Next Sustainability 4 (2024) 100041

Contents lists available at ScienceDirect

Next Sustainability

journal homepage: www.sciencedirect.com/journal/next-sustainability

Review article

Artificial intelligence potential for net zero sustainability: Current evidence and prospects

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ARTICLE INFO

Keywords:
Artificial intelligence
Net zero
Climate change
Sustainability
Machine learning

ABSTRACT

This comprehensive review explores the nexus between AI and the pursuit of net-zero emissions, highlighting the potential of AI in driving sustainable development and combating climate change. The paper examines various threads within this field, including AI applications for net zero, AI-driven solutions and innovations, challenges and ethical considerations, opportunities for collaboration and partnerships, capacity building and education, policy and regulatory support, investment and funding, as well as scalability and replicability of AI solutions. Key findings emphasize the enabling role of AI in optimizing energy systems, enhancing climate modelling and prediction, improving sustainability in various sectors such as transportation, agriculture, and waste management, and enabling effective emissions monitoring and tracking. The review also highlights challenges related to data availability, quality, privacy, energy consumption, bias, fairness, human-AI collaboration, and governance. Opportunities for collaboration, capacity building, policy support, investment, and scalability are identified as key drivers for future research and implementation. Ultimately, this review underscores the transformative potential of AI in achieving a sustainable, net-zero future and provides insights for policymakers, researchers, and practitioners engaged in climate change mitigation and adaptation.

1. Introduction

The urgent need to address climate change and transition to a sustainable future has propelled the exploration of innovative solutions across various sectors [66,92,104]. In recent years, artificial intelligence (AI) has emerged as a powerful tool with the potential to significantly contribute to mitigating climate change and achieving the ambitious goal of net-zero carbon emissions [29,78,100,103,106]. The background of this nexus lies in the recognition of the dire consequences of climate change, including rising global temperatures, extreme weather events, biodiversity loss, and threats to human health and well-being [16,100]. Governments, organizations, and individuals are increasingly acknowledging the need for immediate and effective action to combat these challenges.

AI, with its ability to process vast amounts of data, analyze complex patterns, and make informed predictions, has the potential to drive transformative changes in areas such as energy, transportation, agriculture, and waste management [8,46]. By harnessing the power of AI, it becomes possible to optimize energy systems, enhance renewable energy integration, improve resource efficiency, develop intelligent transportation networks, and facilitate sustainable practices in various domains such as education and finance [48,57,76,126].

Recent empirical evidence underscores the profound impact that AI can have on sustainability initiatives. According to Chen et al. [25], smart manufacturing processes facilitated by AI can decrease energy consumption, waste, and carbon emissions by 30–50%, with similar reductions achievable in energy usage within buildings. In the transportation sector, intelligent systems have been shown to cut carbon

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https://doi.org/10.1016/j.nxsust.2024.100041
Received 9 February 2024; Received in revised form 19 April 2024; Accepted 22 April 2024
Available online 2 May 2024

dioxide emissions by approximately 60%, offering a significant leap toward cleaner urban environments. Moreover, about 70% of the global natural gas industry is now leveraging AI to enhance the accuracy and reliability of weather forecasts, which in turn optimizes resource use and operational planning [25]. Additionally, [109] illustrate how corporate operations have benefited from AI integration, where AI-driven decision-making and prediction tools have notably reduced carbon costs, substantiating the efficacy of AI in corporate sustainability strategies. Di Vaio et al. [34] also reported on how AI could be utilized in developing sustainable business models in agri-food systems, thereby reducing their carbon footprints.

However, the deployment of AI technologies is a double-edged sword. Vinuesa et al. [115] highlight the substantial energy demands and consequent carbon footprint of large computing centers essential for advanced AI research and applications, including cryptocurrency operations like Bitcoin, which alone consumes as much electricity as entire nations. The projected increase in global electricity demand by ICTs to up to 20% by 2030, from about 1% today, emphasizes the critical need for sustainable growth within the ICT sector [115]. Similarly, Nordgren (2022) stresses the importance of ethical considerations, as AI applications, while beneficial, can also lead to significant emissions, necessitating a balanced and thoughtful approach to AI deployment [79].

These insights present a compelling argument for a thorough review of AI's potential in driving net-zero sustainability efforts. By synthesizing current evidence and evaluating both the positive outcomes and the challenges, this review aims to provide a balanced perspective that supports informed decision-making and strategic planning for integrating AI into sustainability initiatives. Such an examination is crucial for ensuring that AI contributes effectively to environmental goals without exacerbating other sustainability challenges.

1.1. Objectives and scope of study

The objectives of this comprehensive narrative review are multi-fold. First, it aims to provide a comprehensive overview of the current state of the relationship between AI and the pursuit of net-zero emissions. It explores the existing literature, research, and developments in this domain, highlighting the key themes, challenges, and opportunities. Second, the review aims to identify and examine the various applications of AI that can contribute to achieving net zero across different sectors. These applications include but are not limited to energy transition and grid optimization, renewable energy integration and forecasting, smart buildings and energy efficiency, intelligent transportation and mobility solutions, sustainable agriculture and land use, waste management, circular economy, and emissions monitoring and tracking.

Furthermore, the review examines the AI-driven solutions and innovations that have been proposed and implemented to address the challenges of climate change. These solutions encompass machine learning for energy optimization, deep learning for climate modeling and prediction, robotics and automation in sustainable practices, natural language processing for policy and decision-making, Internet of Things (IoT) and AI for smart cities, and blockchain and AI for carbon markets.

The scope of this review extends to exploring the challenges and ethical considerations associated with the application of AI in the context of net-zero emissions. It discusses issues related to data availability, quality, and privacy, the energy consumption of AI systems, bias and fairness in AI algorithms, human-centered design, human-AI collaboration, and the governance and regulation of AI in climate applications.

Lastly, the review identifies the opportunities and future directions in leveraging AI for net zero. It emphasizes the importance of collaboration and partnerships, capacity building and education, policy and regulatory support, investment and funding for AI in climate solutions, and scalability and replicability of AI-driven approaches.

