The crucial role of artificial intelligence in addressing climate change

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ABSTRACT

Addressing climate change is one of the fundamental priorities at a global level, given its significant impact on both the environment and society. This systematic literature review explores the role of artificial intelligence (AI) in addressing climate change. It identified applications, contributions to predicting extreme events, techniques used, ethical challenges, and associated biases. The rapid systematic literature review (RSL) was conducted using databases such as Scopus, Dimensions, directory of open access journals (DOAJ), and IEEE Xplore. The preferred reporting items for systematic reviews and meta-analyses (PRISMA) statement was used to ensure the completeness and transparency of the analysis. 40 articles were selected that were published between 2018 and 2023 and addressed AI in climate change. The findings show that AI is being used to predict and mitigate extreme climate events, estimate the greenhouse effect, and predict temperatures. In addition, innovative techniques such as hybrid machine learning models, convolutional neural networks, artificial neural networks, support vector machines, and logistic regression. In conclusion, AI offers a promising approach to addressing climate change, with transformative potential in predicting and mitigating its effects. However, continuous ethical considerations are required to guarantee its conscientious and efficient utilization.

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1. INTRODUCTION

Climate change stands out as one of the most urgent challenges in our era, carrying significant implications for the ecological equilibrium and sustainability of the planet. It has become a paramount challenge confronting humanity [1], [2]. Human activities and accelerated industrialization have triggered serious reactions in the ecosystem, with significant impacts on its basic elements: soil, air, and water [3]. Furthermore, increasing greenhouse gas emissions, loss of biodiversity, and extreme weather events threaten the natural environment and the stability of societies around the world. Aware of this crisis, it is imperative to address these problems more effectively and wisely, using technology to develop solutions that mitigate and reverse environmental impacts [4].

In this context, the importance of artificial intelligence (AI) has reached significant levels, as it has the potential to change the rules of the game in addressing the global challenge of climate change that threatens humanity and promotes sustainable development [5]. The prevailing need to use AI tools is based on understanding the meaning behind the increasing flow of data and adapting to the growing demands of climate change monitoring [6]. Furthermore, global challenges are now being addressed through the use of digital technologies such as data analytics and AI implementation [7], [8]. However, the underlying problem is how to fully harness the potential of AI to effectively combat climate change. As the consequences of global warming become more apparent, it is crucial to evaluate how AI can play a critical role in the fight against climate change. In addition, in recent decades, progress in machine learning algorithms, the accessibility of extensive environmental datasets, and improvements in computing power have transformed the role of AI in climate modeling, predicting extreme events, and optimizing adaptation strategies. This change has created the need to identify and evaluate the most significant contributions of AI in critical areas such as natural resource management, emissions reduction, environmental monitoring, and the ethics of its use.

This study presents a systematic literature review (SLR) focusing on the contribution of AI to climate change mitigation. Specifically, the study comprehensively and critically examines the existing knowledge on how AI is being applied in climate change mitigation. The review analyzes various applications and algorithms of this technology, ranging from energy efficiency optimization to weather forecasting. The main objective of this SLR is to provide a comprehensive and up-to-date perspective on the involvement of AI in the field of climate change. Specifically, it seeks to identify AI applications that play a transformative role in climate change mitigation and adaptation. It also aims to identify how AI contributes to the prediction of climate events and to examine the techniques, ethical considerations, and biases associated with its use in this crucial field.

By providing a deeper understanding of the role of AI in addressing climate change, this review aims to consolidate current knowledge and provide solid guidance for future research and informed public policymaking. In a context where environmental sustainability is increasingly imperative, this consolidation of knowledge is essential to contributing to the global effort to preserve the planet for future generations. Finally, it is hoped that this review will provide clarity and guidance to other researchers interested in this area of study [9].

2. METHOD

2.1. Research questions

The SRL on the role of AI in addressing the climate emergency is based on a set of key questions that guided the research. These questions are designed to accurately and comprehensively address the scope and relevance of AI in endeavors to mitigate and adapt to climate change. These questions are presented in a brief and concise manner [10] to provide a clear and accessible structure for the analysis and synthesis of the information collected Table 1.

Table 1. Research questions

Id	Questions
RQ1	What are the most significant advances in the application of AI to address climate change?
RQ2	How has AI contributed to improving the accuracy and anticipation of extreme weather events, such as droughts, floods, and snowmelt related to climate change?
RQ3	What AI techniques have existing research proposed to mitigate climate change?
RQ4	What are the ethical challenges and biases associated with using AI to mitigate climate change?

2.2. Selection of the information source

Four renowned data sources were chosen to locate the necessary articles: IEEE Xplore, the directory of open access journals (DOAJ), Dimensions, and Scopus. This strategic approach was taken with the aim of covering all relevant literature and providing a comprehensive overview of research efforts in this area [11]. This systematic search method guarantees broad and diverse coverage, thus facilitating an exhaustive review of the available scientific literature on the selected topic. The inclusion of these recognized sources ensures the quality and reliability of the data collected for the study.

2.3. Search strategy

The search strategy for this review was based on clearly defined search strings and selection and eligibility criteria. Specific keywords and boolean operators were used to comprehensively search selected relevant academic databases [12]. The rigorous application of inclusion and exclusion criteria ensured the selection of relevant and high-quality studies, thus ensuring the robustness and consistency of the information collected. This sound methodological approach contributed to the reliability and objectivity of the review process.

2.3.1. Search string

The study search string was constructed using a combination of keywords and the boolean operators "AND" and "OR" [12]. This allowed for an exhaustive search of relevant literature in academic databases.

Figure 1 shows the use of different terms to identify relevant studies related to the intersection of AI and climate change mitigation. In the Scopus database, the search was conducted using titles, abstracts, and keywords, while in Dimensions, the search was limited to titles and abstracts. On the other hand, in IEEE Xplore and DOAJ, the search was carried out only by title. This search strategy ensured the collection of studies that satisfied the systematic review's inclusion criteria.

