerable populations through a well-organized communication system during a crisis. Nevertheless, AI also presents the challenge to social resilience of displacement of jobs, surveillance features, and persuasion bias, which can strengthen the existing susceptibilities. To guarantee that AI is used in a way that leads to positive social resilience, the need to be concerned with equity, inclusion, and participatory governance should be expressed across design and implementation stages.

There should be special consideration given to the relationship between efficiency and resilience where in some cases, these two objectives can be in conflict with each other or they may be in line; this is based on how the systems are designed. Minimal efficiency maximisation can cause a decrease in redundancy and flexibility which give resources of resilience against shocks of the unexpected, resulting in brittle systems. Measures of resilience sustaining excess capacity or diversity, on the other hand, can be seen as inefficient, based on pure cost-reduction views. Green AI should ensure a balance between these aspects via multi objectively optimization that explicitly emphasizes efficiency and resilience as compromising aspects of sustainable systems, as well as sustainable systems, need both. One way of coping with this tension would be to use robust optimization methods that work well in a variety of situations instead of optimizing based on the expected conditions. The governance of Green AI should be sustainable and resolute on its own. There is a need to have adaptive frameworks that can address the emerging knowledge, changing environments and unexpected outcomes due to the rapid changes in AI capabilities as well as environmental issues. With polycentric governance that encompasses many scales and actors, experimentation, learning, and situational contextualization/sensitivity with coherence through the commonality of principles and coordination systems becomes a possibility. The participation processes make sure that the decisions are informed with various knowledge and values and this increases the level of legitimacy and social learning. The mechanism of transparency and accountability instill acknowledgment and permit correction of the course in the event of issues arising.

3.6 Synthesis and Critical Analysis

A widespread analysis of Green AI literature indicates that the sphere is in a state of rapid innovation, rising awareness, and points to an increasing sense of urgency, as well as a need, however, with enormous gaps, incompatibilities, and challenges, in application. A number of cross-cutting themes are identified as the result of the analysis and that should be discussed specifically. To begin with, the literature shows that there has always been a conflict between AI performance optimization and environmental sustainability optimization. Although the new developments have demonstrated that these goals do not necessarily have to be necessarily conflicting, in most cases they include considerable trade-offs. More advanced multi objective optimization models that explicitly model such trade-offs and serve in decision support to navigate them in various application problems would be useful in the field. The existing methods tend to either separate efficiency, or accuracy, or assume one is clearly predominant, where the truth lay in the existence of complex interrelations and interrelationships depending on situation.

Second, lack of enough emphasis on geographic and developmental disparities in the current studies has been exhibited. The literature has largely been biased involving applications and solutions that are applicable to large technology firms in the developed economies with relatively little account of challenges and opportunities in resource-bound environments, small and medium organisations or developing countries. This disparity is rather alarming considering the fact that the consequences of climate change are felt most in the areas that have the least resources to install sophisticated green technologies. Further studies should directly discuss sustainable access to the Green AI abilities and make sure that sustainability transitions would not lead to further inequalities. Third, the heterogeneity of methods and no standardization are hard on the synthesis of the results of studies among studies, comparison of methods, and monitoring of the changes with time. Various research has used incompatible measurement techniques, system limits and reporting standards, resulting in making meta-analysis and systematic comparison very hard. The discipline badly requires the ability to coalesce on consistent metrics, lifecycle assessment models, and reporting standards that can allow significant comparison with sufficient context-specific dispensation. There is need to focus on international collaboration in the measurement standards to avoid disjointedness and carry out international benchmarking.

Fourth, there is a lack of literature on incorporating Green AI as part of larger sustainability models such as the ideas of a circular economy and environmental justice alongside resilience thinking. The research conducted by most is very limited in its area of interest by not giving due attention to the upstream and downstream implications, material movement, electronic waste, water use, social equity aspects as well as systemic implications over time. Less reductionist methods that put Green AI into more holistic sustainability framework would allow to make better-informed decisions and prevent problem-shifting and unintended consequences. Fifth, there is poor coverage of governance, policy and institutional aspects in reference to the relevance of these in facilitating the systemic change. Although the technical solutions prevail in the literature, the political economy of sustainability transitions, efficacy of various policy tools, and governmental design mechanisms receive relative less research attention even though they are vital to extensive implementation. Interdisciplinary studies that clearly deal with the effect of institutional barriers, policy formulations, regulation structures, and governance processes should be given high priority to fill in on technical innovations.

Sixth, transition pathways and temporal dynamics need to be mentioned more explicitly. There are few studies that give a picture of how current capabilities are, or future potential of projects but in most cases they have not sufficiently modeled transition processes, lock-in effects, path dependencies, or sequence of interventions. Diffusion of the knowledge of how to find the way between the present unsustainable practice and the desired future ones, including in between provisions, the pre-requisites, and the challenges that may arise would be more practical to the practitioners and policymakers. Last, but not the least, the review discusses the importance of reflexivity and non-technological solutionism in a critical way. Although AIs provide strong means of environmental assurance and efficiency optimization, issues regarding sustainability are most likely social, political, and economic in nature and cannot be resolved only with the help of technology. Green AI should be placed as a part of an overarching sustainability approach instead of a techno-fix that allows sustaining practices of un-sustainable consumption or postponing systemic transformations. The innovation and capabilities should be accompanied by critical scrutiny of assumptions, unwanted outcomes and constraints of AI-based methods.

4. Conclusion

This is a literature review, which has summarized the existing knowledge in Green Artificial Intelligence as an approach to sustainable and resilient development by reviewing 534 peer-reviewed articles to offer a reliable overview of the current and fast changing area of expertise. As it has been analyzed, Green AI denotes not only minimization of the ecological footprint of the AI systems themselves but also the use of AI features to undertake environmental sustainability, at work in various different fields. Great advancements have been made in creating energy-saving algorithms, eco-friendly hardware, integration of renewable energy and AI technology in actions against climate change, conservation, optimization and monitoring of resources, and other technologies. The main results prove that the technical innovations such as model compression, efficient training techniques, neuromorphic computing, and edge-processing could minimize the energy usage of AI 70-95 percent with tolerable performance in most cases. The use of artificial intelligence to develop sustainability technologies depicts immense opportunities in areas such as smart grids, agricultural solutions, transportation, transforming the circular economy, and weather prediction, and materials discovery. Such features make AI potentially one of the transformational tools in the process of attaining global goals of sustainability and environmental protection.

Nevertheless, the gaps and challenges that concern the progress are also outlined in the review. Comparison and benchmarking is not possible due to methodological inconsistencies and absence of standardization in measurement frameworks. The efficiency versus accuracy performance trade off allows tough choices with no well-marked direction. In the economy, it is common to have economic incentives that emphasize the level of computational intensity over accountability to the environment. The skill gaps and technical complexity are limiting the implementation abilities. Sustainability priorities are not sustained by means of organizational cultures and regulatory structures. Research priorities and unequal capacity access on a geographic basis are a subject of equity. All these notwithstanding there are considerable opportunities to increase the uptake and influence of Green AI in a shorter period. The new technologies are offering the revolutionary efficiency improvement. The current process of policy making is developing more powerful motivations and needs. There is the industry cooperation on standards and best practices. The change of education is developing the needed human capital. The market is harmonizing policies of the economy and the environment. Stakeholders involvement is creating social change pressure. Global participation is also being made to respond to both climatic and technological dimensions around the world.