By addressing these objectives and exploring the defined scope, this comprehensive narrative review provides a holistic understanding of the nexus between AI and net-zero emissions, shedding light on the current advancements, challenges, and potential pathways for leveraging AI to combat climate change and achieve a sustainable future.

2. Methodology

A comprehensive literature search was conducted to identify relevant articles, research papers, reports, and publications related to the nexus between artificial intelligence (AI) and net zero solutions. The search was performed in academic databases, such as PubMed, IEEE Xplore, ScienceDirect. Articles and publications were selected based on their relevance to the topic and alignment with the specific threads identified for analysis. The inclusion criteria included studies published within the last five years (from 2018 to 2023) to ensure the inclusion of recent developments in the field. The selected articles and publications underwent a quality assessment to ensure the inclusion of reputable sources and reliable information. The assessment considered factors such as the credibility of the authors, the peer-review process, and the relevance and reliability of the data and findings. Relevant data and information from the selected articles and publications were extracted, focusing on the key themes of AI applications for net zero, AI-driven solutions and innovations, challenges and ethical considerations, opportunities for collaboration and partnerships, capacity building and education, policy and regulatory support, investment and funding, and scalability and replicability of AI solutions. The extracted data were analyzed thematically, organizing the information based on the identified threads. Patterns, trends, and key findings were identified across the different thematic areas to provide a comprehensive understanding of the current state of AI and its role in achieving net zero goals. This approach allows us to synthesize a wide array of sources and provide an extensive overview of the current scope and advancements of AI in supporting net-zero sustainability goals. Our methodology is particularly suited for this broad overview because it accommodates diverse types of data and facilitates a deep understanding of complex themes which are essential for comprehending the multifaceted role of AI in environmental sustainability.

2.1. AI as an enabler of sustainable development

Artificial intelligence (AI) has emerged as a key enabler of sustainable development in the context of climate change. AI technologies possess the potential to optimize resource allocation, enhance decision-making processes, and drive efficiency across various sectors, thus enabling a more sustainable and climate-resilient future [10,50,112].

One area where AI plays a crucial role is in optimizing energy systems and reducing greenhouse gas emissions [30]. Machine learning algorithms can analyze energy consumption patterns, identify inefficiencies, and recommend strategies for energy optimization [5]. By optimizing energy generation, distribution, and consumption, AI can contribute to significant reductions in carbon emissions. Additionally, AI-driven algorithms can facilitate the integration of renewable energy sources into existing power grids [60], ensuring a more reliable and efficient transition to low-carbon energy systems [1,4,58].

Furthermore, AI aids in the development of intelligent transportation systems that optimize traffic flow, reduce congestion, and promote the use of low-emission vehicles [2,31,54]. Through real-time data analysis and predictive modeling, AI can enhance transportation planning and logistics, leading to reduced fuel consumption and greenhouse gas emissions. In the context of sustainable agriculture, AI technologies can support precision farming practices. By analyzing soil conditions, weather patterns, and crop data, AI algorithms can optimize irrigation, fertilizer usage, and pest control, thereby reducing water waste, chemical inputs, and environmental impacts [89].

2.2. Climate change mitigation and adaptation

AI contributes to both climate change mitigation and adaptation efforts. In terms of mitigation, AI plays a critical role in enabling renewable energy integration and forecasting [14,15,67,87,88,91]. Machine learning algorithms can analyze weather data, historical energy generation patterns, and other relevant factors to optimize the integration of renewable sources such as solar and wind power into the grid [70]. Accurate forecasting of renewable energy generation helps balance supply and demand, reducing the reliance on fossil fuel-based energy generation [45,95,96].

Moreover, AI can support climate modeling and prediction, providing valuable insights into the impacts of climate change and guiding mitigation strategies [24,27]. Deep learning techniques can analyze vast amounts of climate data to identify trends, assess risks, and inform policymakers and stakeholders about potential future scenarios. This enables proactive decision-making and the development of effective adaptation strategies [23,52]. In terms of climate change adaptation, AI technologies can assist in risk assessment and disaster management. By analyzing historical data and real-time information, AI algorithms can identify areas prone to natural disasters such as floods, wildfires, or hurricanes. This knowledge aids in early warning systems, evacuation planning, and emergency response coordination, enhancing community resilience and reducing the impacts of climate-related events [67,70].

2.3. Net zero: concept and challenges

The concept of net zero refers to achieving a balance between the amount of greenhouse gases emitted into the atmosphere and the amount removed or offset. It entails reducing emissions through various measures and compensating for any remaining emissions through carbon removal or offsetting initiatives. Achieving net zero is crucial to limit global warming and mitigate the impacts of climate change [39]. However, several challenges exist in the pursuit of net zero. One challenge is the complexity of accurately measuring and tracking emissions across various sectors. AI can help address this challenge by developing advanced monitoring systems that analyze data from multiple sources, such as satellite imagery, sensors, and IoT devices [49,106]. AI algorithms can enable real-time emissions tracking, ensuring transparency and accountability in emission reduction efforts [90].

Another challenge is the availability and quality of data required for effective AI-driven climate solutions. Data collection processes and standards need to be established, and data sharing among stakeholders must be encouraged to facilitate the development and training of AI models [53]. Additionally, privacy concerns related to the collection and utilization of personal data need to be addressed to ensure the responsible and ethical use of AI in climate applications. Furthermore, ensuring the fairness and impartiality of AI algorithms is essential. Biases in data or algorithmic decision-making could perpetuate existing inequalities or hinder progress toward achieving equitable and just climate outcomes. Efforts must be made to mitigate bias in AI algorithms and ensure fairness in their application [72,130].

Energy consumption is another challenge associated with AI systems. As AI requires significant computational power, the energy requirements of AI infrastructure and data centers can be substantial [43]. To address this challenge, efforts should focus on developing energy-efficient AI hardware and optimizing algorithms to minimize energy consumption without compromising performance. The use of renewable energy sources to power AI systems can also contribute to reducing their carbon footprint [128].