("artificial intelligence" OR "machine learning" OR "deep learning") AND ("climatic change" OR "global galantamine" OR "Environmental Sustainability" OR "emergency climatic")

Figure 1. Main search string

2.3.2. Selection and eligibility criteria

Inclusion criterion: open-access scientific articles published in English in journals between January 2018 and October 2023 were included. Quantitative or qualitative research that examined the application of AI in various areas, such as emissions reduction, natural resource management, and prediction of extreme weather events, among others. Exclusion criterion: non-academic reports, blogs, news stories, and other materials that were not peer-reviewed or lacked scientific rigor were excluded. Also excluded were studies that did not directly address the use of AI in climate change mitigation or adaptation, studies that did not provide detailed information about their methodology, or studies that lacked relevant data for critical evaluation. In addition, repeated or duplicate studies were excluded, as well as those that were not available in their entirety or in their full version. Finally, studies published before January 2018 were excluded. These criteria were rigorously applied during the study selection process to ensure the quality and relevance of the review.

2.3.3. Conducting review process

The review process was conducted in accordance with the preferred reporting items for systematic reviews and meta-analyses (PRISMA) 2020 statement, as shown in Figure 2. An exhaustive search of academic databases was performed to gather relevant literature. Inclusion and exclusion criteria were applied, data were extracted, methodological quality was assessed, and results were presented coherently and transparently. This ensured a high-quality systematic review of the contribution of AI in combating climate change.

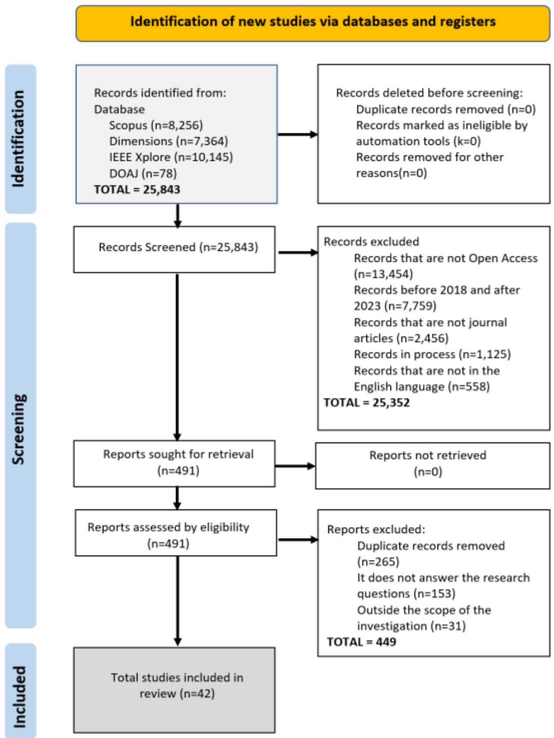

Figure 2. PRISMA 2020 flow diagram of the study

Initially, the search string defined in each of the databases was applied, which resulted in the identification of a total of 25,843 articles. Subsequently, the automatic filters available in the databases were used in the screening process, which allowed a total of 25,352 articles to be excluded according to the inclusion and exclusion criteria. These criteria included the exclusion of articles that were not available in open access, published before 2018 or after 2023, not from journals, in the process of publication, and written in languages different from English. After applying these filters, a total of 491 articles were obtained. These articles were imported into Mendeley, a bibliographic manager, where duplicates were removed. Subsequently, the titles and abstracts were reviewed to exclude articles that did not answer the research questions or were outside the scope of the research. Finally, 42 articles were selected to be included in the review.

3. RESULTS

This section explores and analyzes in depth the fundamental research questions that guide the study. Each question is addressed in detail, breaking down its relevant aspects and providing a thorough analysis. This detailed examination allows for a comprehensive understanding of the topic, ensuring that all critical dimensions are thoroughly covered and explained.

3.1. RQ1: What are the most significant advances in the application of AI to address climate change?

The application of AI in the fight against climate change covers several areas, as demonstrated by various studies. These include significant contributions to the understanding and prediction of climate change based on the analysis of greenhouse gas emissions [13]. Also noteworthy is the improvement in the estimation of reference evapotranspiration, which contributes to more accurate environmental modeling [14]. The application of AI also extends to the field of forest management, providing predictions of tree growth to optimize forestry practices [15]. This encompasses the capacity to forecast tree growth amidst present and anticipated climatic circumstances, providing valuable predictive tools for sustainable forest management. In addition, the effective classification of wetlands is highlighted to address the loss of these critical ecosystems, highlighting the usefulness of the technology in environmental conservation in the context of climate change [16], [17].

AI also plays a crucial role in estimating greenhouse gas emissions, providing essential information for decision-making in environmental mitigation policies [18], and not only drives effective measures to combat climate change but also highlights the relevance of AI in the transition to more sustainable business practices [19]. It also highlights the contribution of AI in assessing the impact of climate change on water resources, a crucial aspect of the sustainable management of this fundamental resource [20]. Likewise, the predictive capacity of AI is used to estimate the future production of photovoltaic systems, thus strengthening the tools for assessing renewable energy in light of the phenomenon of climate change [21].

In addition, the application of AI in rainfall forecasting, as mentioned in [22], is demonstrating its usefulness for governmental and non-governmental entities as well as businesses in formulating strategic decisions and undertaking long-range planning across diverse sectors. Furthermore, the ability of AI to predict temperature changes on a global scale, as highlighted in [23], translates into a critical tool for climate prediction and planning adaptation strategies in various sectors. Similarly, AI-based flood detection highlights the technology's ability to efficiently manage natural disasters by providing advanced solutions for flood prediction and rapid response [24]. Exploring spatiotemporal variations in precipitation with AI provides valuable information for water resource management [25], enabling effective adaptation to climate change. Drought prediction using AI not only aims to improve the accuracy of predicting drought events but also suggests the potential of AI to strengthen predictive capabilities in extreme climate situations [26].

