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Machine Learning and the Sustainable Development Goals: Theoretical Insights and Practical Applications

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Machine Learning and the Sustainable Development Goals: Theoretical Insights and Practical Applications

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Abstract

Machine Learning (ML) and Artificial Intelligence (AI) have become powerful tools for overcoming complex global challenges in harmony with the Sustainable Development Goals (SDGs) of the United Nations. In this article, we illustrate ML and AI technology's contribution to sustainable development through theoretical and practical examples in a variety of sectors. In this article, AI-powered interventions in healthcare, agriculture, greenhouse gas emission reduction, environment tracking, and education have been analyzed. Generative AI technology has changed access to education and personalized learning, and environmental tracking and conservation have been aided through machine learning algorithms. Despite such positive development, considerable obstacles include a lack of data, algorithm bias, ethics, and interpretability of complex AI algorithms. All such impediments remind us of multi-sectoral collaboration and responsible AI intervention for delivering equitable and sustainable development. According to the article, overcoming obstacles necessitates transparent and participatory frameworks and deliberate collaborations between governments, private industries, academe, and civil society groups. With full realization of ML and AI through ethics and participatory policies, we can mobilize effective, evidence-guided interventions and hasten success towards attaining the SDGs. With a demand for ongoing studies in case files for responsible AI interventions with a strong bias for equity, consideration, and humanity, in this article, a clarion call for such studies is placed.

1. Introduction

The United Nations Sustainable Development Goals (SDGs) constitute a 17-dimensional collection of ambitious targets for overcoming such obstacles as inequality, poverty, and climate change through 2030 (United Nations, 2015). Pushed in part by accelerated technological advancements, most prominently in machine learning (ML) and the Internet of Things (IoT), novel methodologies have emerged for overcoming complications at a worldwide level (LeCun et al., 2015; Jaber, 2023). With a processing capability for complex and voluminous sets of data, ML algorithms can make out hidden trends, optimize distribution of assets, and make future predictions, and, in consequence, enable fact-based policymaking (Blumenstock, 2016).

Artificial Intelligence (AI), most particularly breakthroughs in Generative AI tools such as Large Language Models (LLM), constitutes a transformational driving force for realizing the SDGs. For example, in the case of SDG 4 (Quality Education), AI-facilitated tools such as ChatGPT have revolutionized educational access through providing scalable and personalized educational experiences and cutting operational costs (AlSagri & Sohail, 2024). In similar terms, AI-facilitated constructs in environment tracking and construction contribute immensely to SDG 6 (Clean Water and Sanitation) and SDG 11 (Sustainable Cities and Communities) through increased operational efficiency and increased availability (Regona et al., 2024; Marques et al., 2024).
What's more, state-of-the-art works have stressed the importance of effectively uniting ML constructs and policy frameworks in overcoming the SDGs (Koundouri et al., 2022; Koundouri et al., 2024a). In such works, a specific observation is drawn about the fact that state-of-the-art ML approaches, when united with transparent policy links—most particularly such examples in European Green Deal—can become a blueprint for developing countries and regions for achieving regions of sustainability
However, the success with ML for sustainable development is a matter of suitability of such algorithms with respective requirements and environments in respective capacities and vulnerabilities in regions. Involvement with everyone in access to proper care, greenhouse gas emissions curbing, agricultural productivity in increased forms, and mapping output in science and technology are areas in which ML interventions have shown effectiveness (Esteva et al., 2017; Hajikhani & Suominen, 2022; Rolnick et al., 2019). Latest research, in fact, considers mapping of policies in terms of SDGs in web-portable forms with ML in an attempt to map security and relations in terms of sustainability (Koundouri et al., 2024a). In this article, theoretical underpinnings of ML in face of requirements of sustainable development and real-life pragmatic implementations and challenge scenarios in deploying such technology in practice have been discussed. Apart from that, it considers ethical AI, implementations and collaboration between respective disciplines in quest for full potentials of such technology in driving worldwide strategies towards sustainability.

