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REVIEW

May AI be sustainable? An outlook on sustainability and technology

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Abstract
The paper studies two of the most relevant tendencies of the modern world, which will change the way we live and think. The first tendency is the development of sustainable societies, which already significantly affects global technologies, policy, and economics. The second tendency is the rapid development of Artificial Intelligence, whose applications and capabilities are expanding at an extraordinary pace. The development of Sustainable AI is at the intersection of those tendencies. Progress in this field will shape the basics and the ground rules for applying AI in future societies. The present paper discusses the terms and definitions of Sustainable AI and reviews its existing and potential applications in different domains of science, technology, economics, and policy. Besides, the study analyses tendencies potentially leading to non-sustainable AI and reflects on how to avoid the corresponding complications.

Keywords Sustainable development · Artificial intelligence · Sustainability · AI

1 Introduction

1.1 Sustainability and sustainable development

The issue of global climate change was raised already in the early twentieth century by Arrhenius et al. in their work on the evolution of the universe (Arrhenius and Borns 1908). However, it became highly relevant much later when, in 2016, almost two hundred countries signed the Paris Agreement to prevent the rising of the global surface temperature. Since then, the terms "sustainability" and "sustainable development" have become very popular and mainly used in the context of climate and environmental issues. This tendency resulted in significantly simplifying the terms compared to how sustainability science understands them based on the concept of the three pillars.

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Sustainability is the ability of a system to sustain itself over time. Purvis et al. (2019) traced the origins of the three pillars of sustainability— environmental, economic, and social—to the work of Edward B. Barbier (1987), published in 1987, where he proposed it within the Concept of Sustainable Economic Development. The main idea behind the three pillars is that all aspects of sustainability are equally important, and prioritizing some of them over others may hinder sustainable development. According to Fig. 1, the United Nations (UN) accepted this systemic vision when formulating the Sustainable Development Goals (SDGs), which support all three pillars. The social, economic, and environmental aspects of sustainability can be represented in technologies by the three corresponding key performance indicators estimated for a lifecycle—safety, cost-efficiency, and environmental efficiency (often mistakenly labeled sustainability).

1.2 Requirements for sustainable technologies

One exercise can help demonstrate the requirements for sustainable technologies. The exercise asks to evaluate a ship for sustainability using its description. It is a specialized zero-emission ship with the most advanced wind-assistant propulsion, energy-efficient hull shape, the best available task-related equipment, and advanced decorative design solutions. This description seems to fit