In summary, Figure 3 shows the diversity of applications of AI in climate change mitigation, highlighting its essential role in different areas. From climate forecasting to drought prediction, AI stands out for its ability to understand and predict weather patterns, allowing for more accurate management of natural resources. The use of AI to predict forest growth and wetland management demonstrates its versatility in preserving ecosystems and making environmental decisions to counteract climate change. In addition, the use of AI to estimate greenhouse gas emissions and predict hydrological responses contributes to mitigation and adaptation strategies. Similarly, the analysis of precipitation variability and the proposal of an innovative approach to drought forecasting expand the range of applications of AI in the management of water resources and extreme climate events. These applications highlight the importance of AI as a comprehensive tool to address the challenges of climate change, providing valuable insights and supporting informed decision-making in environmental management.

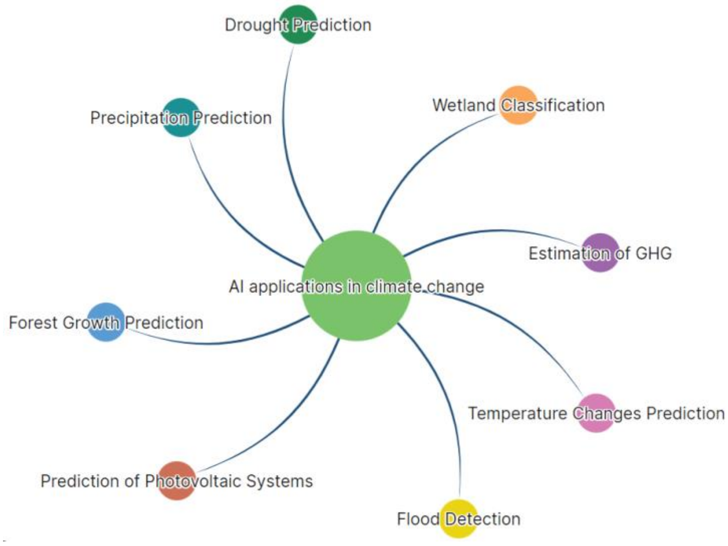

Figure 3. AI applications identified to address climate change

3.2. RQ2: How has AI contributed to improving the accuracy and anticipation of extreme weather events, such as droughts, floods, and snowmelt related to climate change?

In the complex scenario of climate change, AI has emerged as an essential tool to improve our ability to predict and understand extreme climate events. Its application has been particularly prominent in predicting and mitigating risks associated with floods, storms, droughts, and melting glaciers. The contribution of AI to each climate event is detailed as follows.

3.2.1. Drought

Drought presents itself as a multifaceted and financially burdensome natural hazard. Precise recognition of the pivotal elements linked to drought is crucial for proficient modeling and prediction of this occurrence [27]. By reviewing various studies, there is a convergence of evidence that supports the positive contribution of AI in this field. One of the highlights is the development of advanced models, such as the extreme learning machine (ELM) based on enhanced variational mode decomposition (VMD), orthogonal triangular (QR), and online sequence (OS), which are combined to form the VMD-OS-QR-ELM model [26], which incorporates novel techniques such as VMD and hidden layer optimization, achieving significant improvements in the reliability and accuracy of drought prediction. This approach reflects the ability of AI to integrate innovative methods and improve the efficiency of existing models.

In addition, the use of algorithms such as extremely random trees (ERT) and ELM demonstrates how AI can effectively address the complexity of extreme climate events at different time scales [27]. Furthermore, the integration prediction model [28], which fuses independent models with signal decomposition algorithms to achieve greater accuracy and stability in drought prediction, suggests that synergy between traditional and modern techniques can lead to significant advances. In addition, hybrid models incorporating beluga whale optimization (BWO) [29], have the potential to significantly improve the accuracy of drought and hotspot prediction. These models provide valuable information for decision-making and water management. Among the hybrid models, the outstanding performance of the regularized extreme learning model with beluga whale optimization (RELM-BWO) stands out, attaining the highest precision and surpassing traditional as well as other combined models by a substantial margin. On the other hand, the novel hybrid model that fuses a regularized ELM with the Snake algorithm [30], has shown a significant improvement in prediction accuracy and has the precise ability to predict the occurrence of droughts and evaluate the trends, supplying valuable insights for water resource management and aiding decision-making in regions susceptible to this phenomenon.

3.2.2. Flood

A comprehensive analysis of various research studies shows the effectiveness of AI-based approaches in flood vulnerability assessment. In the context of flood vulnerability assessment, machine learning algorithms and artificial neural networks have a vital role in providing advanced tools for analyzing and predicting possible flood scenarios. These approaches were represented by remarkable accuracy rates of 89% and 90.8% [31], and the newly synthesized hybrid machine-learning model demonstrated an accuracy of 90.8% [32]. The ability of AI to provide detailed and reliable assessments for identifying flood-prone areas is of paramount importance.

In addition, the effectiveness of models based on support vector machines (SVM) and random forests is highlighted to improve the accuracy of predicting monthly flood flows. This methodology has proven to be essential to face the temporal variability of extreme climate events, thus contributing to the more efficient management of water resources [33]. On the other hand, models such as SVM and back-propagation neural networks (BPNN) and the integration of support vector machines with particle swarm optimization models (PSO-SVM) have improved flood prediction [34]. The PSO-SVM hybrid model demonstrated superior performance compared to BPNN and SVM, using five meteorological parameters to achieve higher flood prediction accuracy. This approach provides an improved and reliable alternative for forecasting extreme weather events.

In addition, the introduction of AI-based river monitoring systems [35] has demonstrated significant improvements in the accuracy of flood predictions. The integration of real-time climate and river data has provided a more holistic and dynamic understanding of environmental conditions, thereby improving the ability to anticipate and manage extreme weather events. Similarly, in the context of urban flood forecasting [36], the spatiotemporal graph convolution network model has demonstrated the ability of AI to integrate different data sources, including physically based features and human-collected data. This multidimensional approach has significantly improved the real-time accuracy of urban flood predictions, highlighting the versatility and effectiveness of AI in nowcasting situations.