2. Theoretical Insights

2.1 Machine Learning Approaches

Machine learning (ML) is a group of computer and statistics techniques for computers to learn and produce information. There have been three categories of ML techniques: supervised, unsupervised, and reinforcement, with a mechanism and application for one for each in individual cases. Supervised techniques learn with labelled datasets for a prediction, for instance, classification and regression, and unsupervised techniques unveil and reveal hidden structures and trends in unlabeled datasets. Reinforcement techniques, alternatively, allow an agent to learn an ideal behavior via environment interaction and maximization of accumulated reward via feedback loops.

The development of deep neural networks, generative techniques, and ensemble methodologies in current years have immensely augmented the range of ML use cases (LeCun et al., 2015). Generative AI technology, including Large Language Models (LLM), have been successful at reading and producing human-language-typed information, transforming industries such as education and information creation (AlSagri & Sohail, 2024). Ensemble techniques such as Random Forest and Gradient Boosting boost prediction accuracy via combining numerous decision trees or models, applicable in a variety of industries such as environment observation and medical care (Marques et al., 2024). In addition, integration of ML with remote observation information and cloud processing platforms, including Google Earth Engine, have facilitated environment estimation at a grand level and administration of assets (Marques et al., 2024).

The success of ML models hinges on three factors: (1) availability, diversity, and quality of information; (2) analysis and processing software and computational infrastructure; and (3) algorithm and hyperparameters specific to a task (LeCun et al., 2015). Breakthroughs in most branches have been encouraged through ongoing refinement in information collection techniques, computational powers, and algorithm development. Trends in technological and computational improvements encouraged academicians and policymakers to utilize ML for simplifying complex environment and society-related issues at the epicenter of Sustainable Development Goals (SDGs). In specific, an increasingly larger collection of studies utilizes ML and AI techniques in big picture analysis for sustainability, beginning with theoretical analysis to hands-on implementations (Koundouri et al., 2024a). Besides that, a collection of work conducted by Koundouri et al. (2022) deals in detail with adaptability of ML frameworks for a range of SDG-focussed implementations and its synergy with theoretical underpinnings and real-life implementations.

2.2 Relevance to the SDGs

The Sustainable Development Goals (SDGs) seek to mitigate a range of interconnected ills worldwide, including eradicating extreme poverty and supporting environment and sustainability, providing access to quality and fair and equitable and environment and educational and gender equality (United Nations, 2015). ML can manage and analyze high-dimensional, big datasets and thus embody a key tool for dealing with such complex, multi-faceted ills. For instance, ML algorithms can use satellite photos to monitor land use and deforestation, contribute towards forecasting for disasters through predictive model training and apply mobile phone metadata for estimating trends and poverty in areas with a lack of conventional datasets (Blumenstock, 2016; Jaber, 2023).

ML-promoted predictive models can enable forecasting for future scenarios and alternative intervention impact analysis and, therefore, for flexible and proactive governance (Rolnick et al., 2019). In environment tracking, a variety of ML algorithms such as a Random Forest model have been effective in tracking variation in preserved environments, supporting administration of ecosystems and contributing towards supporting SDG 6 for healthy and sanitation water (Marques et al., 2024). Reinforcement learning, for its part, facilitated shaping and optimizing energy networks and contributing towards supporting SDG 7 for cheap and clean energy through efficiency boost and reduced emissions (Khanna et al., 2024). AI integration planning studies in energy frameworks (Koundouri et al., 2024b) reveal AI-facilitated modeling can make decarbonization avenues and consultation with stakeholders easier and can hasten towards a transition towards a secure, safe future for energy.

Further, ML tools can enable systematic mapping of technological innovation and scientific studies to respective SDGs. Text mining and NLP methodologies have been utilized in evaluating the contribution of academic studies and patents to sustainability targets, orienting decision-makers towards effective innovation (Hajikhani & Suominen, 2022). Bibliometric studies have also uncovered trends and gaps in studies, and have discovered avenues for focused investments in technology and science in consonance with SDG objectives (AlSagri & Sohail, 2024).