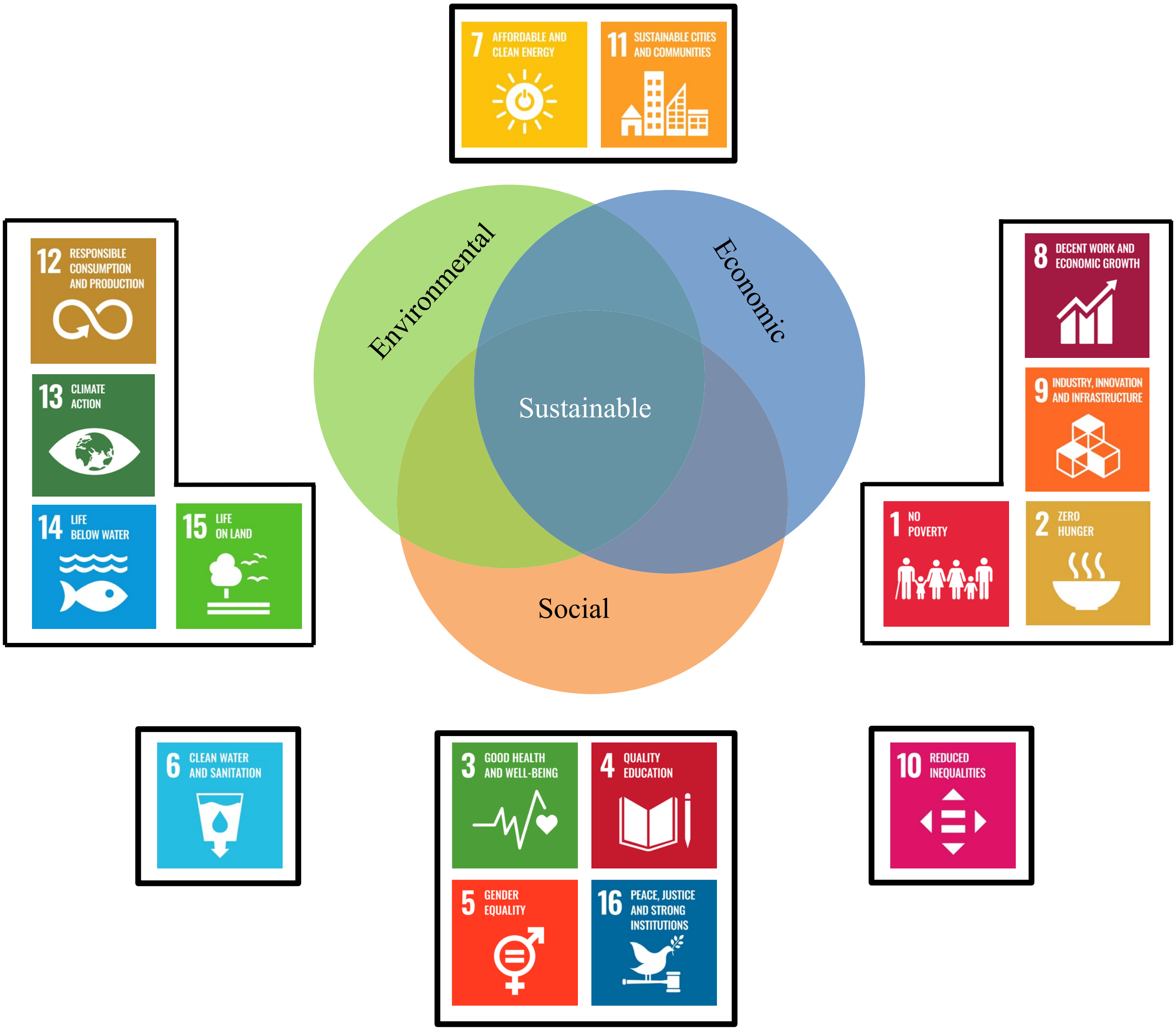

Fig. 1 The pillars of sustainability and the corresponding UN sustainable development goals

the definition of a sustainable ship. Also, this describes the galleon Vasa, built in 1627 in Sweden, famous for its disastrous maiden trip—the ship sailed only about 1300 m before sinking. According to different sources, the maiden trip claimed 30 to 50 lives, including the crew and guests (Freckelton 2018; Kessler et al. 2004). The Swedish King Gustavus Adolphus supervised the ship design to have the biggest and best possible sails, many cannons, and the most impressive decorations, which resulted in poor stability—the inability of a ship to return to the upright original state after inclination. Despite the perfect environmental performance of this zero-emission ship made of wood, safety and cost-efficiency are compromised. The ship apparently cannot sustain itself over time and is non-sustainable by definition.

The Vasa example demonstrates that sustainable technology must perform satisfactorily in all three aspects of sustainability. Besides, it shows that an efficient system is not a simple combination of the best components optimized in isolation but a tradeoff, indicating that sustainable technology development requires a systemic approach. Finally, consideration of different aspects of sustainability requires interdisciplinary or transdisciplinary approaches, where insights from different research and practical disciplines are equally represented (Schwaninger 2018).

A prominent example of sustainable technology is waterborne cargo transport (Xue and Lai 2023)—the most environmentally efficient in CO_2 emissions per tonne-kilometer (Klein et al. 2021), the most cost-efficient in USD per tonne-kilometer (Pienaar 2013), and one of the leaders in safety, considering human fatality risks (Savage 2013). The International Maritime Organization (IMO) has effectively implemented efficient regulations for preventing air pollution from ships, which resulted in a drastic reduction in SO_x emissions, harmful to the health of humans and animals, soil, and broader ecosystems (Kondratenko et al. 2025). The closed-loop scrubber technology significantly reduced air pollution from ships at a low cost with limited discharge of polluted water (Lunde Hermansson et al. 2024). The automotive industry has advertised electric vehicles as the primary means of addressing environmental concerns. They have great potential to reduce CO_2 up to about 50 percent (Guo et al. 2023), but only if charged with electricity produced from renewable energy. The lifecycle of electric vehicles remains more expensive than diesel- or gasoline-fueled vehicles (Furch et al. 2022; Guo et al. 2023; Verma et al. 2022). Besides, Verma et al. (2022) report increased lifecycle emissions of substances toxic to humans and animals related to the production of powertrains and batteries. Aviation is one of the safest and fastest transport modes with satisfactory cost-efficiency (Pienaar 2013; Savage 2013) but with the most greenhouse gas emissions. According to Bergero et al. (Bergero et al. 2023), improving the energy efficiency of aviation can reduce emissions by about 27 percent. Replacing jet fuel with zero-emission fuels is not viable because it makes airborne transportation unaffordable.