3.2.3. Glacier melting

In the context of climate change and glacial melting, progress in machine learning and deep learning models, as evidenced by the studies reviewed, allow for more accurate modeling of glacier evolution in the face of key climate variables such as air temperature. In this sense, the analysis of the massive losses of glaciers and polar caps worldwide focuses specifically on the projections of the evolution of glaciers in the French Alps [37]. Applying deep learning, they estimated that towards the end of the 21st century, a decrease in the volume of glaciers is expected, projecting a loss between 75% and 88%. In addition, the excessive sensitivity of temperature index models is highlighted, emphasizing the importance of more advanced approaches. Similarly, the study of the impact on Andean glaciers [38], which uses remote sensing data and an innovative spectral index to map the precarious state of the glaciers, demonstrates the direct influence of air temperature on the retreat of these glaciers. Furthermore, Katwyk *et al.* [39] provides another perspective by introducing a neural network emulator to approximate the ice sheet model intercomparison project (ISMIP6) models and study the evolution of the Antarctic ice sheet. It highlights the importance of AI in accurately and efficiently forecasting the factors influencing sea level fluctuations. Similarly, the accurate mapping of glaciers in Peru [40], using machine learning models and applying spatial cross-validation to improve mapping reliability, provides critical data for research related to glacier mapping and for future targeted initiatives. in monitoring glacier melt.

Similarly, a concrete example is presented in the study [41], which uses optical imaging together with machine learning algorithms to map and study the distribution and changes of glaciers in the Tianshan Mountains. This approach reveals a significant acceleration of glacier retreat and highlights the direct influence of summer temperatures on these changes. Finally, the use of a deep learning classifier to accurately delineate glacier boundaries in the Himalayas [42] highlights the effectiveness of deep learning in producing accurate classified maps, improving the reliability of cryosphere monitoring. These demonstrate the critical role of AI in providing advanced approaches to understanding and managing glacier change globally.

In summary, using AI to predict extreme weather events is crucial for effective risk planning and mitigation. This capability allows communities to anticipate and prepare for droughts, floods, and thaws caused by climate change, thereby minimizing the economic and social impacts of these events. It also facilitates adaptation to climate change and rapid response to emergencies, thereby promoting the safety and resilience of affected populations. Drought, being among the most notable natural occurrences, impacts diverse facets of human existence and the surrounding environment [43], [44]. Similarly, in cold and snowy areas, reservoirs store snowmelt to fulfill water requirements from spring through summer. However, the onset of snowmelt, coupled with a sudden temperature accompanied by intense precipitation could trigger large-scale flooding [45]. Therefore, AI must be used to predict the occurrence of disasters in advance, allowing the timely implementation of mitigation measures that help minimize the impact in terms of human and material losses [46].

3.3. RQ3: What AI techniques have existing research proposed to mitigate climate change?

Table 2 presents a list of AI techniques from different fields, such as machine learning and deep learning, that have been proposed and used in previous research. The different techniques evaluated in terms of their performance are included, highlighting the one with the highest score. As can be seen, these techniques include convolutional neural networks (CNN), logistic regression (LR), SVM, and hybrid machine learning (HML) approaches. These techniques have been applied to predict greenhouse gas emissions and examine the correlations among them, climate change, flooding, and other relevant factors. The fundamental purpose of these techniques is to develop effective strategies to mitigate climate emergencies, thus providing a comprehensive approach to addressing this global challenge.

Table 2. AI techniques that existing research has proposed

Reference	Propose	Techniques	Technique with best results
[13]	Analyze the relationship between greenhouse gas emissions and climate change in Africa and develop a model to predict short- and long-term climate variables.	– Long short-term memory – Autoencoders – CNN	The CNN model obtained better performance according to the metrics: mean square error, mean absolute error, Pearson and R^2 coefficient.
[32]	Detect flash flood-prone areas using machine learning algorithms and hydrological indices in the context of climate change.	– HML – Naïve Bayes (NïB)	The HML demonstrated superior prediction performance with an accuracy of 90.8%.
[47]	Predict methane gas emissions using machine learning techniques.	– LR – Artificial neural networks (ANN) – Support vector regression (SVR)	The LR model has greater prediction success with R^2 of 94.9%.
[34]	Usability evaluation of AI models for flood forecasting in the context of climate changes.	– SVM – BPNN – Integration of PSO-SVM. Models	The PSO-SVM hybrid model has superior performance with root mean square error (RMSE-0.04962) and Nash sutcliffe coefficient (NSE-0.99334) compared to other models.
[48]	Predict greenhouse gas emissions generated by road transport of passengers and goods in Canada.	– Multiple linear regression – Multinomial logistic regression – Decision tree – Neural network (NN) – Multilayer perceptron (MLP) artificial	The neural network with an artificial multilayer perceptron model exhibited superior predictive performance compared to other models.
[49]	Predict drought conditions in the Wadi Mina basin in Algeria.	– ELM – Wavelet-based ELM (W-ELM)	Better performance with W-ELM: average coefficient of determination=0.74, mean square error=0.36, and mean absolute error=0.43.
[18]	Estimate greenhouse gas emissions in Saudi Arabia using AI based models.	– Bagged decision tree – Boosted decision tree – Gradient boosted decision tree	Better performance with Bagged decision tree: higher R^2 in test (0.90), lower mean square error (0.84 GtCO2e), and mean absolute percentage error (0.29 GtCO2e).
[50]	Predict solar energy production in Morocco using daily data from a solar power plant that helps mitigate the impacts of climate change through the reduction of carbon emissions.	– SVR – ANN – Decision tree (DT) – Random forest (RF) – Generalized additive model (GAM) – Extreme gradient boosting (XGBoost)	The ANN model has the best performance with a higher R^2, indicating higher prediction accuracy.