The scalability and replicability of AI-driven solutions are additional challenges to consider. While many promising AI applications have been developed, scaling them up to a global level and replicating their success across different regions and contexts can be challenging [116]. The availability of resources, expertise, and infrastructure varies, requiring tailored approaches and capacity-building efforts to ensure the widespread adoption of AI in achieving net-zero goals. Ethical considerations also play a crucial role in the application of AI for net zero. The potential unintended consequences of AI-driven decisions, the impact on employment and socioeconomic factors, and the need for transparency and accountability are important ethical dimensions to be addressed [101]. It is crucial to involve diverse stakeholders, including communities, policymakers, and experts, in the design, implementation, and governance of AI systems to ensure that their deployment aligns with societal values and goals.

In summary, the concept of achieving net zero requires addressing several challenges. However, AI has the potential to be a powerful tool in the fight against climate change. Through its application, AI can enable sustainable development, enhance climate change mitigation and adaptation efforts, and contribute to the realization of a net-zero emissions future. To maximize the benefits of AI in addressing climate change, it is essential to address challenges related to data availability and quality, energy consumption, bias and fairness, scalability, and ethical considerations. By doing so, we can harness the full potential of AI to accelerate the transition toward a sustainable and climate-resilient future.

3. AI applications for net zero

Civilization has led to more energy generation across the world leading to an increased generation of greenhouse gases. An energy conservation method (ECM) is an official approach that is commonly used to lower the energy consumption from sectors generating energy leading to the emission of greenhouse gases. The energy conservation method is digitized using modern sensor technology in the form of AI to enhance human activities [77]. This approach helps to achieve a net zero environment and to increase the efficiency, accuracy, and consistency of the measurement and verification protocols for a sustainable environment. The highlights for the applications of AI in achieving net zero is represented in Fig. 1.

3.1. Energy transition and grid optimization

AI applications play a crucial role in facilitating the transition to clean and renewable energy sources while optimizing energy grids for improved efficiency. AI algorithms can analyze energy consumption patterns, weather data, and grid conditions to optimize energy generation, distribution, and storage [41,51]. By predicting demand and supply patterns, AI can enable effective load balancing and grid management, leading to reduced reliance on fossil fuels and enhanced integration of renewable energy sources.

Grid optimization is essential for maintaining grid stability and ensuring a reliable energy supply. AI can help identify potential bottlenecks, predict equipment failures, and optimize the scheduling of energy generation and distribution [18,105]. By dynamically adjusting energy flows and optimizing the operation of distributed energy resources, AI algorithms can enhance the resilience and efficiency of energy grids, enabling the effective integration of intermittent renewable energy sources.

3.2. Renewable energy integration and forecasting

The variability and intermittency of renewable energy sources, such as solar and wind power, present challenges in their integration into existing energy grids. AI offers solutions for accurate renewable energy forecasting and improved integration strategies. AI algorithms can analyze historical and real-time data, including weather patterns, solar radiation, wind speed, and energy generation data, to predict and optimize the production of renewable energy. Accurate forecasting enables grid operators to balance supply and demand, reduce curtailment, and optimize energy storage and distribution [53].