This review has implications that cannot be reduced to technical aspects but on basic questions like the role of technology in society and the way to go to achieve sustainable development. Green AI is an example of what the technologization of the future can look like, oriented at both social and environmental objectives based on purposeful design, the right governance model, and co-operation. The solution to this demands integration at a variety of scales and groups of stakeholders such as researchers, developers, policymakers, business leaders, civil society and international institutions in order to achieve success. In prospect, a number of research, policymaking, and research priorities are identified. To be able to make a significant comparison, monitor the progress, and hold the leaders accountable, first, the standardized measurement frameworks and reporting protocols should be developed and adopted. Second, studies that feature geographic differentials, formations of development, and equity areas ought to be broadened in order to achieve holistic and equitable sustainability changes. Third, more comprehensive sustainability models incorporating Green AI do not only need promotion but also trademarks such as circular economy, environmental justice and resilience planning. Fourth, the studies on governance and policy of investigating institutional barriers, regulatory effectiveness, and pathways of implementation should be paid more attention to.

Fifth, education training both present and upcoming practitioners on the required interdisciplinary skills needs to be speeded up. Sixth, the participation of international collaboration on standards, technological transfer, and climate financing of sustainable AI infrastructure should be enhanced. Seventh, technological optimism should be accompanied by the critical reflexivity of assumptions, limitations, and unintended effects of AI-based approaches. Eighth, demonstration projects of effective Green AI applications in a variety of settings would be evidence of concept and learning experiences. Climate change and environmental degradation is an urgent event that requires quick change of AI systems and practices. The time slot of not exceeding dangerous temperatures in the world is shrinking, as the requirements of AI computing keep expanding exponentially. It is tension that ensures abundant challenges and exceptional opportunities. Artificial intelligence is one of the strongest technological capacities that mankind has ever produced, being capable of boosting the speed at which the environment is becoming unsustainable or playing a crucial role in the sustainability-related solutions. The direction that materialises is seriously reliant on the decisions made today about how AI should be created, implemented and regulated.

This review indicates that the technical capacity, policy challenges, market dynamics, and social consciousness to effect Green AI transformation is becoming reality but much effort is needed to harness the opportunities of the same. The sector is at a crossroads at the place where concerted efforts must take place on several fronts simultaneously with the possibility of launching rapid development, and any further measures of business-as-usual will lead to the threat of locking-in and sustaining the unsustainable ways of doing things, with long-term effects. All the research fraternity, technology industry, policymakers, and civil society have crucial roles to play to determine this transition. Green Artificial Intelligence is not about automatic optimization or eco-friendliness. It represents a radical re-evaluation of how technological innovation interacts with planetary wellbeing understanding that the sustainable flourishing of humanity in the long-term requires it to operate within environmental parameters. The experiences of Green AI can be generalized in terms of how the powerful technologies may be used responsibly in the society to balance innovation and sustainability, economic growth and environmental preservation, and the current generation with the generation to come.

Finally, Green AI does not solve issues of sustainable and resilient development due to technical solutions only, but demands a systemic change in values, institutions, practices, and power systems. This is the broadest review that enables one to know what is available, what is missing and what is possible, and subsequent directions to take. The next task is to convert this knowledge into action at the level and speed required to deal with the challenges defining our environmental experience in the present time. The rewards of potential success are immense: the artificial intelligence systems that bring benefits to the environmental sustainability and human wellbeing, economic prosperity, and social justice. To make this vision come true, it requires dedication, innovation and cross-field, inter-industry, and inter-national cooperation. The future of the artificial intelligence as well as the environmental sustainability is based on the decisions made today. The way forward will be considered the realization of Green AI as a journey and not a destination but to continue as an improvement, learning, and adapting endeavor. The methods need to be dynamic and adaptive as AI quality and environmental concerns are changing. On-frequency re-alignment of priorities, tactics, and performance level will make sure that the efforts are carried out with regards to the existing needs and opportunities. Knowledge exchange, co-ordination and overall advancement of the field through building communities of practice will bring about faster achievements that no single organization or country would achieve on its own. One of the characteristic challenges and opportunities of the twenty-first century is the transition to sustainable artificial intelligence, the implications of which go way beyond the sphere of technology and touch upon some of the most basic issues of human-environment interaction, intergenerational obligations, and the purpose of progress in a world with limited ecological resources.

These measures of success will also rely not on technical measures of energy efficiency, or model output, but on bigger measures of environmental health, social equity and overall system resilience. Are the emission of greenhouse gases on the decrease that is required to achieve climate goals? Is the recovery of the ecosystems and stabilization of biodiversity? Do the advantages of sustainable AI available to everyone within the community and the countries, or are they greater with powerful groups? Are the societies getting tougher to changes and disruptions in technology and environment? These are the core questions that should be used to assess the progress of Green AI and make corrections to the course. The synthesis in this review demonstrates that even though there are great challenges faced, the technical abilities, policy structures and market dynamics and social consciousness required to facilitate Green AI transition are becoming apparent. The strategy that is needed now is the co-ordinated effort on various fronts in order to achieve this potential. The AI systems should also be made more efficient and the application to the environmental problems should be further refined by the researchers. Practitioners have to adopt sustainable practices during lifecycles of AI development. The policymakers should be able to develop enabling structures that would encourage responsible innovation. Sustainability is the key concept that business leaders should acknowledge because it is critical to sustainable competitiveness in the long term and social license. The civil society should be able to keep all the parties on the frontline and help in bringing positive change. The worldwide institutions should also be able to collaborate in dealing with common issues that are outside the boundaries of a single country.

There is indeed too much urgarity. The climate tipping point is near and biodiversity will be more and more scarce and resource limitations will become even stricter when the demands of AI computing are growing exponentially. The time elapses with which it is possible to prevent catastrophic environmental changes reduces year by year. But in this panic opportunity. It is the scale and pace of AI development that allows deliberate interventions to spread across the entire ecosystem of technology quickly to produce compound benefits. Even minor shifts in the algorithmic defaults, the hardware specifications or industry standards can equally alter the environmental impact of AI across the world. This leverage effect implies that the canons of the strategic investments of the Green AI today can give disproportional profits in technological innovation and environmental sustainability. Green Artificial Intelligence represents an illustration of how mighty technologies can be guided to benefit people by defining the decisions of the design, implementation, and managing innovations. The same AI and other possibilities may lead to escalation of the environmental crisis, but the opposite may also take place, as a faster response can be achieved, provided by priorities and incentives and the limitations used to harness it. This realization is a source of power to act and in the recognition of the responsibility. Individuals in the field of AI have a particular responsibility as custodians of extremely influential technologies whose effects on the environment will splay on future generations. But they do not act alone. To achieve this sustainable AI change, all layers of the society have to be involved bringing in different types of knowledge, resources and influence.

Author Contributions

DRP: Conceptualization, methodology, visualization, writing original draft, writing review and editing, and supervision. NLR: Analysis, data collection, methodology, software, resources, visualization, writing original draft, writing review and editing, and supervision. OMN: Conceptualization, study design, writing review and editing, and supervision. JR: methodology, visualization, writing original draft.

Conflict of interest

The authors declare no conflicts of interest.