Also, in the educational sector (SDG 4), ML and AI-facilitated platforms such as language generating models enable personalized educational experiences, adaptive guidance, and content creation, enhancing access to high-quality learning worldwide (AlSagri & Sohail, 2024). Not only do such applications drive educational performance, but also counter systemic inequity, closing gaps in learning between socio-economic groups.

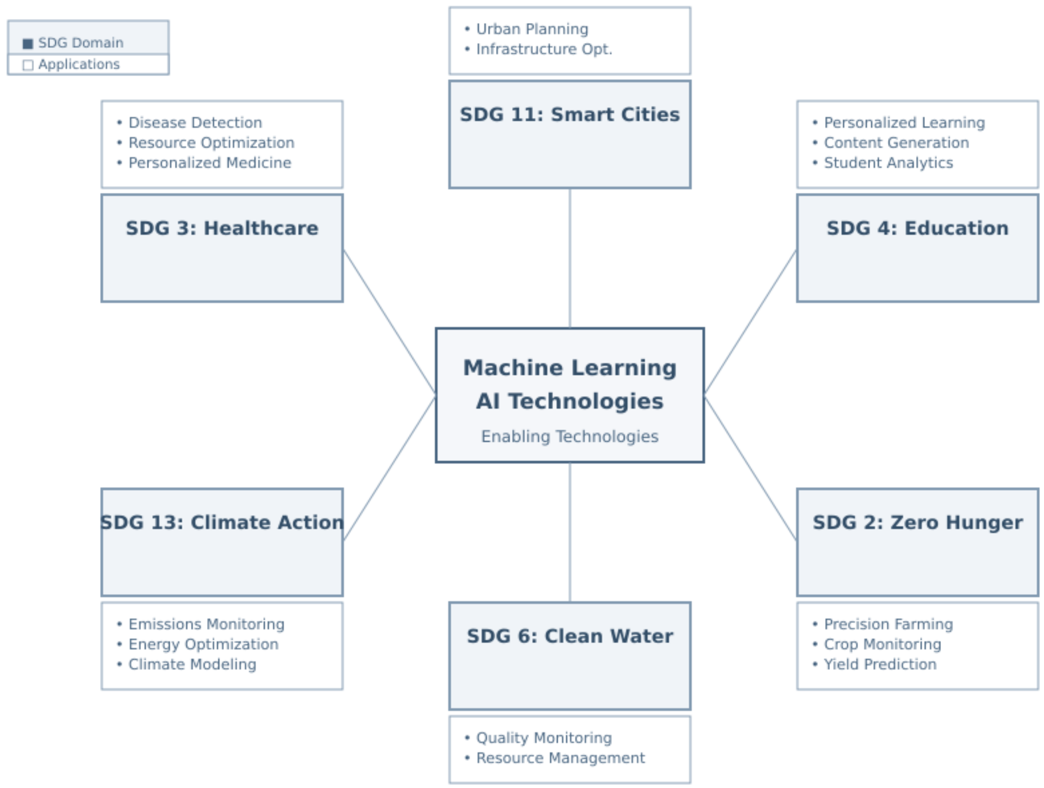

Figure 1: Machine Learning and AI Applications for Sustainable Development Goals.

Figure 1 illustrates a systemic model depicting how AI and ML technology serve as an enablement for driving a range of SDGs. There are six such principal areas for SDG including disease diagnostics, efficient use of resources, and personalized medicine in healthcare (SDG 3), personalized educational experiences, creation of content, and analysis of students in educational use cases (SDG 4), tracking of emissions, efficiency in energy, and simulation of climate in actions for climate (SDG 13), precision in agriculture, yield prediction, and analysis of crops in agricultural use cases (SDG 2), and in management of water in terms of resources (SDG 6) and smart city programs (SDG 11) for urban planning and infrastructure efficiency.