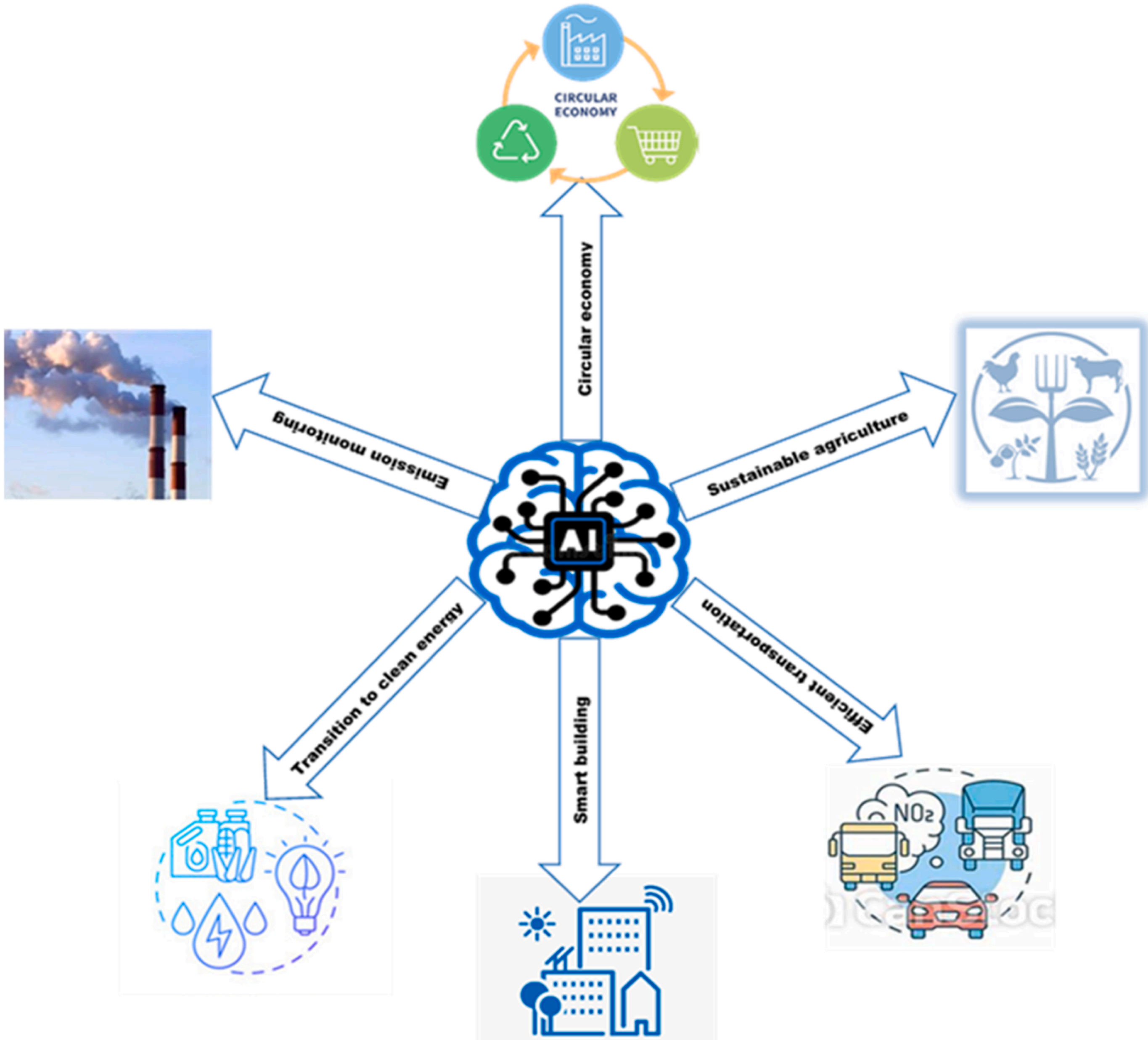

Fig. 1. Highlights of the application of AI in achieving net zero.

Additionally, AI can optimize the placement and operation of renewable energy generation infrastructure. Machine learning algorithms can analyze geographical and topographical data, as well as environmental factors, to identify optimal locations for solar panels, wind turbines, and other renewable energy installations. This optimization helps maximize energy generation while minimizing the environmental impacts and costs associated with renewable energy deployment.

3.3. Smart buildings and energy efficiency

AI plays a significant role in improving energy efficiency in buildings through the concept of smart buildings [3]. AI-powered systems can analyze data from sensors, smart meters, and building management systems to optimize energy consumption, heating, ventilation, air conditioning (HVAC) operations, and lighting control. Machine learning algorithms can learn occupancy patterns, weather conditions, and user preferences to automatically adjust energy usage and ensure optimal comfort while minimizing energy waste [6,40]. Furthermore, AI can facilitate demand response programs by predicting peak energy demand and optimizing energy usage during periods of high demand. By integrating AI with smart grid technologies, buildings can actively participate in load shifting and demand response initiatives, reducing strain on the grid and promoting energy efficiency [26].

3.4. Intelligent transportation and mobility solutions

AI offers innovative solutions for achieving sustainable and efficient transportation systems. Intelligent transportation systems leverage AI technologies to optimize traffic management, reduce congestion, and promote the use of low-emission vehicles [94]. AI algorithms analyze real-time data from sensors, cameras, and traffic patterns to optimize traffic signal timings, route planning, and congestion management. In addition, AI-enabled algorithms can provide personalized travel recommendations, optimizing transportation modes and routes based on individual preferences, traffic conditions, and environmental factors.

This encourages the use of public transportation, shared mobility services, and active modes of transportation, reducing greenhouse gas emissions from the transportation sector [114].

Moreover, AI applications can support the development and operation of autonomous vehicles. AI algorithms enable vehicles to navigate, sense their surroundings, and make informed decisions, improving fuel efficiency, reducing traffic accidents, and enhancing overall transportation efficiency [19,80].

3.5. Sustainable agriculture and land use

AI applications are transforming agriculture and land use practices to promote sustainability and mitigate the environmental impacts of farming [111]. AI algorithms can analyze soil data, weather patterns, crop characteristics, and historical yield data to optimize irrigation, fertilizer usage, and pest control [17,69]. By providing precise recommendations, AI empowers farmers to adopt precision agriculture techniques, minimizing resource waste and environmental pollution while maximizing crop yields [89].

Furthermore, AI can support land use planning and management by analyzing satellite imagery, geospatial data, and ecological indicators [38]. Machine learning algorithms can identify patterns and classify land use types, aiding in the conservation and restoration of ecosystems, protection of biodiversity, and sustainable land management practices [63]. This enables stakeholders to make informed decisions regarding land use, ensuring the preservation of natural resources and reducing the environmental footprint of agricultural activities.

3.6. Waste management and circular economy

AI applications are revolutionizing waste management practices and promoting the transition to a circular economy. AI algorithms can optimize waste collection routes, reducing fuel consumption and greenhouse gas emissions from waste management vehicles [122]. By analyzing historical data and real-time inputs, AI systems can predict waste generation patterns, enabling proactive planning and resource allocation for waste collection and processing [56].

Additionally, AI can facilitate waste sorting and recycling processes. Advanced image recognition algorithms can accurately identify and sort different types of recyclable materials, enhancing recycling efficiency and reducing contamination [28,127]. AI-driven robotics and automation systems can improve waste processing operations, enabling the extraction of valuable materials from waste streams, and promoting a more circular approach to resource utilization. Moreover, AI-powered platforms and marketplaces can connect waste generators with potential users of recycled materials, facilitating the exchange and repurposing of waste products. By promoting resource recovery and reducing waste generation, AI contributes to the development of a more sustainable and circular economy [73].

3.7. Emissions monitoring and tracking

Accurate monitoring and tracking of greenhouse gas emissions are essential for effective climate change mitigation strategies. AI plays a vital role in improving the accuracy and efficiency of emissions monitoring systems [107]. AI algorithms can analyze data from various sources, including remote sensing technologies, IoT devices, and industrial processes, to monitor emissions in real-time and detect anomalies [49,106].

AI-powered emissions monitoring systems can identify emission hotspots, track changes in emissions over time, and assess the effectiveness of emission reduction measures. This information enables policymakers, industries, and stakeholders to make data-driven decisions and implement targeted interventions to reduce emissions.

Furthermore, AI applications can support carbon accounting and reporting processes [74]. By analyzing data from diverse sources, including energy consumption, transportation, and production processes, AI algorithms can estimate and report carbon footprints at individual, organizational, or city-wide scales. This enables the identification of emission reduction opportunities and the monitoring of progress toward net-zero targets [32,81].

AI applications have significant potential to contribute to achieving net zero emissions across various sectors. From optimizing energy grids and integrating renewable energy sources to promoting energy efficiency in buildings and transforming transportation systems, AI offers innovative solutions for sustainable development. Additionally, AI facilitates sustainable agriculture, waste management, and emissions monitoring, supporting the transition to a low-carbon and circular economy. By harnessing the power of AI, we can advance climate change mitigation and adaptation efforts, paving the way toward a sustainable and net-zero future.