References

[1] Kshetri N, Dwivedi YK, Davenport TH, Panteli N. Generative artificial intelligence in marketing: Applications, opportunities, challenges, and research agenda. International Journal of Information Management. 2024 Apr 1;75:102716. https://doi.org/10.1016/j.ijinfomgt.2023.102716

[2] Ahmad SF, Han H, Alam MM, Rehmat M, Irshad M, Arraño-Muñoz M, Ariza-Montes A. Impact of artificial intelligence on human loss in decision making, laziness and safety in education. Humanities and Social Sciences Communications. 2023 Jun 9;10(1):1-4. https://doi.org/10.1057/s41599-023-01787-8

[3] Bidyalakshmi T, Jyoti B, Mansuri SM, Srivastava A, Mohapatra D, Kalnar YB, Narsaiah K, Indore N. Application of artificial intelligence in food processing: Current status and future prospects. Food Engineering Reviews. 2025 Mar;17(1):27-54. https://doi.org/10.1007/s12393-024-09386-2

[4] Law R, Ye H, Lei SS. Ethical artificial intelligence (AI): principles and practices. International Journal of Contemporary Hospitality Management. 2025 Jan 2;37(1):279-95. https://doi.org/10.1108/IJCHM-04-2024-0482

[5] Cukurova M. The interplay of learning, analytics and artificial intelligence in education: A vision for hybrid intelligence. British Journal of Educational Technology. 2025 Mar;56(2):469-88. https://doi.org/10.1111/bjet.13514

[6] Agha RA, Mathew G, Rashid R, Kerwan A, Al-Jabir A, Sohrabi C, Franchi T, Nicola M, Agha M. Transparency in the reporting of artificial intelligence-the TITAN guideline. Premier Journal of Science. 2025;10:100082. https://doi.org/10.70389/PJS.100082

[7] Hanna MG, Pantanowitz L, Dash R, Harrison JH, Deebajah M, Pantanowitz J, Rashidi HH. Future of artificial intelligence (AI)-machine learning (ML) trends in pathology and medicine. Modern Pathology. 2025 Jan 4:100705. https://doi.org/10.1016/j.modpat.2025.100705

[8] Chen E, Prakash S, Janapa Reddi V, Kim D, Rajpurkar P. A framework for integrating artificial intelligence for clinical care with continuous therapeutic monitoring. Nature Biomedical Engineering. 2025 Apr;9(4):445-54. https://doi.org/10.1038/s41551-023-01115-0

[9] Liu SY. Artificial intelligence (AI) in agriculture. IT professional. 2020 May 21;22(3):14-5. https://doi.org/10.1109/MITP.2020.2986121

[10] Shimizu H, Nakayama KI. Artificial intelligence in oncology. Cancer science. 2020 May;111(5):1452-60. https://doi.org/10.1111/cas.14377

[11] Schwendicke FA, Samek W, Krois J. Artificial intelligence in dentistry: chances and challenges. Journal of dental research. 2020 Jul;99(7):769-74. https://doi.org/10.1177/0022034520915714

[12] Verganti R, Vendraminelli L, Iansiti M. Innovation and design in the age of artificial intelligence. Journal of product innovation management. 2020 May;37(3):212-27. https://doi.org/10.1111/jpim.12523

[13] Novelli C, Taddeo M, Floridi L. Accountability in artificial intelligence: What it is and how it works. Ai & Society. 2024 Aug;39(4):1871-82. https://doi.org/10.1007/s00146-023-01635-y

[14] Rashidi HH, Pantanowitz J, Hanna MG, Tafti AP, Sanghani P, Buchinsky A, Fennell B, Deebajah M, Wheeler S, Pearce T, Abukhiran I. Introduction to artificial intelligence and machine learning in pathology and medicine: generative and nongenerative artificial intelligence basics. Modern Pathology. 2025 Apr 1;38(4):100688. https://doi.org/10.1016/j.modpat.2024.100688

[15] Waisberg E, Ong J, Kamran SA, Masalkhi M, Paladugu P, Zaman N, Lee AG, Tavakkoli A. Generative artificial intelligence in ophthalmology. Survey of ophthalmology. 2025 Jan 1;70(1):1-1. https://doi.org/10.1016/j.survophthal.2024.04.009

[16] Wang H, Fu T, Du Y, Gao W, Huang K, Liu Z, Chandak P, Liu S, Van Katwyk P, Deac A, Anandkumar A. Scientific discovery in the age of artificial intelligence. Nature. 2023 Aug 3;620(7972):47-60. https://doi.org/10.1038/s41586-023-06221-2

[17] Banh L, Strobel G. Generative artificial intelligence. Electronic Markets. 2023 Dec;33(1):63. https://doi.org/10.1007/s12525-023-00680-1

[18] Ahmed I, Jeon G, Piccialli F. From artificial intelligence to explainable artificial intelligence in industry 4.0: a survey on what, how, and where. IEEE transactions on industrial informatics. 2022 Jan 27;18(8):5031-42. https://doi.org/10.1109/TII.2022.3146552

[19] Alqahtani T, Badreldin HA, Alrashed M, Alshaya AI, Alghamdi SS, Bin Saleh K, Alowais SA, Alshaya OA, Rahman I, Al Yami MS, Albekairy AM. The emergent role of artificial intelligence, natural learning processing, and large language models in higher education and research. Research in social and administrative pharmacy. 2023 Aug 1;19(8):1236-42. https://doi.org/10.1016/j.sapharm.2023.05.016

[20] Bankins S, Formosa P. The ethical implications of artificial intelligence (AI) for meaningful work. Journal of Business Ethics. 2023 Jul;185(4):725-40. https://doi.org/10.1007/s10551-023-05339-7

[21] Abulibdeh A, Zaidan E, Abulibdeh R. Navigating the confluence of artificial intelligence and education for sustainable development in the era of industry 4.0: Challenges, opportunities, and ethical dimensions. Journal of Cleaner Production. 2024 Jan 15;437:140527. https://doi.org/10.1016/j.jclepro.2023.140527

[22] King MR, ChatGPT. A conversation on artificial intelligence, chatbots, and plagiarism in higher education. Cellular and molecular bioengineering. 2023 Feb;16(1):1-2. https://doi.org/10.1007/s12195-022-00754-8

[23] Ikhsan RB, Fernando Y, Prabowo H, Gui A, Kuncoro EA. An empirical study on the use of artificial intelligence in the banking sector of Indonesia by extending the TAM model and the moderating effect of perceived trust. Digital Business. 2025 Jun 1;5(1):100103. https://doi.org/10.1016/j.digbus.2024.100103

[24] Cui M, Zhang DY. Artificial intelligence and computational pathology. Laboratory Investigation. 2021 Apr 1;101(4):412-22. https://doi.org/10.1038/s41374-020-00514-0

[25] Messeri L, Crockett MJ. Artificial intelligence and illusions of understanding in scientific research. Nature. 2024 Mar 7;627(8002):49-58. https://doi.org/10.1038/s41586-024-07146-0

[26] Salvagno M, Taccone FS, Gerli AG. Can artificial intelligence help for scientific writing?. Critical care. 2023 Feb 25;27(1):75. https://doi.org/10.1186/s13054-023-04380-2

[27] Holzinger A, Keiblinger K, Holub P, Zatloukal K, Müller H. AI for life: Trends in artificial intelligence for biotechnology. New biotechnology. 2023 May 25;74:16-24. https://doi.org/10.1016/j.nbt.2023.02.001

[28] Kaplan A, Haenlein M. Rulers of the world, unite! The challenges and opportunities of artificial intelligence. Business horizons. 2020 Jan 1;63(1):37-50. https://doi.org/10.1016/j.bushor.2019.09.003

[29] Thiebes S, Lins S, Sunyaev A. Trustworthy artificial intelligence. Electronic Markets. 2021 Jun;31(2):447-64. https://doi.org/10.1007/s12525-020-00441-4

[30] Ullah F, Saqib S, Xiong YC. Integrating artificial intelligence in biodiversity conservation: bridging classical and modern approaches. Biodiversity and Conservation. 2025 Jan;34(1):45-65. https://doi.org/10.1007/s10531-024-02977-9

[31] An X, Chai CS, Li Y, Zhou Y, Yang B. Modeling students' perceptions of artificial intelligence assisted language learning. Computer Assisted Language Learning. 2025 Jul 4;38(5-6):987-1008. https://doi.org/10.1080/09588221.2023.2246519