Carbon pricing and green subsidies are universal measures for the decarbonization of industries. Carbon pricing requires paying for emissions, motivating the emitters to adopt more environmentally friendly technologies. Green subsidies provide favorable conditions or funding to developers and users of green technologies. Although carbon pricing has theoretically better decarbonizing efficiency than green subsidies (Gugler et al. 2021), there are ethical (Caney and Hepburn 2011) and practical (Caney and Hepburn 2011; Hoag 2011) concerns regarding its sustainability. One ethical issue is that wealthy companies can pay to evade environmental commitments, especially if the carbon price is low. Another issue is related to the potential distributional injustice of emissions trading when the carbon tax burden will lie more on the poor and middle-income households (Caney and Hepburn 2011). Besides, emission trade makes environmental solutions artificially cost-efficient, which does not motivate the development of economically competitive ecological innovations. Carbon pricing has significant potential to make services and goods less affordable for the population, contributing to reduced living standards and stratification of society, especially in underdeveloped parts of the world. In contrast, subsidies to the developers of green technologies reduce their costs and make them more competitive in the market, resulting in lower prices for the end consumers and correspondingly seeming more sustainable.

The provided analysis of the technologies shows significant complexity and uncertainty of sustainability. Sustainable solutions must be diversified, and the available resources and practical constraints must be proactively considered. Overly optimistic reliance on a limited number of technologies often requires reactive corrective action later, resulting in extensive environmental, social, and economic costs (Kondratenko et al. 2025).

2 Artificial intelligence

Literature has no standard definition of Artificial Intelligence (AI) (Sheikh et al. 2023). Artificial intelligence can be defined as a technology that performs some intellectual tasks with efficiency close, equal to, or surpassing human abilities. According to this definition, an electronic calculator or a smartphone are examples of AI (Stone et al. 2016). Artificial intelligence is classified into narrowly specialized AI or weak AI, and artificial general intelligence (AGI) or strong AI, capable of general reasoning like humans. Most developments in the AI field represent weak AI (Goertzel 2014).

Alan Turing proposed an experiment to identify a game-changing threshold in the development of AI—the Imitation Game, usually referred to as The Turing Test (Turing 1980). The threshold is ultimately reached when, after a conversation without direct contact, a human interrogator cannot differ whether its conversation partner is human or AI, which requires advanced reasoning for imitation. Remarkably, a chatbot developed by a Russian-Ukrainian team in St. Petersburg named Eugene Goostman, imitating a 13-year-old Ukrainian boy, passed the Turing Test in 2014 by convincing 33 percent of interrogators that he is a human (Warwick and Shah 2016).

In contrast, John Searle proposed another experiment (Searle 1980) to show that an AI that executes computational operations based on formal logic can never achieve actual reasoning or understanding like a human. The experiment asks to put a person who does not speak Chinese inside a room with comprehensive instructions, written in the native language of the person, on how to interpret Chinese symbols. The person receives requests in Chinese, interprets them, and replies in Chinese according to the instructions. Searle argues that even if the person provides perfect responses that are indistinguishable from those of someone proficient in Chinese, it does not indicate that the person in the room understands Chinese. Similarly, an AI does not understand the material but only imitates understanding. Such a statement is valid if we assume that only structures operating similarly to a human brain qualify for comprehension, which is arguable (Goertzel 2014).