The variety of AI techniques being used to address climate emergencies reflects the diversity of challenges we face in the field. From predicting greenhouse gas emissions to analyzing complex interactions between different climate variables, these tools offer a promising approach to understanding and mitigating the impacts of climate change. However, it is important to emphasize that the effectiveness of these techniques depends largely on the quality of the data used and the ability to translate the results into concrete policies and practices. Furthermore, there is a need for continued research and refinement of these techniques to adapt to a constantly evolving climate environment.

3.4. RQ4: What are the ethical challenges and biases associated with using AI to mitigate climate change?

Currently deployed AI systems are trained on data sets that are susceptible to bias, the effects of which can have a negative impact in several areas, such as influencing government policies, making decisions concerning climate change mitigation and adaptation. This scenario could potentially trigger significant events that alter the course of society [51]. Furthermore, as noted in [52], biases can be classified into data bias, lack of transparency, inadequate representation, potential unintended consequences, and lack of ethical use of data. It is also emphasized that resolving these ethical quandaries and possible biases entails ensuring transparency, accountability, and inclusivity in the design and implementation of AI systems. This includes ensuring diversity, representativeness, and the elimination of bias in the datasets used to train AI models, as well as conducting periodic ethical reviews to identify potential biases or unintended outcomes. In addition, ethical and legal compliance must be ensured in the use of sensitive data.

In this context, especially in situations of ethical relevance, it is crucial that ethical principles guide AI-driven research and development to promote social and environmental benefits and sustainability. This includes promoting well-being and avoiding any form of harm for all stakeholders [5]. It is essential that advances in AI are governed by a sound ethical framework. Furthermore, oversight and accountability mechanisms must be established to ensure that these ethical principles are effectively implemented at all stages of AI development and utilization for addressing climate change mitigation. In this way, the positive potential of AI to solve complex problems and contribute to the well-being of society as a whole can be maximized.

4. DISCUSSION

This SRL study analyzed the role of AI in combating climate change, focusing on identifying AI applications to mitigate climate change, improve accuracy, and predict extreme weather events. It also explored the application of AI techniques to mitigate climate change and delved into the ethical challenges and biases that arise when using AI in this context. While previous SRL research has explored the use of AI in the context of climate change, particularly in urban climate change adaptation and promoting environmental sustainability, this study provides a broader and more detailed perspective on its application in climate change mitigation. The study's findings show that AI is being used in various applications, from climate forecasting and estimating greenhouse gas emissions to predicting extreme events such as droughts and analyzing rainfall variability. AI also plays a critical role in mitigating extreme weather events such as droughts, floods, and snowmelt. The implementation of these technologies is based on the use of machine learning and deep learning algorithms, including CNN, LR, SVM, HML, and other novel techniques. These methods have demonstrated a significant improvement in the accuracy of predicting meteorological events, allowing for more accurate anticipation of natural disasters and the development of more effective strategies to deal with them. In this sense, AI improves the response capacity to extreme weather events; it also contributes to a better understanding and management of the effects of climate change, highlighting its importance in the global fight against this problem.

When comparing the findings with previous SRL studies, similar results are observed, highlighting, as in the present study, the application of a variety of algorithms, such as decision trees, random forests, and artificial neural networks, in the analysis of climate events such as floods and landslides [53]. These algorithms are often used in a joint or hybrid manner to improve the accuracy of the models. They are also used in climate simulation, weather forecasting, and ecological monitoring [54]. As well as in greenhouse gas estimation, prediction of temperature changes, drought prediction, and snowmelt prediction. identified in this study. In this sense, the advantages and novelty of using AI in the fight against climate change reveal several promising aspects. First, AI provides advanced tools that significantly improve the accuracy and predictive power of climate models. This allows scientists and policymakers to more effectively anticipate and plan responses to greenhouse gas emissions and extreme events such as floods and droughts, thereby reducing negative impacts on communities and ecosystems. In addition, the use of machine learning and deep learning algorithms not only optimizes the analysis of large volumes of climate data but also enables the efficient integration of multiple data sources. This is critical for ecological monitoring and weather forecasting, areas where the accuracy and processing power of AI can make a significant difference.

Although technological advances have enabled more effective integration of AI into climate change research and mitigation, significant challenges remain. The present study identified ethical and bias issues, such as data bias, lack of transparency, and inadequate representation, that require continued attention. Furthermore, studies such as [55] underscores further challenges, including an excessive dependence on historical data, unpredictable human reactions to AI-driven interventions, heightened cybersecurity threats, negative consequences of AI implementations, and challenges in assessing the outcomes of intervention strategies. To address these challenges, fostering international collaboration and knowledge sharing, as suggested in [56] is essential to fully exploit AI capabilities in climate adaptation. Technology transfer and global collaboration can accelerate the implementation of AI-based strategies, ensuring that best practices and the latest innovations are available globally.

On the other hand, it is important to consider the constraints of this study when interpreting the findings. The inclusion of sources published exclusively between 2018 and 2023 may have missed more recent developments that could affect the role of AI in addressing climate change. In addition, the limitation on journal articles and open-access sources may have excluded relevant information contained in other types of documents and paid-for resources. Although various databases were used, it is important to recognize that other sources may not have been considered, which could affect the comprehensiveness of the review. In forthcoming investigations, it is suggested to expand the exploration of the impact of AI on climate change mitigation by incorporating more recent approaches and addressing the associated ethical and bias challenges.

Finally, the observations suggest that AI plays a crucial role in combating climate change through the application of various tools and algorithms. These tools allow for improved analysis of various climate change events, contributing significantly to the prediction and mitigation of events. However, important ethical challenges are also identified that require continued and careful attention. International collaboration and knowledge sharing are essential to overcome these obstacles and maximize the benefits of AI in climate change adaptation and mitigation on a global scale.