[32] Crawford J, Cowling M, Allen KA. Leadership is needed for ethical ChatGPT: Character, assessment, and learning using artificial intelligence (AI). Journal of University Teaching and Learning Practice. 2023 Apr;20(3):1-9. https://doi.org/10.53761/1.20.3.02

[33] Naser MZ, Alavi AH. Error metrics and performance fitness indicators for artificial intelligence and machine learning in engineering and sciences. Architecture, Structures and Construction. 2023 Dec;3(4):499-517. https://doi.org/10.1007/s44150-021-00015-8

[34] Babina T, Fedyk A, He A, Hodson J. Artificial intelligence, firm growth, and product innovation. Journal of Financial Economics. 2024 Jan 1;151:103745. https://doi.org/10.1016/j.jfineco.2023.103745

[35] Alahi ME, Sukkuea A, Tina FW, Nag A, Kurdthongmee W, Suwannarat K, Mukhopadhyay SC. Integration of IoT-enabled technologies and artificial intelligence (AI) for smart city scenario: recent advancements and future trends. Sensors. 2023 May 30;23(11):5206. https://doi.org/10.3390/s23115206

[36] Bostrom N. Ethical issues in advanced artificial intelligence. Machine Ethics and Robot Ethics. 2020 Sep 10:69-75. https://doi.org/10.4324/9781003074991-7

[37] Cesaro A, Hoffman SC, Das P, de la Fuente-Nunez C. Challenges and applications of artificial intelligence in infectious diseases and antimicrobial resistance. npj Antimicrobials and Resistance. 2025 Jan 7;3(1):2. https://doi.org/10.1038/s44259-024-00068-x

[38] Fountzilas E, Pearce T, Baysal MA, Chakraborty A, Tsimberidou AM. Convergence of evolving artificial intelligence and machine learning techniques in precision oncology. NPJ Digital Medicine. 2025 Jan 31;8(1):75. https://doi.org/10.1038/s41746-025-01471-y

[39] Benbya H, Davenport TH, Pachidi S. Artificial intelligence in organizations: Current state and future opportunities. MIS Quarterly Executive. 2020 Dec 3;19(4). https://doi.org/10.2139/ssrn.3741983

[40] Kaur D, Uslu S, Rittichier KJ, Durresi A. Trustworthy artificial intelligence: a review. ACM computing surveys (CSUR). 2022 Jan 18;55(2):1-38. https://doi.org/10.1145/3491209

[41] Meskó B, Görög M. A short guide for medical professionals in the era of artificial intelligence. NPJ digital medicine. 2020 Sep 24;3(1):126. https://doi.org/10.1038/s41746-020-00333-z

[42] Sanchez TW, Brenman M, Ye X. The ethical concerns of artificial intelligence in urban planning. Journal of the American Planning Association. 2025 Apr 3;91(2):294-307. https://doi.org/10.1080/01944363.2024.2355305

[43] Fountzilas E, Pearce T, Baysal MA, Chakraborty A, Tsimberidou AM. Convergence of evolving artificial intelligence and machine learning techniques in precision oncology. NPJ Digital Medicine. 2025 Jan 31;8(1):75. https://doi.org/10.1038/s41746-025-01471-y

[44] Nguyen-Duc A, Cabrero-Daniel B, Przybylek A, Arora C, Khanna D, Herda T, Rafiq U, Melegati J, Guerra E, Kemell KK, Saari M. Generative artificial intelligence for software engineering-A research agenda. Software: Practice and Experience. 2025 Nov;55(11):1806-43. https://doi.org/10.1002/spe.70005

[45] Hopgood AA. Intelligent systems for engineers and scientists: a practical guide to artificial intelligence. CRC press; 2021 Dec 9. https://doi.org/10.1201/9781003226277

[46] Matheny ME, Whicher D, Israni ST. Artificial intelligence in health care: a report from the National Academy of Medicine. Jama. 2020 Feb 11;323(6):509-10. https://doi.org/10.1001/jama.2019.21579

[47] Khan B, Fatima H, Qureshi A, Kumar S, Hanan A, Hussain J, Abdullah S. Drawbacks of artificial intelligence and their potential solutions in the healthcare sector. Biomedical Materials & Devices. 2023 Sep;1(2):731-8. https://doi.org/10.1007/s44174-023-00063-2

[48] Dunleavy P, Margetts H. Data science, artificial intelligence and the third wave of digital era governance. Public Policy and Administration. 2025 Apr;40(2):185-214. https://doi.org/10.1177/09520767231198737

[49] Li J, Herdem MS, Nathwani J, Wen JZ. Methods and applications for Artificial Intelligence, Big Data, Internet of Things, and Blockchain in smart energy management. Energy and AI. 2023 Jan 1;11:100208. https://doi.org/10.1016/j.egyai.2022.100208

[50] Kumar S, Lim WM, Sivarajah U, Kaur J. Artificial intelligence and blockchain integration in business: trends from a bibliometric-content analysis. Information systems frontiers. 2023 Apr;25(2):871-96. https://doi.org/10.1007/s10796-022-10279-0

[51] Hassija V, Chamola V, Mahapatra A, Singal A, Goel D, Huang K, Scardapane S, Spinelli I, Mahmud M, Hussain A. Interpreting black-box models: a review on explainable artificial intelligence. Cognitive Computation. 2024 Jan;16(1):45-74. https://doi.org/10.1007/s12559-023-10179-8

[52] Bond M, Khosravi H, De Laat M, Bergdahl N, Negrea V, Oxley E, Pham P, Chong SW, Siemens G. A meta systematic review of artificial intelligence in higher education: A call for increased ethics, collaboration, and rigour. International journal of educational technology in higher education. 2024 Jan 19;21(1):4. https://doi.org/10.1186/s41239-023-00436-z

[53] Kumar D, Ratten V. Artificial intelligence and family businesses: a systematic literature review. Journal of Family Business Management. 2025 Apr 17;15(2):373-92. https://doi.org/10.1108/JFBM-08-2024-0160

[54] Gama F, Magistretti S. Artificial intelligence in innovation management: A review of innovation capabilities and a taxonomy of AI applications. Journal of Product Innovation Management. 2025 Jan;42(1):76-111. https://doi.org/10.1111/jpim.12698

[55] Kumar A, Shankar A, Hollebeek LD, Behl A, Lim WM. Generative artificial intelligence (GenAI) revolution: A deep dive into GenAI adoption. Journal of Business Research. 2025 Feb 1;189:115160. https://doi.org/10.1016/j.jbusres.2024.115160

[56] Jarrahi MH, Kenyon S, Brown A, Donahue C, Wicher C. Artificial intelligence: A strategy to harness its power through organizational learning. Journal of Business Strategy. 2023 Apr 14;44(3):126-35. https://doi.org/10.1108/JBS-11-2021-0182

[57] Gabriel I. Artificial intelligence, values, and alignment. Minds and machines. 2020 Sep;30(3):411-37. https://doi.org/10.1007/s11023-020-09539-2

[58] Javaid M, Haleem A, Khan IH, Suman R. Understanding the potential applications of Artificial Intelligence in Agriculture Sector. Advanced Agrochem. 2023 Mar 1;2(1):15-30. https://doi.org/10.1016/j.aac.2022.10.001

[59] Peres RS, Jia X, Lee J, Sun K, Colombo AW, Barata J. Industrial artificial intelligence in industry 4.0-systematic review, challenges and outlook. IEEE access. 2020 Dec 7;8:220121-39. https://doi.org/10.1109/ACCESS.2020.3042874