The variety of such use cases identifies with the versatility of ML/AI technology in driving a range of types of sustainability challenge and depicting the interconnected nature of technology interventions in a range of SDG spaces.

ML technology, with its capabilities in supplying fact-bound information, optimizing use of assets, and driving innovation, can serve a catalyst in driving achievement towards realization of a range of the SDGs, but its full realization must face such challenge in access and preparation and processing of relevant information, bias in algorithms, and ethics of use, such that ML-powered interventions become accessible, equitable, and enduring.

3. Practical Applications

3.1 Healthcare

Healthcare is at the nexus of a range of SDGs, including Goal 3 (Good Health and Well-being). ML algorithms have been applied in early disease diagnosis and enhanced accuracy in diagnostics (Esteva et al., 2017). Convolutional neural networks, for example, can scan medical images in an attempt to detect a lesion or a tumor in the skin, sometimes with and even at a similar level to humans (Esteva et al., 2017). Besides diagnostics, ML has been applied in personalized medicine, epidemiologic modeling, and planning for resources—helping hospitals and clinics manage limited resources in an effective manner (LeCun et al., 2015).

3.2 Agriculture

Addressing SDG 2 (Zero Hunger) requires increases in agricultural productivity and the optimization of supply chains. ML-driven solutions can guide precision agriculture, where farmers use sensor data (including IoT-enabled devices) to monitor soil conditions, pest infestations, and weather forecasts (Rolnick et al., 2019; Jaber, 2023). For instance, machine vision systems can assess crop health via drone imagery and advise on the best times for irrigation or pesticide application. By tailoring interventions to specific needs, ML can reduce both resource wastage and environmental damage, thereby aligning with the broader sustainability objectives (United Nations, 2015). AI systems can also optimize supply chains, reducing post-harvest losses and improving market access for smallholder farmers (Regona et al., 2024).

3.3 Climate Change Mitigation

Climate change is an issue cutting across a portfolio of several of a range of the SDGs, for example, SDG 13 (Climate Action). ML has been consistently effective in offering aide in terms of simulation of climate, maximization of renewable sources of energy, and management of natural assets (Rolnick et al., 2019). First, algorithms in reinforcement training have been developed in an attempt at maximization of delivery of energy in smart networks, balancing demand and supply dynamically with lesser emissions of carbon (Wang et al., 2024). Besides, ML can integrate satellite and sensor observations for tracking environment change—from melting arctic caps through tree cover change—and inform policymaking and conservation in an efficient manner (IPCC, 2021). In between, injecting AI frameworks in programs at the Global Climate Hub has proven effective in developing resilient decarbonization scenarios and participatory approaches in a view towards prioritization of stakeholders (Koundouri et al., 2024b).

AI-powered predictive tools increasingly function in evaluation of extreme weather impact, allowing preparedness and minimizing danger in disaster, and AI use in constructions enables activity towards a climate through optimized energy efficient constructions and minimizing consumption, and in consequence, a lessening constructions sector's footprint in terms of carbon (Regona et al., 2024).

3.4 Mapping Science and Technology for SDGs

An emerging use of ML is in mapping technological artefacts and research output systemically onto individual SDGs in search for overlaps and gaps in innovation (Hajikhani & Suominen, 2022). It entails recourse to big bibliometric or patent databases and use of text mining, natural language processing, and supervised training in search for an association with an SDG basis. In such a way, such information can inform funders and policymakers about most in demand investments, and synergies and collaborations between academia and industries.

AI can, in addition, promote sustainability in construction, harmonising infrastructure investments towards SDGs including SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 11 (Sustainable Cities and Communities) (Regona et al., 2024). For example, AI-en-powered Building Information Modeling (BIM) systems streamline construction processes with a view towards minimizing constructions and conserving energy in a life-cycle in a construction project. Prediction maintenance and smart infrastructure observation amplify durability and efficiency in constructed environments (Regona et al., 2024).