Weak AI has had many practical applications since the late 2000s, for example, in speech recognition (Amodei et al. 2016), the development of autopilot technologies for autonomous vehicles (Favarò et al. 2017) and helicopters (Abbeel et al. 2007). The weak AI field had significant breakthroughs in the 2020s, mainly associated with substantial advancements in theory and practical application of generative AI based on large language models—a subclass of deep neural networks. The prominent examples of them are ChatGPT—the most popular chatbot that passed the Turing Test in specifically designed challenging circumstances (Mei et al. 2024), Midjourney, a model creating images from text (Chiu 2024), Sora, a model generating video from text (Liu et al. 2024), and Suno, a model generating songs from text (Nugroho and Manggala 2024). However, the tasks where AI performs better than a human specialist are still limited (Brynjolfsson 2022).

The critics of AI performance argue that generative AI cannot produce something truly original as it depends on the pre-produced human-created feed (Runco 2023). The novelty requirement demands that AI development companies continuously collect new data from the internet or hire people to create authentic materials for AI training (Peroptyx, 2025). According to Jiang et al. (Jiang et al. 2023), a prominent direction for AGI development is enhancing its exploration capabilities to learn better from the internet and the real world.

However, even the constantly updated advanced AI models demonstrate innate quality issues with novelty and creativity—they can produce content that seems creative when the outcome is examined individually, but collectively, pieces of AI-generated content are similar (Doshi and Hauser 2024). One can argue, like John Locke (Locke 1690), that "For, since there appear not to be any ideas in the mind before the senses have conveyed any in" or that everything that the human brain produces is based on ideas and perceptions that we once learned or felt from the real world. In this regard, we are not conceptually too far from AI because the outcome of human activity may be considered novel only because the mechanism behind our thinking is complex enough not to allow us to trace the origins of our idea came from.

Although the performance of existing AI is limited, the potential for its development and practical application is difficult to overstate. The mass deployment and using AI technology and robots in daily routine is approaching. AI can have the same impact in the twenty-first century as the invention of electricity and the conveyor had in the past. They became crucial drivers for progress and social changes. As AI will create opportunities for some, it may become civilizational and cultural "climate change" for others, requiring much preparation and adaptation effort.

3 Sustainable AI

According to the analysis provided in Sects. 1–2, Sustainable AI must meet the requirements for sustainable technologies. Similar to the UN framework (see Fig. 1), the present study proposes Sustainable AI Development Goals in Fig. 2. AI is sustainable if it actively contributes to some goals without negatively impacting others.

AI applications have significant potential to reduce costs and boost decision-making performance in different industries (Moro-Visconti et al. 2023), e.g., healthcare (Al Meslamani 2023; Wang et al. 2024), logistics (Yaiprasert and Hidayanto 2024), intellectual technologies (Hartley 2019), and teaching (Miralay 2024), contributing to affordable and high-quality products and services. Scientists have made revolutionary achievements by using AI in preventive medicine and diagnostics—it has already surpassed the performance of human specialists in the early identification of breast cancer (McKinney et al. 2020) and prostate cancer (Saha et al. 2024). Early diagnostics of health issues allow for the most effective, timely patient treatment, avoiding severe complications. Olawade et al. demonstrated prospects for AI-driven detection and treatment of mental health disorders (Olawade et al. 2024).

Another promising development is AI application in prosthetics and exoskeleton technologies to improve the quality of life for disabled and older people (Chopra and Emran 2024; Lee et al. 2024), advance patient rehabilitation performance (Xia et al. 2024), and enhance natural human abilities, for example, by enabling lifting heavier cargo or reducing loads on the musculoskeletal system (Siedl and Mara 2024; Zhu et al. 2021). Modern prosthetic and exoskeleton AI-powered technologies allow for their human brain-driven, high-precision control. Lee et al. (2024) report more than 96 percent movement accuracy at up to 550 ms response rate for their upper-limb exoskeleton. European Commission sees AI as a driving force for the future of medicine but confirms that its application is limited because of the absence of a proper regulation framework (European Commission 2025).