[60] Mohsen SE, Hamdan A, Shoaib HM. Digital transformation and integration of artificial intelligence in financial institutions. Journal of Financial Reporting and Accounting. 2025 Mar 20;23(2):680-99. https://doi.org/10.1108/JFRA-09-2023-0544

[61] Tuo Y, Wu J, Zhao J, Si X. Artificial intelligence in tourism: insights and future research agenda. Tourism Review. 2025 Mar 25;80(4):793-812. https://doi.org/10.1108/TR-03-2024-0180

[62] Chen Y, Prentice C. Integrating artificial intelligence and customer experience. Australasian Marketing Journal. 2025 May;33(2):141-53. https://doi.org/10.1177/14413582241252904

[63] Salih AM, Raisi-Estabragh Z, Galazzo IB, Radeva P, Petersen SE, Lekadir K, Menegaz G. A perspective on explainable artificial intelligence methods: SHAP and LIME. Advanced Intelligent Systems. 2025 Jan;7(1):2400304. https://doi.org/10.1002/aisy.202400304

[64] Alowais SA, Alghamdi SS, Alsuhebany N, Alqahtani T, Alshaya AI, Almohareb SN, Aldairem A, Alrashed M, Bin Saleh K, Badreldin HA, Al Yami MS. Revolutionizing healthcare: the role of artificial intelligence in clinical practice. BMC medical education. 2023 Sep 22;23(1):689. https://doi.org/10.1186/s12909-023-04698-z

[65] Ahmad T, Zhang D, Huang C, Zhang H, Dai N, Song Y, Chen H. Artificial intelligence in sustainable energy industry: Status Quo, challenges and opportunities. Journal of cleaner production. 2021 Mar 20;289:125834. https://doi.org/10.1016/j.jclepro.2021.125834

[66] Farhud DD, Zokaei S. Ethical issues of artificial intelligence in medicine and healthcare. Iranian journal of public health. 2021 Nov;50(11):i. https://doi.org/10.18502/ijph.v50i11.7600

[67] Chiu TK, Meng H, Chai CS, King I, Wong S, Yam Y. Creation and evaluation of a pretertiary artificial intelligence (AI) curriculum. IEEE Transactions on Education. 2021 Jun 15;65(1):30-9. https://doi.org/10.1109/TE.2021.3085878

[68] Jan Z, Ahamed F, Mayer W, Patel N, Grossmann G, Stumptner M, Kuusk A. Artificial intelligence for industry 4.0: Systematic review of applications, challenges, and opportunities. Expert Systems with Applications. 2023 Apr 15;216:119456. https://doi.org/10.1016/j.eswa.2022.119456

[69] Dogru T, Line N, Mody M, Hanks L, Abbott JA, Acikgoz F, Assaf A, Bakir S, Berbekova A, Bilgihan A, Dalton A. Generative artificial intelligence in the hospitality and tourism industry: Developing a framework for future research. Journal of Hospitality & Tourism Research. 2025 Feb;49(2):235-53. https://doi.org/10.1177/10963480231188663

[70] Vieriu AM, Petrea G. The impact of artificial intelligence (AI) on students' academic development. Education Sciences. 2025 Mar 11;15(3):343. https://doi.org/10.3390/educsci15030343

[71] Kim H, So KK, Shin S, Li J. Artificial intelligence in hospitality and tourism: Insights from industry practices, research literature, and expert opinions. Journal of Hospitality & Tourism Research. 2025 Feb;49(2):366-85. https://doi.org/10.1177/10963480241229235

[72] Aijaz N, Lan H, Raza T, Yaqub M, Iqbal R, Pathan MS. Artificial intelligence in agriculture: Advancing crop productivity and sustainability. Journal of Agriculture and Food Research. 2025 Feb 23:101762. https://doi.org/10.1016/j.jafr.2025.101762

[73] Ocana A, Pandiella A, Privat C, Bravo I, Luengo-Oroz M, Amir E, Gyorffy B. Integrating artificial intelligence in drug discovery and early drug development: a transformative approach. Biomarker Research. 2025 Mar 14;13(1):45. https://doi.org/10.1186/s40364-025-00758-2

[74] Naz H, Kashif M. Artificial intelligence and predictive marketing: an ethical framework from managers' perspective. Spanish Journal of Marketing-ESIC. 2025 Jan 2;29(1):22-45. https://doi.org/10.1108/SJME-06-2023-0154

[75] Malik AR, Pratiwi Y, Andajani K, Numertayasa IW, Suharti S, Darwis A. Exploring artificial intelligence in academic essay: higher education student's perspective. International Journal of Educational Research Open. 2023 Dec 1;5:100296. https://doi.org/10.1016/j.ijedro.2023.100296

[76] Díaz-Rodríguez N, Del Ser J, Coeckelbergh M, De Prado ML, Herrera-Viedma E, Herrera F. Connecting the dots in trustworthy Artificial Intelligence: From AI principles, ethics, and key requirements to responsible AI systems and regulation. Information Fusion. 2023 Nov 1;99:101896. https://doi.org/10.1016/j.inffus.2023.101896

[77] Bates T, Cobo C, Mariño O, Wheeler S. Can artificial intelligence transform higher education?. International Journal of Educational Technology in Higher Education. 2020 Jun 15;17(1):42. https://doi.org/10.1186/s41239-020-00218-x

[78] Felzmann H, Fosch-Villaronga E, Lutz C, Tamò-Larrieux A. Towards transparency by design for artificial intelligence. Science and engineering ethics. 2020 Dec;26(6):3333-61. https://doi.org/10.1007/s11948-020-00276-4

[79] Robles P, Mallinson DJ. Artificial intelligence technology, public trust, and effective governance. Review of Policy Research. 2025 Jan;42(1):11-28. https://doi.org/10.1111/ropr.12555

[80] Waqas M, Humphries UW, Chueasa B, Wangwongchai A. Artificial intelligence and numerical weather prediction models: A technical survey. Natural Hazards Research. 2025 Jun 1;5(2):306-20. https://doi.org/10.1016/j.nhres.2024.11.004

[81] Balasubramanian S, Shukla V, Islam N, Upadhyay A, Duong L. Applying artificial intelligence in healthcare: lessons from the COVID-19 pandemic. International Journal of Production Research. 2025 Jan 17;63(2):594-627. https://doi.org/10.1080/00207543.2023.2263102

[82] Weiner EB, Dankwa-Mullan I, Nelson WA, Hassanpour S. Ethical challenges and evolving strategies in the integration of artificial intelligence into clinical practice. PLOS digital health. 2025 Apr 8;4(4):e0000810. https://doi.org/10.1371/journal.pdig.0000810

[83] Hashmi E, Yamin MM, Yayilgan SY. Securing tomorrow: a comprehensive survey on the synergy of Artificial Intelligence and information security. AI and Ethics. 2025 Jun;5(3):1911-29. https://doi.org/10.1007/s43681-024-00529-z

[84] Jin F, Zhang X. Artificial intelligence or human: when and why consumers prefer AI recommendations. Information Technology & People. 2025 Jan 8;38(1):279-303. https://doi.org/10.1108/ITP-01-2023-0022

[85] Owan VJ, Abang KB, Idika DO, Etta EO, Bassey BA. Exploring the potential of artificial intelligence tools in educational measurement and assessment. Eurasia journal of mathematics, science and technology education. 2023 Aug 1;19(8):em2307. https://doi.org/10.29333/ejmste/13428

[86] Al Kuwaiti A, Nazer K, Al-Reedy A, Al-Shehri S, Al-Muhanna A, Subbarayalu AV, Al Muhanna D, Al-Muhanna FA. A review of the role of artificial intelligence in healthcare. Journal of personalized medicine. 2023 Jun 5;13(6):951. https://doi.org/10.3390/jpm13060951