AI integration in planning, designing, and maintenance in construction can make a big contribution towards realising environment suitability, minimizing its ecological footprint, and contributing towards values in a circular economy. For effective and responsible use of such AI tools, confronting ethics in view, securing information, and training and utilizing workers competently is imperative (Regona et al., 2024).

3.5 Monitoring Through Machine Learning Monitoring progress towards clean water and sanitation

Marques et al. (2024) proposed a machine learning technique employing the Random Forest algorithm for tracking environment shifts in Brazil's Permanent Protected Areas (PPAs), specifically in riparian areas. Employing high-resolution Sentinel-2 satellite images and the Google Earth Engine platform, a 6% expansion in native vegetation between 2015 and 2022 was detected through tracking land-use shifts. Classification accuracy between 83% and 88%, and 0.73 and 0.84 Kappa coefficients, were achieved through the use of a Random Forest model. The strong methodology improves tracking capabilities, with policymakers having access to proper information for deciding on ecosystem administration and conservation approaches. Employing free datasets and open-source tools ensures its scalability and repeatability, and a cost-effective and long-term environment tracking capability (Marques et al., 2024).

The work of Marques et al. (2024) also identifies the revolutionized role of machine learning in driving SDG 6 through overcoming scarcity in terms of data and enhancing accuracy in environment tracking. Employing a Random Forest technique showed high improvements in following shifts in ecosystems, and providing a scalable model for worldwide use in similar capacities. Not only does such an approach contribute towards a review of success in terms of targets for water and sanitation, but it can also contribute towards effective management in protected areas and promote ecosystem restoration and sustainability in general. Integrating sophisticated ML strategies in environment tracking in coordination with worldwide efforts towards sustainability promotes effective realization towards SDG 6 targets.

3.6 Advancing Quality Education through Artificial Intelligence Artificial Intelligence (AI) has shown its worth in driving Sustainable Development Goal 4 (Quality Education). AI in its form of Generative AI tools in terms of Large Language Models (LLMs) is discussed in (AlSagri & Sohail, 2024) in relation to increased educational access and educational quality. AI tools enable individual, personalized, and scaled learning experiences, expand access to educational materials, and enable effective use of resources. AI eradicates educational inequality through adaptable training processes, which respond to individual requirements for learning, providing accessible and fair education.

AI application in educational environments in addition promotes opportunity for a life of continuous learning through offering personalized and interactive educational contents. Generative AI tools such as ChatGPT enable virtual mentoring in real-time, personalized creation of learning contents, and real-time feedback, and can promote learner performance and motivation. Despite this, ethical AI use in educational environments entails consideration of proper review of confidentiality in terms of providing access to information, accuracy in algorithms, and incorporation with policies for effective, fair, and continuous use. Long-term social consequences and ethics of AI use in educational environments have to receive consideration in future studies in full awareness of its worth in driving realization of SDG 4 (AlSagri & Sohail, 2024).

4. Challenges and Limitations

Despite the future with AI and ML in supporting Sustainable Development Goals (SDGs), such key deterrents surround them. Quality and availability of information present a big hurdle—especially in low-income countries with unsound infrastructure for collecting and processing information (Blumenstock, 2016). In tracking environment, unavailability of information at national scales according to Marques et al. (2024) holds it back in tracking transformations in ecosystems, and in its turn, its effectiveness and achievement towards SDG 6 suffers. Overreliance in free datasets, convenient and inexpensive, can restrict its span and granularity, and investments in high resolution sources and upgraded frameworks for integration will have to follow.