4. AI-driven solutions and innovations

In recent times, most selected policy initiatives are driven by innovations from AI solutions characterized by the fast and efficient mode of handling a large volume of data through algorithms. Compared to the measurement and forecasting of the effects of climate change by practitioners and analysts, AI-driven innovations as presented dynamic explanations and conclusions through a minimalistic, object-oriented, and functional representation [82,124]. Fig. 2 represents the summary of AI-driven solutions and innovations.

4.1. Machine learning for energy optimization

Machine learning techniques are increasingly being employed to optimize energy systems and improve energy efficiency. These AI-driven solutions analyze vast amounts of data related to energy consumption, weather patterns, and grid conditions to identify patterns and optimize energy generation, distribution, and consumption [7,83]. For instance, machine learning algorithms can analyze historical energy consumption data from buildings and predict future demand patterns. This enables the implementation of demand response strategies, where energy usage is adjusted based on real-time pricing or grid. conditions, resulting in reduced energy costs and improved grid stability [61].

Machine learning also plays a critical role in optimizing renewable energy integration. By analyzing weather data, energy production patterns, and grid conditions, algorithms can predict renewable energy generation and optimize its integration into the grid. This facilitates the efficient utilization of renewable sources and reduces the reliance on fossil fuels. Furthermore, machine learning can optimize energy storage systems by predicting energy demand and supply, ensuring that energy is stored and released when most needed. This improves the overall efficiency of energy storage technologies, such as batteries, and enhances the resilience of the energy system [20].

4.2. Deep learning for climate modeling and prediction

Deep learning, a subset of machine learning, has shown remarkable potential in climate modeling and prediction. Deep neural networks can analyze large and complex climate datasets, including historical climate records, satellite imagery, and climate model simulations, to identify patterns, make accurate predictions, and simulate future climate scenarios [38].

Deep learning models can capture intricate relationships and nonlinearities in climate data, enabling more accurate projections of climate variables such as temperature, precipitation, and sea-level rise [13]. These models enhance our understanding of climate dynamics and aid in the development of climate change mitigation and adaptation strategies. Additionally, deep learning algorithms can analyze climate model outputs and observational data to improve climate model performance and reduce uncertainties. This iterative process of model evaluation and

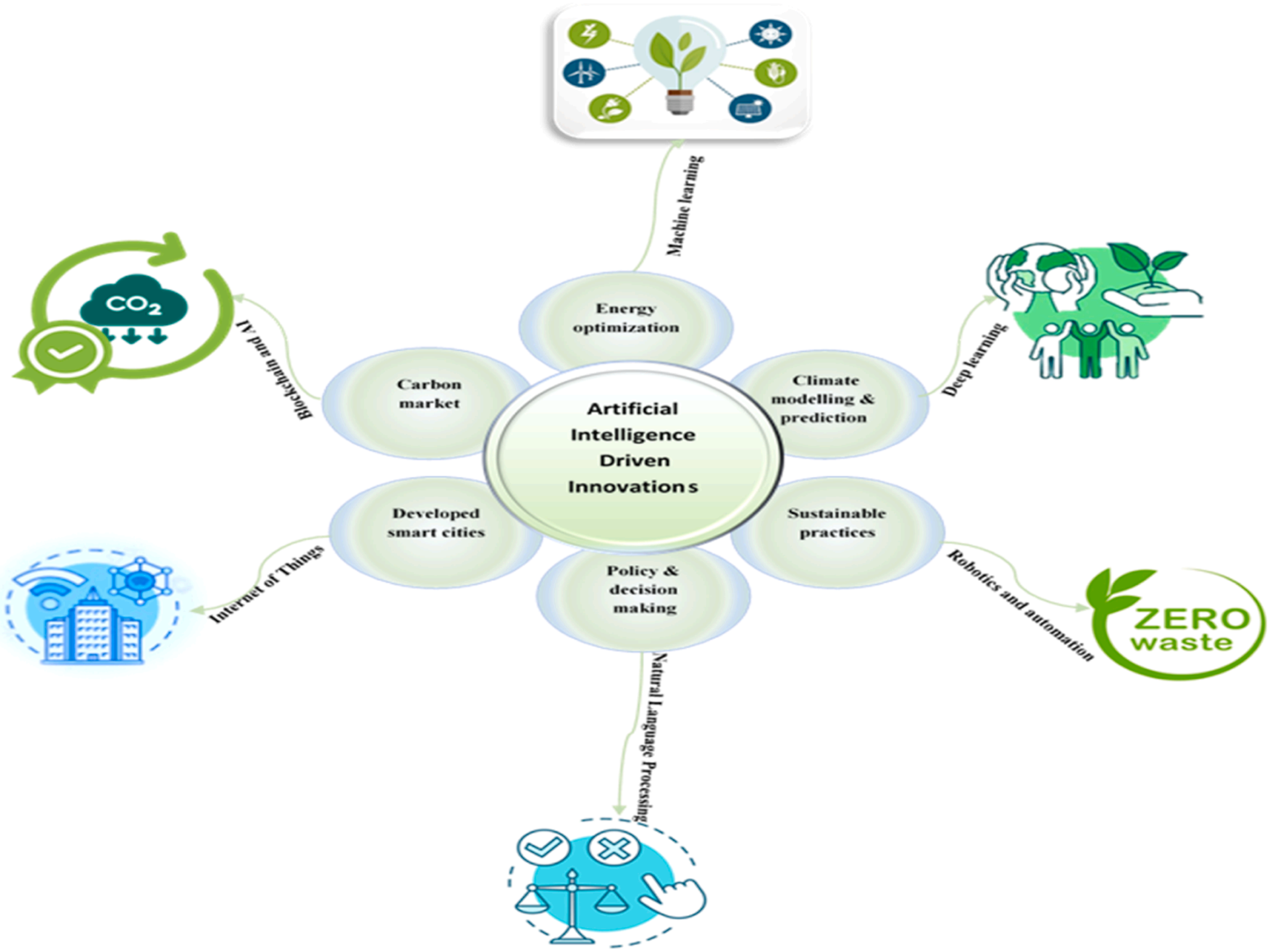

Fig. 2. Summary of AI-driven solutions and innovations in achieving net zero.

refinement helps refine climate projections and enhance the reliability of climate change impact assessments [9].