Technologies preventing anthropogenic pollution of the environment and corresponding influence on climate change use the strength of AI to improve their performance (Pop et al. 2023). AI applications can be divided into ones actively using AI for better energy efficiency and emissions reduction (Bolón-Canedo et al. 2024; Kondratenko et al. 2025) and others contributing to better energy consumption prediction (Nguyen et al. 2025; Zhang et al. 2024). Besides, AI contributes to better safety by providing advanced methods for collision damage predictions and avoidance for self-driving cars (Manoharan 2019) and ships (Liu et al. 2022; Zhang et al. 2025). Finally, AI can be trained to detect and prevent cybersecurity threats and fraud (Kaur et al. 2023).

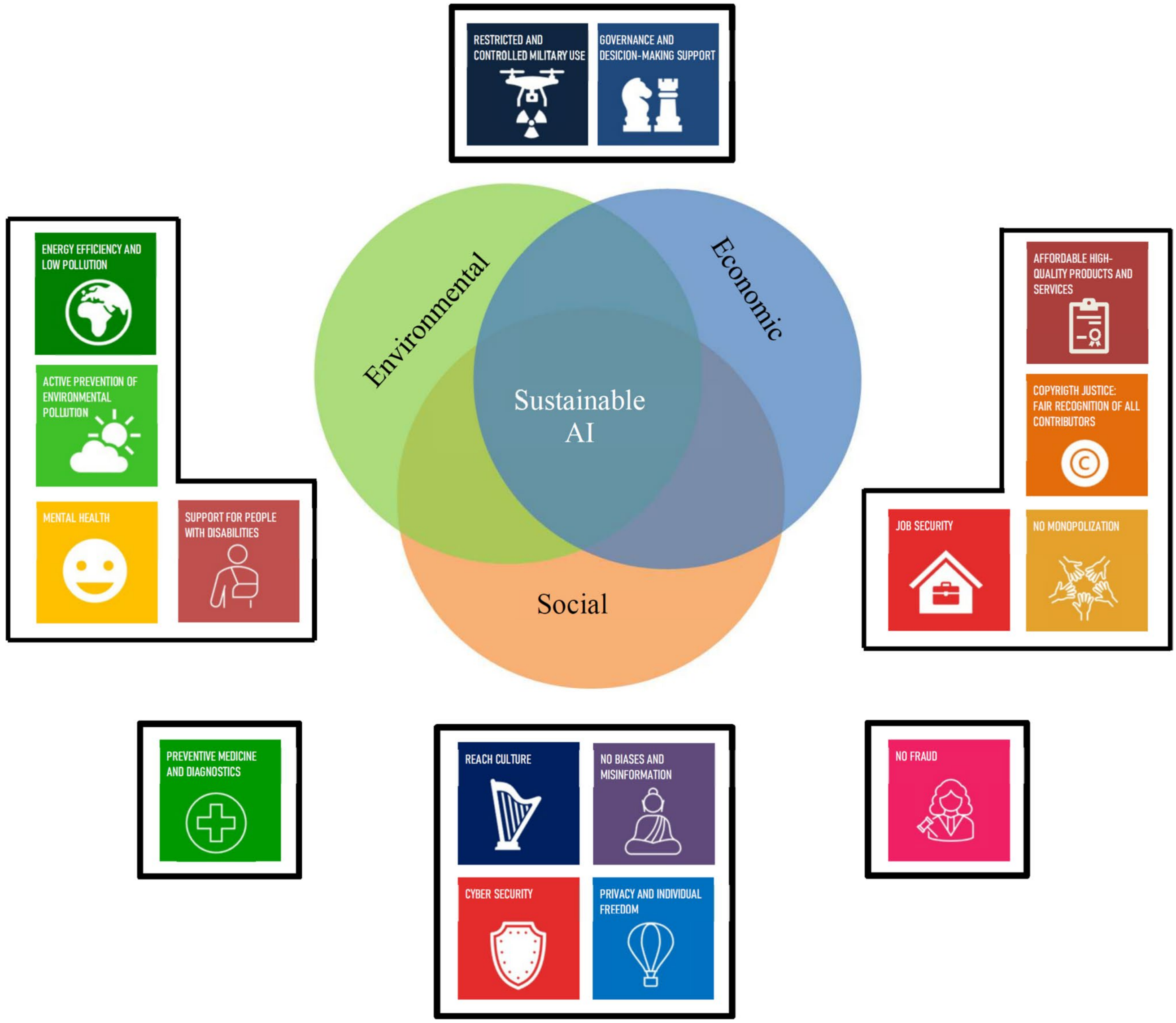

Fig. 2 Sustainable AI development goals

4 Discussion: non-sustainable AI

In contrast to sustainable AI, non-sustainable AI advances some goals in Fig. 2 but negatively influences others. AI demonstrates substantial gains for companies regarding operational cost and time efficiency, but poses significant threads in other aspects of sustainability, which is indicated by leading AI developers (Bengio et al. 2024).