Algorithm bias is a long-lasting challenge. Where ML and AI tools lack proper representations for disadvantaged groups, a high susceptibility to replicate and even widen social and economic gaps exists (Hanna et al., 2024). In educational AI, such biases in training datasets can deliver unbalanced educational experiences, and disadvantaged groups become even disadvantaged (AlSagri & Sohail, 2024). Ethical concerns dominate, most badly in industries such as medical and mapping of welfare, particularly in cases of sensitive use of individual information (Esteva et al., 2017). Application of AI in schools brings similar ethical concerns regarding information and data in terms of consent, and misuse through individual tracking, and therefore stricter frameworks in legislation and governance will have to follow (AlSagri & Sohail, 2024).

Moreover, the "black box" character of most sophisticated ML algorithms can obstruct interpretability and trust, and cause a lack of full acceptance in such tools use amongst non-tech and policymaking communities (LeCun et al., 2015). In tracking in environments, such as with work by Marques et al. (2024), high performance with algorithms such as Random Forest comes at a price of complexity, obstructing transparency, and undermining decision-makers in terms of model output evaluation and understanding. In educational settings, AI technology such as LLMs can deliver personalized educational experiences but with no explainability, and accountability and educational value of contents will become a concern (AlSagri & Sohail, 2024).

As illustrated in Fig. 2, impediments in deploying AI and ML technology for sustainable development can be situated in five interconnected domains. The first domain addresses data-related impediments, whose case, in regards to scarcity and poor quality, notably in low-income countries, have a deleterious impact in model development and operationalization. Algorithm-related concerns such as model bias, model complexity, and model interpretability, and model trust and acceptance concerns, constitute the second one. Implementation concerns constitute the third one, including high demand for resources, high demand for expertise, and concerns about ML/AI technology scalability in a real-life environment. The fourth domain addresses ethical concerns in terms of concerns about data privacy, security concerns, and consent management, particularly in sensitive use cases such as in schools and in healthcare. Domain five and concluding concerns with policy impediments revolve around having sound frameworks for legislation, efficient governance, and proper coordination with pertinent stakeholders in a manner that fosters responsible and equitable use and access to ML/AI technology. All these impediments cannot stand alone but speak to one another and compound one another, and therefore demand an overall, multi-faceted, and overall resolution for each impediment bearing on a variety of domains at a go.

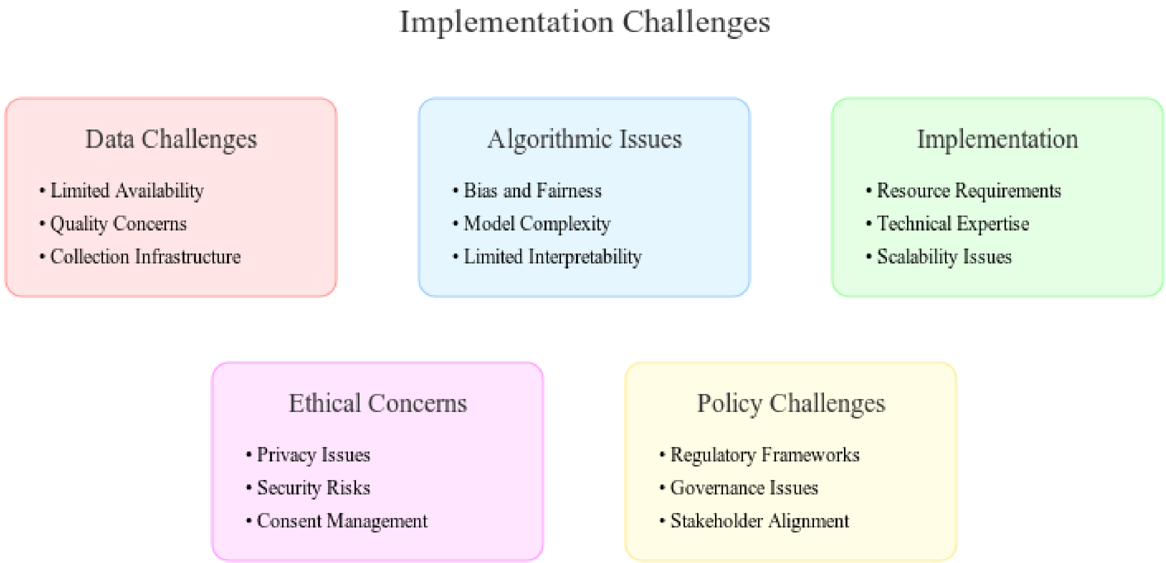

Figure 2: Key Challenges in ML/AI Implementation for SDGs.