5. CONCLUSION

This study's observations on the role of AI in climate change mitigation highlight its significant use in several key areas. From accurately predicting extreme weather events to optimizing greenhouse gas mitigation strategies, AI has proven to be a critical tool. In addition to improving the accuracy of climate predictions, AI introduces innovative techniques such as HML models and diverse methodologies such as random forests, and artificial neural networks. However, the study also identifies ethical and technical challenges, such as data bias and a lack of transparency, that require continued attention. The fundamental importance of these findings lies in the transformative potential that AI can have in understanding and addressing climate change. Using AI in an ethical and thoughtful way can strengthen mitigation and adaptation strategies and improve understanding of complex climate systems. Future work is suggested to address and mitigate the ethical and technical biases associated with the use of AI in the context of climate change, with the goal of establishing more transparent, equitable, and responsible practices in its application. In addition, it should be explored how AI can facilitate international cooperation and coordination of efforts to improve the sharing of data and knowledge between countries and regions, thereby promoting a more effective and coordinated response to global climate challenges.

REFERENCES

[1] V.-P. Hoang, M.-H. Nguyen, T. Q. Do, D.-N. Le, and D. D. Bui, "A long range, energy efficient internet of things based drought monitoring system," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 2, Apr. 2020, doi: 10.11591/ijece.v10i2.pp1278-1287.

[2] V. A. Pizzulli, V. Telesca, and G. Covatariu, "Analysis of correlation between climate change and human health based on a machine learning approach," *Healthcare*, vol. 9, no. 1, Jan. 2021, doi: 10.3390/healthcare9010086.

[3] K. Y. Mahmood, "Restoring the global ecosystem health through artificial intelligence: a sustainable approach," *Natural Resources and Sustainable Development*, vol. 12, no. 2, pp. 345–356, 2022, doi: 10.31924/nrsd.v12i2.110.

[4] R. Bamdale, S. Shelar, and V. Khandekar, "How to tackle climate change using artificial intelligence," in *2021 12th International Conference on Computing Communication and Networking Technologies (ICCCNT)*, Kharagpur, India, 2021, pp. 1-7, doi: 10.1109/ICCCNT51525.2021.9579674.

[5] E. Hermann, G. Hermann, and J.-C. Tremblay, "Ethical artificial intelligence in chemical research and development: a dual advantage for sustainability," *Science and Engineering Ethics*, vol. 27, no. 4, Jul. 2021, doi: 10.1007/s11948-021-00325-6.

[6] T. Dhar, B. S. Rawat, S. Pandev, V. Pachouri, and A. Kathuria, "Artificial intelligence in contending climate change to achieve environmental justice," in *2023 3rd International Conference on Pervasive Computing and Social Networking (ICPCSN)*, Jun. 2023, doi: 10.1109/icpcsn58827.2023.00087.

[7] A. K. Priya, B. Devarajan, A. Alagumalai, and H. Song, "Artificial intelligence enabled carbon capture: a review," *Science of The Total Environment*, vol. 886, Aug. 2023, doi: 10.1016/j.scitotenv.2023.163913.

[8] H. Lv, B. Shi, N. Li, and R. Kang, "Intelligent manufacturing and carbon emissions reduction: evidence from the use of industrial robots in China," *International Journal of Environmental Research and Public Health*, vol. 19, no. 23, Nov. 2022, doi: 10.3390/ijerph192315538.

[9] Z. Z. Zulkipli, R. Maskat, and N. H. I. Teo, "A systematic literature review of automatic ontology construction," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 28, no. 2, pp. 878-889, Nov. 2022, doi: 10.11591/ijeecs.v28.i2.pp878-889.

[10] N. E. Mohamed and I. I. Radwan, "Traffic light control design approaches: a systematic literature review," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 12, no. 5, pp. 5355-5363, Oct. 2022, doi: 10.11591/ijece.v12i5.pp5355-5363.

[11] E. A. Raheem, S. M. S. Ahmad, and W. A. W. Adnan, "Insight on face liveness detection: a systematic literature review," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 9, no. 6, pp. 5865-5175, Dec. 2019, doi: 10.11591/ijece.v9i6.pp5865-5175.

[12] R. J. -Velarde, D. H. Celis, C. Y. Arias, and L. A. -Arenas, "A critical review of the state of computer security in the health sector," *Bulletin of Electrical Engineering and Informatics*, vol. 12, no. 6, pp. 3805–3816, Dec. 2023, doi: 10.11591/eei.v12i6.5394.

[13] S. Ibrahim, I. Ziedan, and A. Ahmed, "Study of climate change detection in north-east africa using machine learning and satellite data," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 14, pp. 11080–11094, 2021, doi: 10.1109/jstars.2021.3120987.

[14] T. A. Spontoni *et al.*, "Evaluation and modelling of reference evapotranspiration using different machine learning techniques for a brazilian tropical savanna," *Agronomy*, vol. 13, no. 8, Aug. 2023, doi: 10.3390/agronomy13082056.

[15] M. I. Ashraf, F.-R. Meng, C. P.-A. Bourque, and D. A. MacLean, "A novel modelling approach for predicting forest growth and yield under climate change," *PLOS ONE*, vol. 10, no. 7, Jul. 2015, doi: 10.1371/journal.pone.0132066.

[16] A. Jamali, M. Mahdianpari, F. Mohammadimanesh, B. Brisco, and B. Salehi, "A synergic use of sentinel-1 and sentinel-2 imagery for complex wetland classification using generative adversarial network (GAN) scheme," *Water*, vol. 13, no. 24, Dec. 2021, doi: 10.3390/w13243601.

[17] H.-T. Pham, H.-Q. Nguyen, K.-P. Le, T.-P. Tran, and N.-T. Ha, "Automated mapping of wetland ecosystems: a study using google earth engine and machine learning for lotus mapping in Central Vietnam," *Water*, vol. 15, no. 5, Feb. 2023, doi: 10.3390/w15050854.