4.3. Robotics and automation in sustainable practices

Robotics and automation technologies, powered by AI, are transforming various sustainable practices across sectors. In manufacturing and industry, AI-driven robots can optimize production processes, reduce energy consumption, and minimize waste generation. Robots equipped with sensors and AI algorithms can identify anomalies, optimize resource usage, and perform tasks with precision, leading to improved efficiency and reduced environmental impact [33].

In agriculture, robotics and automation contribute to sustainable farming practices. AI-powered robots can perform tasks such as precision seeding, selective harvesting, and targeted pesticide application, reducing the need for chemical inputs and minimizing soil erosion [64]. Robotic systems can also monitor plant health, optimize irrigation, and manage crops individually, leading to improved resource efficiency and higher yields. Furthermore, in waste management, robotics, and automation technologies aid in waste sorting, recycling, and disposal. AI-driven robots can accurately identify and separate recyclable materials, improving recycling efficiency and reducing contamination. Robotic systems can also handle hazardous waste materials, ensuring worker safety and minimizing environmental risks [28,127].

4.4. Natural language processing for policy and decision-making

Natural Language Processing (NLP) techniques enable computers to understand and process human language, facilitating policy and decision-making processes related to sustainability and climate change. NLP algorithms can analyze large volumes of textual data, including scientific literature, policy documents, and social media conversations, to extract relevant information, identify trends, and inform decision-making [71]. NLP-based sentiment analysis helps understand public opinion and perceptions regarding sustainability issues, enabling policymakers to gauge public support and design effective communication strategies. NLP can also assist in policy analysis by extracting key policy insights from legal and regulatory documents, aiding in the development of evidence-based policies and frameworks [47].

Moreover, NLP-powered chatbots and virtual assistants provide interactive platforms for disseminating information, answering queries, and engaging with the public on sustainability and climate-related topics [47,71]. These conversational agents can educate and raise awareness, empowering individuals to make informed choices and contribute to sustainable practices.

Furthermore, NLP techniques support the analysis of stakeholder feedback and engagement. By analyzing public discourse and social media conversations, NLP algorithms can identify emerging issues, concerns, and priorities related to sustainability. This helps policymakers and organizations understand public sentiment, incorporate diverse perspectives, and develop more inclusive and effective policies and strategies.

4.5. Internet of things (IoT) and AI for smart cities

The combination of the Internet of Things (IoT) and AI is driving the development of smart cities, where interconnected devices and AI algorithms enable efficient resource management, improved infrastructure, and enhanced quality of life. In smart cities, IoT sensors and devices collect real-time data on energy consumption, air quality, traffic patterns, and waste management. AI algorithms process and analyze this data to optimize energy usage, reduce pollution, and improve urban mobility [85]. For example, AI can analyze traffic patterns and adjust traffic signal timings in real-time real time, leading to reduced congestion and emissions.

AI-powered smart grid systems, integrated with IoT devices, enable efficient energy management in buildings and infrastructure. Real-time energy monitoring, predictive maintenance, and demand response systems optimize energy consumption, reduce costs, and enhance grid reliability. Moreover, AI and IoT facilitate the development of intelligent and sustainable transportation systems [113]. Connected vehicles, supported by AI algorithms, enable real-time traffic monitoring, efficient route planning, and personalized transportation services. This reduces traffic congestion, lowers emissions, and promotes the use of public transportation and shared mobility options efficiency [19,80].

4.6. Blockchain and AI for carbon markets

The integration of blockchain technology and AI has the potential to transform carbon markets and enhance transparency, accountability, and efficiency in tracking and trading carbon credits. Blockchain technology provides a decentralized and immutable ledger that securely records transactions and carbon emissions data. AI algorithms can analyze this data, validate emissions reductions, and ensure the integrity of carbon credits [55,93]. By combining AI with blockchain, the process of monitoring, reporting, and verifying carbon emissions becomes more streamlined and trustworthy. AI-driven algorithms can automate the calculation of carbon footprints, allowing businesses and organizations to measure their emissions accurately [110]. This enables the creation of reliable and transparent carbon credits, which can be traded in carbon markets.

Additionally, AI and blockchain can enhance the monitoring and tracking of emissions throughout supply chains. By integrating IoT devices and sensors, data on energy usage, transportation, and production processes can be collected and securely recorded on the blockchain [42,59]. AI algorithms can analyze this data, identify inefficiencies, and provide recommendations for emission reductions, enabling organizations to make data-driven decisions and improve sustainability performance [118].

Furthermore, the combination of blockchain and AI can facilitate the creation of decentralized and peer-to-peer carbon trading platforms. Smart contracts, powered by blockchain technology, can automate the trading and verification of carbon credits, ensuring transparency and reducing transaction costs [117]. In summary, AI-driven solutions and innovations are revolutionizing various aspects of sustainable development and climate change mitigation. From optimizing energy systems and enabling climate modeling to enhance automation in sustainable practices and supporting policymaking, AI is driving transformative change. When combined with technologies like IoT, blockchain, and NLP, AI unlocks new possibilities for achieving net-zero emissions, promoting sustainable practices, and building a resilient future.

5. Challenges and ethical considerations

The widespread adoption of AI technologies for addressing climate change and achieving sustainable goals brings forth several challenges and ethical considerations. It is crucial to acknowledge and address these challenges to ensure the responsible and equitable deployment of AI in climate applications [102,120].

5.1. Data availability, quality, and privacy

One of the key challenges in leveraging AI for climate-related tasks is the availability and quality of data. AI algorithms heavily rely on large datasets for training and validation. However, in the context of climate change, obtaining comprehensive and reliable data can be challenging. Climate-related data is often incomplete, fragmented, or limited in scope, making it difficult to train accurate and robust AI models [35]. Moreover, ensuring data privacy and protection is crucial when dealing with sensitive environmental and personal information. Proper measures must be in place to safeguard data from unauthorized access, manipulation, or misuse [108]. Striking a balance between data availability for AI applications and protecting individual privacy is a significant ethical consideration that requires careful attention.