AI automatization and assistance can negatively affect CO_2 emissions if AI is not specialized to reduce environmental impacts. Although some academics insist on the higher environmental efficiency of AI than humans in some tasks, such as writing and illustrating (Tomlinson et al. 2024), other research findings (Tamburrini 2022) and practical data demonstrate the opposite. For example, in the 2024 Environmental Sustainability Report, Microsoft indicated a more than 29 percent increase in carbon emissions in 2023 than the 2020 baseline (Microsoft 2024). According to the report, the growth of emissions mainly relates to the infrastructure and electricity needed for generative AI. Similarly, in their Environmental Report 2024, Google indicated a 48 percent increase in carbon emissions in 2023 than the 2019 baseline (Google 2024). The report attributes the additional emissions mainly to the increased energy consumption of data centers and supply chains, which is significantly related to AI integration into Google products.

Collaborative work of researchers from the Allen Institute for AI and Carnegie Mellon University has shown that optimistic estimates of AI environmental impact are typically made considering only the final training runs of the latest

AI models and their operational demands, failing to consider most of the development phase (Morrison et al. 2024). They also holistically measured and reported the realistic environmental impact of developing their own large language model family with advanced energy-efficient equipment, which accounted for carbon emissions equivalent for the US to power about one average household for 100 years and consumed water equivalent to about 25 years of water usage by an average person (Morrison et al. 2024). According to Goldman Sachs (2024), a ChatGPT query requires ten times the energy of a Google search query, meaning that replacing search engines with AI models can hinder efforts to fight climate change.

Concerns are raised regarding the potential of generative AI for copyright infringement (Lim 2023)—the existing copyright legislation is developed for human activity and does not work appropriately for AI (Al-Busaidi et al. 2024; Zeng and Chen 2024). The developers of generative AI often harvest copyrighted texts, images, videos, and music available on the internet to train their models without consent, recognition, or any form of remuneration for the authors of the original works. This issue resulted in significant strikes of content creators, including the 2024 Screen Actors Guild–American Federation of Television and Radio Artists (SAG-AFTRA) video game strike—ongoing in March 2025, and the finished Holywood strikes—the 2023 Writers Guild of America strike with about 11 500 members, joined by the SAG-AFTRA with about 160 000 members. The Holywood strikes resulted in new regulations for more transparent use of AI (The Writers Guild of America 2023), which supports augmenting content creators instead of replacing them. Besides, film creators must obtain consent to use the appearance of actors to create their digital copies by AI and remunerate them with the same money as they would get acting. There is significant protest activity among visual artists who want to protect their artworks or the entire art style from unauthorized use for AI development (Ong 2023; Zeng and Chen 2024), e.g., by removing their content from the internet.

Systematic potential violations of the rights of content creators by AI resulted in numerous lawsuits, including The New York Times (NYT) case against Microsoft and OpenAI for creating competing AI tools based on the NYT copyrighted materials available online (The New York Times, 2023), Asian News International case against OpenAI for non-consensual use of training materials and misinformation (Asian News International 2024), Getty Images case against Stability AI for using its copyrighted visual assets—photographs, video, and illustrations—to train their generative AI (Getty Images 2023).

Finally, the fair recognition of the work of content creators is crucial for the survival of AI. If content creators are not remunerated according to their contributions, they will post their works on the internet less often, and the proportion of AI-generated online content will increase significantly. Studies show that AI models rapidly collapse when trained on data with a high proportion of AI-generated content (Gibney 2024; Shumailov et al. 2024). Although generative AI can effectively produce average-quality content, it often fails to provide high quality and uniqueness (Doshi and Hauser 2024; Gray 2024), indicating that the domination of AI-generated content may hinder the diversity and richness of human culture.