[18] M. M. Rahman *et al.*, "Decision tree-based ensemble model for predicting national greenhouse gas emissions in Saudi Arabia," *Applied Sciences*, vol. 13, no. 6, Mar. 2023, doi: 10.3390/app13063832.

[19] Y. Chen and S. Jin, "Artificial intelligence and carbon emissions in manufacturing firms: the moderating role of green innovation,"

Processes, vol. 11, no. 9, Sep. 2023, doi: 10.3390/pr11092705.
[20] R. Zhu, L. Yang, T. Liu, X. Wen, L. Zhang, and Y. Chang, "Hydrological responses to the future climate change in a data scarce region, Northwest China: application of machine learning models," *Water*, vol. 11, no. 8, Jul. 2019, doi: 10.3390/w11081588.
[21] A. B. Othman, A. Ouni, and M. Besbes, "Deep learning-based estimation of PV power plant potential under climate change: a case study of El Akarit, Tunisia," *Energy, Sustainability and Society*, vol. 10, no. 1, Sep. 2020, doi: 10.1186/s13705-020-00266-1.
[22] W. T. Abebe and D. Endalie, "Artificial intelligence models for prediction of monthly rainfall without climatic data for meteorological stations in Ethiopia," *Journal of Big Data*, vol. 10, no. 1, Jan. 2023, doi: 10.1186/s40537-022-00683-3.
[23] T. Ise and Y. Oba, "Forecasting climatic trends using neural networks: an experimental study using global historical data," *Frontiers in Robotics and AI*, vol. 6, Apr. 2019, doi: 10.3389/frobt.2019.00032.
[24] A. Alsumayt, N. El-Haggar, L. Amouri, Z. M. Alfawaer, and S. S. Aljameel, "Smart flood detection with AI and blockchain integration in Saudi Arabia using drones," *Sensors*, vol. 23, no. 11, May 2023, doi: 10.3390/s23115148.
[25] M. M. Monir, M. Rokonuzzaman, S. C. Sarker, E. Alam, M. K. Islam, and A. R. M. T. Islam, "Spatiotemporal analysis and predicting rainfall trends in a tropical monsoon-dominated country using MAKESENS and machine learning techniques," *Scientific Reports*, vol. 13, no. 1, Aug. 2023, doi: 10.1038/s41598-023-41132-2.
[26] Y. Liu, L. H. Wang, L. B. Yang, and X. M. Liu, "Drought prediction based on an improved VMD-OS-QR-ELM model," *PLOS ONE*, vol. 17, no. 1, Jan. 2022, doi: 10.1371/journal.pone.0262329.
[27] Q. Zhang *et al.*, "Droughts across China: drought factors, prediction and impacts," *Science of The Total Environment*, vol. 803, Jan. 2022, doi: 10.1016/j.scitotenv.2021.150018.
[28] S. Li, J. Xie, X. Yang, and X. Jing, "Comparison of hybrid machine learning models to predict short-term meteorological drought in Guanzhong region, China," *Water Science & Technology*, vol. 87, no. 11, pp. 2756–2775, May 2023, doi: 10.2166/wst.2023.162.
[29] M. M. Hameed, S. F. M. Razali, W. H. M. W. Mohtar, N. A. Rahman, and Z. M. Yaseen, "Machine learning models development for accurate multi-months ahead drought forecasting: case study of the Great Lakes, North America," *PLOS ONE*, vol. 18, no. 10, Oct. 2023, doi: 10.1371/journal.pone.0290891.
[30] M. M. Hameed, S. F. M. Razali, W. H. M. W. Mohtar, M. O. A. Alsaydalani, and Z. M. Yaseen, "Deep learning versus hybrid regularized extreme learning machine for multi-month drought forecasting: A comparative study and trend analysis in tropical region," *Heliyon*, vol. 10, no. 1, Jan. 2024, doi: 10.1016/j.heliyon.2023.e22942.
[31] R. R. Rudra and S. K. Sarkar, "Artificial neural network for flood susceptibility mapping in Bangladesh," *Heliyon*, vol. 9, no. 6, Jun. 2023, doi: 10.1016/j.heliyon.2023.e16459.
[32] S. A. A. El-Magd, A. Maged, and H. I. Farhat, "Hybrid-based Bayesian algorithm and hydrologic indices for flash flood vulnerability assessment in coastal regions: machine learning, risk prediction, and environmental impact," *Environmental Science and Pollution Research*, vol. 29, no. 38, pp. 57345–57356, Mar. 2022, doi: 10.1007/s11356-022-19903-7.
[33] N. M. Gharakhanlou and L. Perez, "Spatial prediction of current and future flood susceptibility: examining the implications of changing climates on flood susceptibility using machine learning models," *Entropy*, vol. 24, no. 11, Nov. 2022, doi: 10.3390/e24111630.
[34] S. Samantaray, A. Sahoo, and A. Agnihotri, "Prediction of flood discharge using hybrid PSO-SVM algorithm in Barak River Basin," *Methods X*, vol. 10, 2023, doi: 10.1016/j.mex.2023.102060.
[35] L. Mdegela, Y. D. Bock, E. Municio, E. Luhanga, J. Leo, and E. Mannens, "A multi-modal wireless sensor system for river monitoring: a case for kikuletwa river floods in Tanzania," *Sensors*, vol. 23, no. 8, Apr. 2023, doi: 10.3390/s23084055.
[36] H. Farahmand, Y. Xu, and A. Mostafavi, "A spatial–temporal graph deep learning model for urban flood nowcasting leveraging heterogeneous community features," *Scientific Reports*, vol. 13, no. 1, Apr. 2023, doi: 10.1038/s41598-023-32548-x.
[37] J. Bolibar, A. Rabatel, I. Gouttevin, H. Zekollari, and C. Galiez, "Nonlinear sensitivity of glacier mass balance to future climate change unveiled by deep learning," *Nature Communications*, vol. 13, no. 1, Jan. 2022, doi: 10.1038/s41467-022-28033-0.
[38] J. Podgórski, M. Pętlicki, A. Fernández, R. Urrutia, and C. Kinnard, "Evaluating the impact of the central chile mega drought on debris cover, broadband albedo, and surface drainage system of a dry andes glacier," *Science of The Total Environment*, vol. 905, Dec. 2023, doi: 10.1016/j.scitotenv.2023.166907.
[39] P. V. Katwyk, B. Fox-Kemper, H. Seroussi, S. Nowicki, and K. J. Bergen, "A variational LSTM emulator of sea level contribution from the antarctic ice sheet," *Journal of Advances in Modeling Earth Systems*, vol. 15, no. 12, Dec. 2023, doi: 10.1029/2023ms003899.
[40] M. Bueno, B. Macera, and N. Montoya, "A comparative analysis of machine learning techniques for national glacier mapping: evaluating performance through spatial cross-validation in Perú," *Water*, vol. 15, no. 24, Dec. 2023, doi: 10.3390/w15244214.
[41] L. Zhuang, C. Ke, Y. Cai, and V. Nourani, "Measuring glacier changes in the Tianshan Mountains over the past 20 years using google earth engine and machine learning," *Journal of Geographical Sciences*, vol. 33, no. 9, pp. 1939–1964, Sep. 2023, doi: 10.1007/s11442-023-2160-4.
[42] V. Sood, R. K. Tiwari, S. Singh, R. Kaur, and B. R. Parida, "Glacier boundary mapping using deep learning classification over bara shigri glacier in Western Himalayas," *Sustainability*, vol. 14, no. 20, Oct. 2022, doi: 10.3390/su142013485.
[43] S. Azimi, M. A. Moghaddam, and S. A. H. Monfared, "Large-scale association analysis of climate drought and decline in groundwater quantity using Gaussian process classification (case study: 609 study area of Iran)," *Journal of Environmental Health Science and Engineering*, vol. 16, no. 2, pp. 129–145, May 2018, doi: 10.1007/s40201-018-0301-y.
[44] L. Čubanová and W. Almikaeel, "Drought assessment and prediction for gidra river, Slovakia," *IOP Conference Series: Materials Science and Engineering*, vol. 1209, no. 1, Dec. 2021, doi: 10.1088/1757-899x/1209/1/012074.
[45] M. Abe, H. Takiguchi, and Y. Hida, "Development of the snowmelt prediction model using artificial intelligence (AI)," *E3S Web of Conferences*, vol. 346, 2022, doi: 10.1051/e3sconf/202234603026.
[46] K. E. Adikari, S. Shrestha, D. T. Ratnayake, A. Budhathoki, S. Mohanasundaram, and M. N. Dailey, "Evaluation of artificial intelligence models for flood and drought forecasting in arid and tropical regions," *Environmental Modelling & Software*, vol. 144, Oct. 2021, doi: 10.1016/j.envsoft.2021.105136.
[47] G. F. Ü. Uyar *et al.*, "Estimation of methane gas production in turkey using machine learning methods," *Applied Sciences*, vol. 13, no. 14, Jul. 2023, doi: 10.3390/app13148442.
[48] M. J. U. R. Khan and A. Awasthi, "Machine learning model development for predicting road transport GHG emissions in Canada," *WSB Journal of Business and Finance*, vol. 53, no. 2, pp. 55–72, Jan. 2019, doi: 10.2478/wsbjbf-2019-0022.
[49] M. Achite, O. M. Katipoğlu, M. Jehanzaib, N. Elshaboury, V. Kartal, and S. Ali, "Hydrological drought prediction based on hybrid extreme learning machine: wadi mina basin case study, Algeria," *Atmosphere*, vol. 14, no. 9, Sep. 2023, doi: 10.3390/atmos14091447.
[50] Y. Ledmaoui, A. El Maghraoui, M. El Aroussi, R. Saadane, A. Chebak, and A. Chehri, "Forecasting solar energy production: a comparative study of machine learning algorithms," *Energy Reports*, vol. 10, pp. 1004–1012, Nov. 2023, doi: 10.1016/j.egyr.2023.07.042.