[87] Ameen N, Tarhini A, Reppel A, Anand A. Customer experiences in the age of artificial intelligence. Computers in human behavior. 2021 Jan 1;114:106548. https://doi.org/10.1016/j.chb.2020.106548

[88] Hwang GJ, Chien SY. Definition, roles, and potential research issues of the metaverse in education: An artificial intelligence perspective. Computers and Education: Artificial Intelligence. 2022 Jan 1;3:100082. https://doi.org/10.1016/j.caeai.2022.100082

[89] Alier M, Peñalvo FJ, Camba JD. Generative Artificial Intelligence in Education: From Deceptive to Disruptive. International Journal of interactive multimedia and artificial intelligence. 2024 Mar 1;8(5):5-14. https://doi.org/10.9781/ijimai.2024.02.011

[90] Walter Y. Embracing the future of Artificial Intelligence in the classroom: the relevance of AI literacy, prompt engineering, and critical thinking in modern education. International Journal of Educational Technology in Higher Education. 2024 Feb 26;21(1):15. https://doi.org/10.1186/s41239-024-00448-3

[91] Chiu TK, Moorhouse BL, Chai CS, Ismailov M. Teacher support and student motivation to learn with Artificial Intelligence (AI) based chatbot. Interactive Learning Environments. 2024 Aug 8;32(7):3240-56.

[92] Cai H, Ao Z, Tian C, Wu Z, Liu H, Tchieu J, Gu M, Mackie K, Guo F. Brain organoid reservoir computing for artificial intelligence. Nature Electronics. 2023 Dec;6(12):1032-9. https://doi.org/10.1038/s41928-023-01069-w

[93] Jackson I, Ivanov D, Dolgui A, Namdar J. Generative artificial intelligence in supply chain and operations management: a capability-based framework for analysis and implementation. International Journal of Production Research. 2024 Sep 1;62(17):6120-45. https://doi.org/10.1080/00207543.2024.2309309

[94] Bibri SE, Krogstie J, Kaboli A, Alahi A. Smarter eco-cities and their leading-edge artificial intelligence of things solutions for environmental sustainability: A comprehensive systematic review. Environmental Science and Ecotechnology. 2024 May 1;19:100330. https://doi.org/10.1016/j.ese.2023.100330

[95] Sarraju A, Bruemmer D, Van Iterson E, Cho L, Rodriguez F, Laffin L. Appropriateness of cardiovascular disease prevention recommendations obtained from a popular online chat-based artificial intelligence model. Jama. 2023 Mar 14;329(10):842-4. https://doi.org/10.1001/jama.2023.1044

[96] Belhadi A, Mani V, Kamble SS, Khan SA, Verma S. Artificial intelligence-driven innovation for enhancing supply chain resilience and performance under the effect of supply chain dynamism: an empirical investigation. Annals of operations research. 2024 Feb;333(2):627-52. https://doi.org/10.1007/s10479-021-03956-x

[97] Gligorea I, Cioca M, Oancea R, Gorski AT, Gorski H, Tudorache P. Adaptive learning using artificial intelligence in e-learning: A literature review. Education Sciences. 2023 Dec 6;13(12):1216. https://doi.org/10.3390/educsci13121216

[98] Lee D, Yoon SN. Application of artificial intelligence-based technologies in the healthcare industry: Opportunities and challenges. International journal of environmental research and public health. 2021 Jan;18(1):271. https://doi.org/10.3390/ijerph18010271

[99] Anantrasirichai N, Bull D. Artificial intelligence in the creative industries: a review. Artificial intelligence review. 2022 Jan;55(1):589-656. https://doi.org/10.1007/s10462-021-10039-7

[100] Haug CJ, Drazen JM. Artificial intelligence and machine learning in clinical medicine, 2023. New England Journal of Medicine. 2023 Mar 30;388(13):1201-8. https://doi.org/10.1056/NEJMra2302038

[101] Krakowski S, Luger J, Raisch S. Artificial intelligence and the changing sources of competitive advantage. Strategic Management Journal. 2023 Jun;44(6):1425-52. https://doi.org/10.1002/smj.3387

[102] Abioye SO, Oyedele LO, Akanbi L, Ajayi A, Delgado JM, Bilal M, Akinade OO, Ahmed A. Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges. Journal of Building Engineering. 2021 Dec 1;44:103299. https://doi.org/10.1016/j.jobe.2021.103299

[103] Aung YY, Wong DC, Ting DS. The promise of artificial intelligence: a review of the opportunities and challenges of artificial intelligence in healthcare. British medical bulletin. 2021 Sep;139(1):4-15. https://doi.org/10.1093/bmb/ldab016

[104] Kousha K, Thelwall M. Artificial intelligence to support publishing and peer review: A summary and review. Learned Publishing. 2024 Jan;37(1):4-12. https://doi.org/10.1002/leap.1570

[105] Gangwal A, Lavecchia A. Artificial intelligence in natural product drug discovery: current applications and future perspectives. Journal of medicinal chemistry. 2025 Feb 7;68(4):3948-69. https://doi.org/10.1021/acs.jmedchem.4c01257

[106] Crompton H, Burke D. Artificial intelligence in higher education: the state of the field. International journal of educational technology in higher education. 2023 Apr 24;20(1):22. https://doi.org/10.1186/s41239-023-00392-8

[107] Puntoni S, Reczek RW, Giesler M, Botti S. Consumers and artificial intelligence: An experiential perspective. Journal of marketing. 2021 Jan;85(1):131-51. https://doi.org/10.1177/0022242920953847

[108] Kumar I, Rawat J, Mohd N, Husain S. Opportunities of artificial intelligence and machine learning in the food industry. Journal of Food Quality. 2021;2021(1):4535567. https://doi.org/10.1155/2021/4535567

[109] Moor M, Banerjee O, Abad ZS, Krumholz HM, Leskovec J, Topol EJ, Rajpurkar P. Foundation models for generalist medical artificial intelligence. Nature. 2023 Apr 13;616(7956):259-65. https://doi.org/10.1038/s41586-023-05881-4

[110] Jaiswal A, Arun CJ, Varma A. Rebooting employees: Upskilling for artificial intelligence in multinational corporations. InArtificial intelligence and international HRM 2023 May 22 (pp. 114-143). Routledge. https://doi.org/10.4324/9781003377085-5

[111] Nie J, Jiang J, Li Y, Wang H, Ercisli S, Lv L. Data and domain knowledge dual-driven artificial intelligence: Survey, applications, and challenges. Expert Systems. 2025 Jan;42(1):e13425. https://doi.org/10.1111/exsy.13425

[112] Nenni ME, De Felice F, De Luca C, Forcina A. How artificial intelligence will transform project management in the age of digitization: a systematic literature review. Management Review Quarterly. 2025 Jun;75(2):1669-716. https://doi.org/10.1007/s11301-024-00418-z

[113] Qin C, Zhang L, Cheng Y, Zha R, Shen D, Zhang Q, Chen X, Sun Y, Zhu C, Zhu H, Xiong H. A comprehensive survey of artificial intelligence techniques for talent analytics. Proceedings of the IEEE. 2025 Jun 6. https://doi.org/10.1109/JPROC.2025.3572744

[114] Kaack LH, Donti PL, Strubell E, Kamiya G, Creutzig F, Rolnick D. Aligning artificial intelligence with climate change mitigation. Nature Climate Change. 2022 Jun;12(6):518-27. https://doi.org/10.1038/s41558-022-01377-7