The experience of authors with ChatGPT shows that it can be very persuasive when it provides false information caused by a hallucination. This behavior can be stopped by directly pointing out the problem, but it is not always possible considering the natural limitations of the user. Park et al. (2024) show the significant threat and capacity of using AI to commit financial fraud and deception. Some other sources report potential risks of misinformation (Asian News International 2024; Bond 2024) related to the application of AI chatbots, e.g., spreading gender and racial biases (Fang et al. 2024; Vicente and Matute 2023). A significant thread of radicalization and supporting narrow-mindedness comes from so-called Filter Bubbles created by social media AIs (Rodilosso 2024). Another issue is the unlimited potential of AI for privacy violation and control—autocratic governments already use face and expression recognition, big data collection and analysis, and unauthorized collection of health information to control, monitor, and influence their population and suppress opposition or dissent (Directorate-General for External Policies of the Union (European Parliament) and Ünver 2024).

Erik Brynjolfsson (Brynjolfsson 2022) points out that prioritizing AI automation over AI human augmentation can hinder job security, prosperity, and well-being for most of the population, but the present taxation systems in many countries encourage business for automation. He formulates it as the Turing Trap: "As machines become better substitutes for human labor, workers lose economic and political bargaining power and become increasingly dependent on those who control the technology." The recent data supports this principle—Sebastian Siemiatkowski, the head and founder of Klarna, said in an interview (Gani and Hyde 2024) that his company stopped hiring a year ago and reduced the number of employees by 22 percent because AI does their work. Siemiatkowski argues it allowed other employees an undisclosed pay increase, demonstrating how AI can fuel income inequality. Another company—Peroptyx, hires human analysts to create AI training data and test and validate AI models. According to Glassdoor (Glassdoor 2025), current and former employees often report being severely underpaid, considering high qualification requirements and the efforts needed to work at Peroptyx. This example shows that AI augmentation can result in unfair compensation, even for highly skilled professionals.

Rapid development and cost-efficiency of AI technologies can result in a situation when most people live under the new "embrace AI or perish" paradigm, similar to the "publish or perish" principle in academia, where active publishing or research is necessary for a successful career. In that case, only a minority of the highest-class professionals will maintain the qualification level to be competitive without using AI.

Considering the limited number of those who develop and control AI technologies, there is a high risk of disproportional concentration of significant power in their hands (Brynjolfsson 2022), shifting the power balance between nations and classes. Although AI can significantly increase productivity and global wealth, there is no mechanism to distribute them equally under the present circumstances. AI makes the job market more competitive, resulting in rising expectations of employee qualification and contribution, which may threaten work-life balance and the quality of life. Although modern life expectancy is much higher than ever, people have never worked so much—working hours of medieval peasants is already an unattainable dream (Schor 1993).

Another issue is that, in contrast to common expectations, AI technologies are mainly oriented toward creative tasks, leaving routine and non-creative jobs to humans. This point is perfectly illustrated by Joanna Maciejewska, who has written, "I want AI to do my laundry and dishes so that I can do art and writing, not for AI to do my art and writing so that I can do my laundry and dishes." Art and creativity have always been essential to human civilization and self-identification. It is unclear how AI-generated art will affect this aspect of humanity.

5 Conclusion

AI must correspond to the principles of sustainable development in all its aspects to be sustainable. AI technology shows outstanding achievements in reducing the costs of products and services and boosting decision-making performance. Scientists have made revolutionary achievements by using AI in preventive medicine and diagnostics and developing prosthetics and exoskeleton technologies to improve the quality of life. Technologies preventing anthropogenic pollution of the environment and corresponding influence on climate change can effectively use the strength of AI to improve their performance. However, the scope of sustainability threads from AI is also significant—they include the risks of increased carbon emissions because of low energy efficiency, the risks of copyright infringement due to unauthorized harvesting of copyrighted materials to train AI, risks of high unemployment because of human replacement and augmentation by AI, and disproportional concentration of significant political and financial power in the hands of a limited number of companies. The title of the papers formulates the question—May AI be sustainable? The answer is yes, but only if AI developers, regulators, and governments correspond to the specific goals of Sustainable AI development, which are formulated in the present study.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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