5.2. Energy consumption of AI systems

AI systems, particularly deep learning models, are computationally intensive and often require substantial computing resources. The energy consumption associated with training and deploying AI models raises concerns about its environmental impact. As the demand for AI applications grows, it is essential to develop energy-efficient algorithms and hardware solutions to mitigate the carbon footprint of AI systems [37,68]. Furthermore, organizations and researchers must explore renewable energy sources and adopt sustainable practices in their data centers and computing infrastructure to minimize the environmental impact of AI-driven solutions.

5.3. Bias and fairness in AI algorithms

AI algorithms are susceptible to bias, which can perpetuate and amplify existing inequalities. Biased training data, lack of diversity in the development teams, and algorithmic decision-making processes can lead to discriminatory outcomes and exacerbate social and environmental disparities [75,130]. Ensuring fairness, transparency, and accountability in AI algorithms is a critical ethical consideration. Rigorous testing and validation processes, diverse and representative training data, and continuous monitoring are necessary to detect and mitigate biases in AI systems. Moreover, promoting diversity and inclusivity in AI development teams can help address biases and improve the fairness of AI applications [84].

5.4. Human-centered design and human-AI collaboration

AI technologies should be designed with a human-centered approach, keeping human values, needs, and preferences at the forefront. It is essential to involve stakeholders, including communities, policymakers, and experts, in the design, development, and deployment of AI solutions for climate applications [12,98]. Human-AI collaboration is crucial for effective decision-making and accountability. AI systems should be designed to augment human capabilities, providing meaningful insights and recommendations that empower individuals and communities to make informed decisions. Transparent communication and explainability of AI algorithms are necessary to ensure that humans can understand and interpret AI-generated results [97].

5.5. Governance and regulation of AI in climate applications

As AI becomes increasingly integrated into climate applications, robust governance frameworks and regulations are necessary to address ethical, legal, and social implications. Clear guidelines are needed to ensure the responsible use of AI, including the collection and use of data, transparency in algorithmic decision-making, and accountability for the impacts of AI systems [21,119]. International collaboration is essential to establish global standards and norms for the development and deployment of AI in climate applications [36]. Multidisciplinary efforts involving policymakers, scientists, technologists, and civil society are required to develop governance mechanisms that foster innovation while safeguarding against potential risks and unintended consequences.

Ethical considerations, such as transparency, accountability, fairness, and privacy, should be embedded in the development and deployment of AI technologies for climate change mitigation and adaptation. By addressing these challenges and adopting responsible practices, we can harness the full potential of AI while ensuring a sustainable and equitable future for all [75,84,97,130].

6. Opportunities and future directions

The integration of AI into climate solutions opens up significant opportunities for advancing sustainable development and combating climate change. As AI technologies continue to evolve, several key areas present opportunities for further exploration and development.

6.1. Collaboration and partnerships

Collaboration and partnerships across various sectors are essential for leveraging the full potential of AI in addressing climate challenges. Collaboration between academia, industry, governments, and civil society can foster knowledge sharing, data exchange, and joint research efforts [92,104]. By working together, stakeholders can pool their expertise and resources to develop innovative AI-driven solutions that have a broader impact. Public-private partnerships can also play a crucial role in accelerating the deployment of AI technologies for climate applications. Collaboration between technology companies, startups, and government agencies can facilitate the development of scalable and sustainable AI solutions, ensuring their effective implementation across different sectors and regions [86].

An emerging trend in collaboration is the formation of multi-stakeholder platforms and consortia focused on AI and climate change. These platforms bring together diverse stakeholders, including researchers, policymakers, industry leaders, and NGOs, to share best practices, collaborate on research projects, and foster innovation. Such collaborations enable a holistic and integrated approach to addressing climate challenges using AI technologies [22,121].

6.2. Capacity building and education

Building capacity and promoting education on AI for climate applications are vital for unlocking its full potential. Training programs, workshops, and educational initiatives should be developed to equip individuals, organizations, and communities with the necessary skills and knowledge to understand, develop, and deploy AI solutions [62]. Capacity-building efforts should focus on diverse stakeholders, including policymakers, scientists, engineers, and practitioners, to foster a multidisciplinary approach. By enhancing AI literacy and technical skills, stakeholders can effectively leverage AI tools and technologies for climate change mitigation and adaptation [67].

In recent years, there has been a growing emphasis on AI education and training programs specifically tailored to climate applications. Universities and research institutions are offering specialized courses and programs that combine AI, data science, and climate science. These initiatives aim to bridge the gap between domain expertise and AI skills, enabling professionals to apply AI techniques in the context of climate change.

6.3. Policy and regulatory support

Clear policy frameworks and supportive regulations are crucial to promote the responsible and ethical deployment of AI in climate solutions. Governments and international organizations can play a pivotal role in shaping policies that encourage innovation, data sharing, and collaboration while safeguarding against potential risks and ensuring fairness. Policy initiatives should focus on data governance, privacy protection, algorithmic transparency, and standards for AI in climate applications [75,84,97,129]. By providing a conducive regulatory environment, policymakers can stimulate investment, encourage research and development, and foster the adoption of AI technologies for sustainable development.

Recent trends indicate an increasing recognition of the need for policy and regulatory support for AI in climate applications. Governments are establishing dedicated task forces, committees, or regulatory bodies to develop guidelines and frameworks specifically addressing the intersection of AI and climate change [29]. These initiatives aim to create a balance between encouraging innovation and ensuring the responsible and ethical use of AI in tackling climate challenges.