[115] Ali S, Abuhmed T, El-Sappagh S, Muhammad K, Alonso-Moral JM, Confalonieri R, Guidotti R, Del Ser J, Díaz-Rodríguez N, Herrera F. Explainable Artificial Intelligence (XAI): What we know and what is left to attain Trustworthy Artificial Intelligence. Information fusion. 2023 Nov 1;99:101805. https://doi.org/10.1016/j.inffus.2023.101805

[116] Kelly S, Kaye SA, Oviedo-Trespalacios O. What factors contribute to the acceptance of artificial intelligence? A systematic review. Telematics and informatics. 2023 Feb 1;77:101925. https://doi.org/10.1016/j.tele.2022.101925

[117] Bhattamisra SK, Banerjee P, Gupta P, Mayuren J, Patra S, Candasamy M. Artificial intelligence in pharmaceutical and healthcare research. Big Data and Cognitive Computing. 2023 Jan 11;7(1):10. https://doi.org/10.3390/bdcc7010010

[118] Pallathadka H, Ramirez-Asis EH, Loli-Poma TP, Kaliyaperumal K, Ventayen RJ, Naved M. Applications of artificial intelligence in business management, e-commerce and finance. Materials Today: Proceedings. 2023 Jan 1;80:2610-3. https://doi.org/10.1016/j.matpr.2021.06.419

[119] McDonald N, Johri A, Ali A, Collier AH. Generative artificial intelligence in higher education: Evidence from an analysis of institutional policies and guidelines. Computers in Human Behavior: Artificial Humans. 2025 Mar 1;3:100121. https://doi.org/10.1016/j.chbah.2025.100121

[120] Emon MM, Khan T. The mediating role of attitude towards the technology in shaping artificial intelligence usage among professionals. Telematics and Informatics Reports. 2025 Mar 1;17:100188. https://doi.org/10.1016/j.teler.2025.100188

[121] Shao X, Cai B, Zou Z, Shao H, Yang C, Liu Y. Artificial intelligence enhanced fault prediction with industrial incomplete information. Mechanical Systems and Signal Processing. 2025 Feb 1;224:112063. https://doi.org/10.1016/j.ymssp.2024.112063

[122] Rožanec JM, Novalija I, Zajec P, Kenda K, Tavakoli Ghinani H, Suh S, Bian S, Veliou E, Papamartzivanos D, Giannetsos T, Menesidou SA. Human-centric artificial intelligence architecture for industry 5.0 applications. International journal of production research. 2023 Oct 18;61(20):6847-72. https://doi.org/10.1080/00207543.2022.2138611

[123] Chander B, John C, Warrier L, Gopalakrishnan K. Toward trustworthy artificial intelligence (TAI) in the context of explainability and robustness. ACM Computing Surveys. 2025 Feb 10;57(6):1-49. https://doi.org/10.1145/3675392

[124] Horani OM, Al-Adwan AS, Yaseen H, Hmoud H, Al-Rahmi WM, Alkhalifah A. The critical determinants impacting artificial intelligence adoption at the organizational level. Information Development. 2025 Sep;41(3):1055-79. https://doi.org/10.1177/02666669231166889

[125] Varriale V, Cammarano A, Michelino F, Caputo M. Critical analysis of the impact of artificial intelligence integration with cutting-edge technologies for production systems. Journal of Intelligent Manufacturing. 2025 Jan;36(1):61-93. https://doi.org/10.1007/s10845-023-02244-8

[126] Fu C, Chen Q. The future of pharmaceuticals: Artificial intelligence in drug discovery and development. Journal of Pharmaceutical Analysis. 2025 Feb 26:101248. https://doi.org/10.1016/j.jpha.2025.101248

[127] Vasishta P, Dhingra N, Vasishta S. Application of artificial intelligence in libraries: a bibliometric analysis and visualisation of research activities. Library Hi Tech. 2025 May 19;43(2/3):693-710. https://doi.org/10.1108/LHT-12-2023-0589

[128] Samala AD, Rawas S, Wang T, Reed JM, Kim J, Howard NJ, Ertz M. Unveiling the landscape of generative artificial intelligence in education: a comprehensive taxonomy of applications, challenges, and future prospects. Education and Information Technologies. 2025 Feb;30(3):3239-78. https://doi.org/10.1007/s10639-024-12936-0

[129] Vora LK, Gholap AD, Jetha K, Thakur RR, Solanki HK, Chavda VP. Artificial intelligence in pharmaceutical technology and drug delivery design. Pharmaceutics. 2023 Jul 10;15(7):1916. https://doi.org/10.3390/pharmaceutics15071916

[130] Loureiro SM, Guerreiro J, Tussyadiah I. Artificial intelligence in business: State of the art and future research agenda. Journal of business research. 2021 May 1;129:911-26. https://doi.org/10.1016/j.jbusres.2020.11.001

[131] Najjar R. Redefining radiology: a review of artificial intelligence integration in medical imaging. Diagnostics. 2023 Aug 25;13(17):2760. https://doi.org/10.3390/diagnostics13172760

[132] Su J, Ng DT, Chu SK. Artificial intelligence (AI) literacy in early childhood education: The challenges and opportunities. Computers and Education: Artificial Intelligence. 2023 Jan 1;4:100124. https://doi.org/10.1016/j.caeai.2023.100124

[133] Soori M, Arezoo B, Dastres R. Artificial intelligence, machine learning and deep learning in advanced robotics, a review. Cognitive Robotics. 2023 Jan 1;3:54-70. https://doi.org/10.1016/j.cogr.2023.04.001

[134] Bhuyan SS, Sateesh V, Mukul N, Galvankar A, Mahmood A, Nauman M, Rai A, Bordoloi K, Basu U, Samuel J. Generative artificial intelligence use in healthcare: opportunities for clinical excellence and administrative efficiency. Journal of medical systems. 2025 Jan 16;49(1):10. https://doi.org/10.1007/s10916-024-02136-1

[135] Cooper G. Examining science education in ChatGPT: An exploratory study of generative artificial intelligence. Journal of science education and technology. 2023 Jun;32(3):444-52. https://doi.org/10.1007/s10956-023-10039-y

[136] Aldoseri A, Al-Khalifa KN, Hamouda AM. Re-thinking data strategy and integration for artificial intelligence: concepts, opportunities, and challenges. Applied Sciences. 2023 Jan;13(12):7082. https://doi.org/10.3390/app13127082

[137] George B, Wooden O. Managing the strategic transformation of higher education through artificial intelligence. Administrative Sciences. 2023 Aug 29;13(9):196. https://doi.org/10.3390/admsci13090196

[138] Wang B, Rau PL, Yuan T. Measuring user competence in using artificial intelligence: validity and reliability of artificial intelligence literacy scale. Behaviour & information technology. 2023 Jul 4;42(9):1324-37. https://doi.org/10.1080/0144929X.2022.2072768

[139] Morandini S, Fraboni F, De Angelis M, Puzzo G, Giusino D, Pietrantoni L. The impact of artificial intelligence on workers' skills: Upskilling and reskilling in organisations. Informing Science. 2023;26:39-68. https://doi.org/10.28945/5078

[140] Topaz M, Peltonen LM, Michalowski M, Stiglic G, Ronquillo C, Pruinelli L, Song J, O'connor S, Miyagawa S, Fukahori H. The ChatGPT effect: nursing education and generative artificial intelligence. Journal of Nursing Education. 2025 Jun 1;64(6):e40-3. https://doi.org/10.3928/01484834-20240126-01

[141] Noy S, Zhang W. Experimental evidence on the productivity effects of generative artificial intelligence. Science. 2023 Jul 14;381(6654):187-92. https://doi.org/10.1126/science.adh2586

[142] Nguyen A, Ngo HN, Hong Y, Dang B, Nguyen BP. Ethical principles for artificial intelligence in education. Education and information technologies. 2023 Apr;28(4):4221-41. https://doi.org/10.1007/s10639-022-11316-w