[51] R. Debnath, F. Creutzig, B. K. Sovacool, and E. Shuckburgh, "Harnessing human and machine intelligence for planetary-level climate action," *NPJ Climate Action*, vol. 2, no. 1, Aug. 2023, doi: 10.1038/s44168-023-00056-3.
[52] H. Jain, R. Dhupper, A. Shrivastava, D. Kumar, and M. Kumari, "AI-enabled strategies for climate change adaptation: protecting communities, infrastructure, and businesses from the impacts of climate change," *Computational Urban Science*, vol. 3, no. 1, Jul. 2023, doi: 10.1007/s43762-023-00100-2.
[53] F. Zennaro *et al.*, "Exploring machine learning potential for climate change risk assessment," *Earth-Science Reviews*, vol. 220, Sep. 2021, doi: 10.1016/j.earscirev.2021.103752.
[54] M. Satish, Prakash, S. M. Babu, P. P. Kumar, S. Devi, and K. P. Reddy, "Artificial intelligence (AI) and the prediction of climate change impacts," in *2023 IEEE 5th International Conference on Cybernetics, Cognition and Machine Learning Applications (ICCCMLA)*, Oct. 2023, doi: 10.1109/icccmla58983.2023.10346636.
[55] R. Nishant, M. Kennedy, and J. Corbett, "Artificial intelligence for sustainability: challenges, opportunities, and a research agenda," *International Journal of Information Management*, vol. 53, Aug. 2020, doi: 10.1016/j.ijinfomgt.2020.102104.
[56] A. Srivastava and R. Maity, "Assessing the potential of AI–ML in urban climate change adaptation and sustainable development," *Sustainability*, vol. 15, no. 23, Nov. 2023, doi: 10.3390/su152316461.

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