6.4. Investment and funding for AI in climate solutions

Significant investment and funding are required to accelerate the development and deployment of AI technologies for climate solutions [44]. Governments, philanthropic organizations, and private investors should allocate resources to support research, development, and implementation of AI-driven initiatives. Investment in AI for climate applications can yield significant returns by unlocking cost savings, driving innovation, and achieving sustainable outcomes. Funding should prioritize projects that demonstrate scalability, feasibility, and clear potential for impact. Additionally, public-private partnerships and financing mechanisms should be established to facilitate access to funding for startups, small and medium-sized enterprises (SMEs), and developing countries.

Recent trends indicate a growing interest from investors and funding agencies in supporting AI-driven climate solutions. Impact investment funds and venture capital firms are specifically focusing on investing in AI startups and initiatives that address climate challenges [65]. Governments are also launching funding programs and grants dedicated to AI in climate solutions. These funding opportunities aim to attract innovative projects and provide the necessary resources for their development and implementation. Furthermore, there is an increasing trend of corporate sustainability commitments and initiatives that involve investment in AI for climate solutions. Companies are recognizing the value of AI in achieving their environmental goals and are allocating funds to support AI-driven projects that contribute to carbon reduction, energy efficiency, and sustainable practices [103].

6.5. Scalability and replicability of AI solutions

To maximize the impact of AI in addressing climate change, it is essential to focus on the scalability and replicability of AI solutions. AI models, algorithms, and frameworks should be designed to be adaptable to different contexts, sectors, and regions [125]. Efforts should be made to develop open-source AI tools and platforms, allowing for knowledge sharing and collaboration. This promotes the widespread adoption of AI technologies and facilitates the replication of successful solutions in diverse settings.

The advancement of cloud computing and edge computing technologies is contributing to the scalability and replicability of AI solutions [123]. Cloud-based platforms enable the deployment of AI models and algorithms at scale, making them accessible to a wide range of users. Edge computing brings AI capabilities closer to the data source, allowing for real-time analysis and decision-making in remote or resource-constrained environments [11]. Moreover, the concept of AI marketplaces and ecosystems is gaining traction. These platforms provide a marketplace for AI models, algorithms, and data, allowing organizations to access and utilize pre-trained models or collaborate with AI experts. By leveraging AI marketplaces, organizations can scale their AI solutions more efficiently and tap into a global network of expertise [99].

In conclusion, the opportunities and future directions for AI in climate solutions revolve around collaboration and partnerships, capacity building and education, policy and regulatory support, investment and funding, and scalability and replicability. These trends reflect a growing recognition of the potential of AI to address climate challenges and the need for collaborative efforts from diverse stakeholders to harness its full potential. By capitalizing on these opportunities and addressing associated challenges, we can accelerate the development and deployment of AI-driven solutions to achieve a sustainable and resilient future [59].

7. Conclusion

As the urgency to tackle climate change intensifies, the integration of artificial intelligence (AI) offers transformative potential across multiple spheres of society. For individuals, especially at the household level, AI technologies provide powerful tools to monitor and manage the consumption of critical resources such as water, energy, and electricity. Smart home devices, for instance, can learn patterns of usage and optimize heating, cooling, and water usage to significantly reduce waste and environmental impact.

Corporations, on the other hand, can leverage AI to enhance operational efficiency and sustainability. An example is the use of AI in supply chain management, where algorithms predict demand more accurately, optimize routes for logistics, and reduce energy usage and emissions. This not only cuts costs but also aligns corporate operations with broader environmental goals, promoting a shift towards sustainability that benefits both the business and the planet.

At the governmental and industrial level, AI tools are indispensable in the optimization of energy systems, management of waste, and efficient utilization of resources. By implementing AI-driven analytics to monitor and control public utilities and services, governments can ensure that cities operate more sustainably, thereby reducing the carbon footprint of urban centers. Moreover, AI can facilitate the development of green infrastructure by providing insights that help in planning and executing projects with minimal environmental impact.

However, the expansive deployment of AI across these domains is not without risks. The significant energy consumption associated with advanced AI systems and the burgeoning field of digital currencies like Bitcoin can paradoxically contribute to the very problem AI seeks to solve. It is crucial, therefore, that this deployment is accompanied by stringent oversight to prevent such unintended consequences. Regulatory bodies play a critical role here, necessitating the establishment of frameworks that monitor the environmental impact of AI technologies and ensure they contribute positively to net-zero goals.

Governments should consider creating specialized departments focused on AI and sustainability to oversee these developments. Similarly, companies should invest in training or hiring AI sustainability specialists who can guide the ethical and efficient use of AI in operations. This proactive approach will not only harness the benefits of AI for climate action but also mitigate risks, ensuring that we remain on the right side of history.

In conclusion, while AI holds exceptional promise for advancing net-zero objectives, its application must be carefully managed to truly benefit the planet. By fostering collaboration among individuals, corporations, and governments and ensuring robust regulatory oversight, we can leverage AI to achieve a sustainable future, marking a significant step forward in the global fight against climate change.

8. Recommendations

Looking ahead, there are several implications for future research in the field of AI and net-zero solutions:

(a) Further research is needed to advance the development of AI algorithms, models, and frameworks specifically tailored to address climate challenges. This includes improving the accuracy and reliability of climate modeling, optimizing energy systems, enhancing prediction, and forecasting capabilities, and integrating AI with other emerging technologies such as IoT and blockchain.
(b) Ethical considerations in AI for climate solutions require ongoing attention and research. Efforts should focus on addressing biases, ensuring algorithmic transparency, promoting fairness and equity, and developing robust governance frameworks to guide the responsible deployment of AI in climate applications.
(c) The impact of AI on energy consumption and carbon footprint needs to be carefully studied. Research should explore ways to optimize AI systems to minimize their energy requirements and develop energy-efficient AI algorithms and hardware.
(d) Long-term monitoring and evaluation of AI-driven climate solutions are crucial to assess their effectiveness, identify areas for improvement, and drive continuous innovation. Research should focus on developing metrics and indicators to measure the impact and sustainability of AI applications in achieving net-zero targets.
(e) International collaboration and knowledge sharing should be fostered to address global climate challenges. Future research should focus on promoting data sharing, interoperability of AI systems, and best practices for AI implementation in different regions and contexts.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data generated or analyzed during this study are included in this published article and would be available upon request.

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