IoT solutions—often coupled with ML—introduce further challenges, including security vulnerabilities and data privacy risks (Jaber, 2023). Securing sensitive data in large AI models, especially LLMs, remains a critical issue, as highlighted by privacy-preserving techniques (Feretzakis et al., 2024a) and trustworthy AI frameworks that dynamically control disclosure of information (Feretzakis et al., 2024b). In agriculture and construction, where IoT devices collect vast amounts of operational data, ensuring the cybersecurity of interconnected systems becomes critical to prevent data breaches and system disruptions. Additionally, the integration of AI into the construction industry, while offering pathways to sustainability, must contend with workforce adaptation, requiring significant investment in upskilling and training to prevent job displacement and ensure equitable technology adoption (Regona et al., 2024).

To address these multifaceted challenges, interdisciplinary research is essential to develop transparent, equitable, and context-sensitive AI and ML solutions that are adaptable to local conditions (Rolnick et al., 2019). This includes designing models with built-in explainability, improving data governance frameworks, and fostering inclusive policy dialogues that prioritize ethical considerations and social equity. Collaborative efforts between technologists, policymakers, educators, and local communities will be vital to ensure that AI and ML technologies contribute meaningfully and responsibly to achieving the SDGs.

5. Conclusion

Machine learning (ML) and artificial intelligence (AI) have a transformational role in realising Sustainable Development Goals (SDGs) through delivering economically-scalable, data-dependent solutions in numerous sectors. Diagnoses become accurate, maximise efficiency in utilisation, and enable individualised therapy, under SDG 3 (Good Health and Well-being). AI-managed agricultural harvesting in agricultural produce maximise yield and maximise utilisation of assets, in supporting SDG 2 (Zero Hunger). Climate change fighting is supported through ML underpinnings, through smarter utilisation of power, and environment tracking changing, and for supporting SDG 13 (Climate Action). Marriage of free, publicly accessible tools and publicly accessible datasets, such as in an exercise conducted for and by Marques et al. (2024), identifies examples of environment and access to clean water conservation alternatives at lesser budget, in realising SDG 6.

AI approaches, such as Large Language Models (LLM) such as ChatGPT, have even brighter future in enriching access and delivery in training, supporting SDG 4 (Quality Education) (AlSagri & Sohail, 2024). Generative AI generates individualised educational experiences and maximise utilisation of educational assets, enhancing life-long access and less educational inequality. Likewise, AI-inspired innovation in buildings maximise planning for buildings, maximise efficiency, and minimise disposal, in working in compliance with both SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities). In synergy with overall frameworks leveraging AI for larger solutions in utilisation for energy and for environment, even larger impact can occur in terms of sustained development

However, realizing AI and ML's full potential for attaining SDGs involves overcoming many impediments. Algorithm bias, insufficiency in data, transparency, and concerns about privacy obstruct widespread use and acceptance of them. Ethical use, transparency, and accountability will have to become part of future development and use work. In addition, multi-disciplinary collaboration between governments, academia, industries, and civil society will become an imperative in creating responsible, contextual, and inclusive AI options.

By creating international collaborations and employing transparent, fair AI frameworks, it will become a reality to maximize the use of machine learning in transforming most significant worldwide concerns towards inclusive and sustainable options. All future work will have to pay utmost regard to ethical dimensions, integration with policies, and capacity development in utilizing AI technology towards effective and responsible contribution in attaining sustainable development.

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