[143] Malatji M, Tolah A. Artificial intelligence (AI) cybersecurity dimensions: a comprehensive framework for understanding adversarial and offensive AI. AI and Ethics. 2025 Apr;5(2):883-910. https://doi.org/10.1007/s43681-024-00427-4

[144] Shata A, Hartley K. Artificial intelligence and communication technologies in academia: faculty perceptions and the adoption of generative AI. International Journal of Educational Technology in Higher Education. 2025 Mar 14;22(1):14. https://doi.org/10.1186/s41239-025-00511-7

[145] Yuan L, Liu X. The effect of artificial intelligence tools on EFL learners' engagement, enjoyment, and motivation. Computers in Human Behavior. 2025 Jan 1;162:108474. https://doi.org/10.1016/j.chb.2024.108474

[146] Malhotra G, Ramalingam M. Perceived anthropomorphism and purchase intention using artificial intelligence technology: examining the moderated effect of trust. Journal of Enterprise Information Management. 2025 Feb 25;38(2):401-23. https://doi.org/10.1108/JEIM-09-2022-0316

[147] Abbasi BN, Wu Y, Luo Z. Exploring the impact of artificial intelligence on curriculum development in global higher education institutions. Education and Information Technologies. 2025 Jan;30(1):547-81. https://doi.org/10.1007/s10639-024-13113-z

[148] Baig MI, Yadegaridehkordi E. Factors influencing academic staff satisfaction and continuous usage of generative artificial intelligence (GenAI) in higher education. International Journal of Educational Technology in Higher Education. 2025 Feb 3;22(1):5. https://doi.org/10.1186/s41239-025-00506-4

[149] Bewersdorff A, Hartmann C, Hornberger M, Seßler K, Bannert M, Kasneci E, Kasneci G, Zhai X, Nerdel C. Taking the next step with generative artificial intelligence: The transformative role of multimodal large language models in science education. Learning and Individual Differences. 2025 Feb 1;118:102601. https://doi.org/10.1016/j.lindif.2024.102601

[150] Fang B, Yu J, Chen Z, Osman AI, Farghali M, Ihara I, Hamza EH, Rooney DW, Yap PS. Artificial intelligence for waste management in smart cities: a review. Environmental Chemistry Letters. 2023 Aug;21(4):1959-89. https://doi.org/10.1007/s10311-023-01604-3

[151] Kaur R, Gabrijelčič D, Klobučar T. Artificial intelligence for cybersecurity: Literature review and future research directions. Information Fusion. 2023 Sep 1;97:101804. https://doi.org/10.1016/j.inffus.2023.101804

[152] Kamalov F, Santandreu Calonge D, Gurrib I. New era of artificial intelligence in education: Towards a sustainable multifaceted revolution. Sustainability. 2023 Aug 16;15(16):12451. https://doi.org/10.3390/su151612451

[153] Naik N, Hameed BM, Shetty DK, Swain D, Shah M, Paul R, Aggarwal K, Ibrahim S, Patil V, Smriti K, Shetty S. Legal and ethical consideration in artificial intelligence in healthcare: who takes responsibility?. Frontiers in surgery. 2022 Mar 14;9:862322. https://doi.org/10.3389/fsurg.2022.862322

[154] Le Berre C, Sandborn WJ, Aridhi S, Devignes MD, Fournier L, Smaïl-Tabbone M, Danese S, Peyrin-Biroulet L. Application of artificial intelligence to gastroenterology and hepatology. Gastroenterology. 2020 Jan 1;158(1):76-94. https://doi.org/10.1053/j.gastro.2019.08.058

[155] Rawashdeh A. The consequences of artificial intelligence: an investigation into the impact of AI on job displacement in accounting. Journal of Science and Technology Policy Management. 2025 Mar 6;16(3):506-35. https://doi.org/10.1108/JSTPM-02-2023-0030

[156] Derakhshan A, Teo T, Khazaie S. Investigating the usefulness of artificial intelligence-driven robots in developing empathy for English for medical purposes communication: The role-play of Asian and African students. Computers in Human Behavior. 2025 Jan 1;162:108416. https://doi.org/10.1016/j.chb.2024.108416

[157] Temsah A, Alhasan K, Altamimi I, Jamal A, Al-Eyadhy A, Malki KH, Temsah MH. DeepSeek in healthcare: revealing opportunities and steering challenges of a new open-source artificial intelligence frontier. Cureus. 2025 Feb 18;17(2). https://doi.org/10.7759/cureus.79221

[158] Wang Y, Wang L, Siau KL. Human-centered interaction in virtual worlds: A new era of generative artificial intelligence and metaverse. International Journal of Human-Computer Interaction. 2025 Jan 17;41(2):1459-501. https://doi.org/10.1080/10447318.2024.2316376

[159] Jarrahi MH, Askay D, Eshraghi A, Smith P. Artificial intelligence and knowledge management: A partnership between human and AI. Business Horizons. 2023 Jan 1;66(1):87-99. https://doi.org/10.1016/j.bushor.2022.03.002

[160] Chen RJ, Wang JJ, Williamson DF, Chen TY, Lipkova J, Lu MY, Sahai S, Mahmood F. Algorithmic fairness in artificial intelligence for medicine and healthcare. Nature biomedical engineering. 2023 Jun;7(6):719-42. https://doi.org/10.1038/s41551-023-01056-8

[161] Malhotra G, Kharub M. Elevating logistics performance: harnessing the power of artificial intelligence in e-commerce. The International Journal of Logistics Management. 2025 Jan 2;36(1):290-321. https://doi.org/10.1108/IJLM-01-2024-0046

[162] Klimova B, Pikhart M. Exploring the effects of artificial intelligence on student and academic well-being in higher education: A mini-review. Frontiers in Psychology. 2025 Feb 3;16:1498132. https://doi.org/10.3389/fpsyg.2025.1498132

[163] Shahzad MF, Xu S, Asif M. Factors affecting generative artificial intelligence, such as ChatGPT, use in higher education: An application of technology acceptance model. British Educational Research Journal. 2025 Apr;51(2):489-513. https://doi.org/10.1002/berj.4084

[164] Hicks SA, Strümke I, Thambawita V, Hammou M, Riegler MA, Halvorsen P, Parasa S. On evaluation metrics for medical applications of artificial intelligence. Scientific reports. 2022 Apr 8;12(1):5979. https://doi.org/10.1038/s41598-022-09954-8

[165] Barsha S, Munshi SA. Implementing artificial intelligence in library services: a review of current prospects and challenges of developing countries. Library Hi Tech News. 2024 Jan 18;41(1):7-10. https://doi.org/10.1108/LHTN-07-2023-0126

[166] Perifanis NA, Kitsios F. Investigating the influence of artificial intelligence on business value in the digital era of strategy: A literature review. Information. 2023 Feb 2;14(2):85. https://doi.org/10.3390/info14020085

[167] Peres R, Schreier M, Schweidel D, Sorescu A. On ChatGPT and beyond: How generative artificial intelligence may affect research, teaching, and practice. International Journal of Research in Marketing. 2023 Jun 1;40(2):269-75. https://doi.org/10.1016/j.ijresmar.2023.03.001

[168] Faiyazuddin M, Rahman SJ, Anand G, Siddiqui RK, Mehta R, Khatib MN, Gaidhane S, Zahiruddin QS, Hussain A, Sah R. The impact of artificial intelligence on healthcare: a comprehensive review of advancements in diagnostics, treatment, and operational efficiency. Health Science Reports. 2025 Jan;8(1):e70312. https://doi.org/10.1002/hsr2.70312