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REVIEW

Next-Generation Environmental Management: A Review of Artificial Intelligence for Ecosystem Monitoring and Sustainable Decision-Making

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ABSTRACT

Artificial Intelligence (AI) has become one of the disruptive technologies in environmental management, providing new ways of monitoring the ecosystem, optimising resources, and making environmentally friendly decisions. This review examines how AI can potentially be used in different environmental areas, such as biodiversity monitoring, ecological change predictions, and how natural resources can be better distributed. Thanks to the incorporation of AI technologies like machine learning, remote sensing, and Internet of Things sensors, real-time data acquisition and analysis can now be conducted, which allows for more informed and timely decisions related to the environment. Predictive models based on AI offer useful information on the possible effects of climate change, loss of biodiversity, and habitat degradation to enable policymakers to engage in proactive environmental management. Nonetheless, the use of AI in environmental governance does not come without its problems. Challenges like data quality and availability, the complexity of ecosystems, ethics, and technological constraints need to be resolved to guarantee the effectiveness and equity of AI-based solutions. This paper addresses these issues and outlines future research opportunities, focusing on the importance of interdisciplinary cooperation and building a strong data infrastructure to maximize the potential of AI. With these obstacles resolved, AI has the potential to become a key factor in sustainability and resilience in ecosystems around the world.

Keywords: Artificial Intelligence; Ecosystem Monitoring; Sustainable Decision-Making; Resource Optimization; Environmental Management

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1. Introduction

The increasing issues of climate change, coupled with the fast deterioration of ecosystems caused by human activity in recent decades, have left a strong demand to implement environmental management in the near future and effectively [1]. Deforestation, loss of biodiversity, pollution, and depletion of resources are just some of the consequences of improper management of the environment, which are extensive and, in most cases, irreversible [2]. To overcome these issues, there is a need to find new methods of dealing with them that would not only comprehend the intricate mechanisms of the ecosystems, but also predict and counteract environmental risks. The conventional ways of monitoring and managing ecosystems, though useful, are limited in terms of scope, effectiveness, and responsiveness. Such methods tend to be unable to match the growing complexity and urgency of environmental problems. The incorporation of Artificial Intelligence (AI) into the field of environmental management is a promising way to overcome such challenges and make decisions with increased accuracy, speed, and scalability [3].

Artificial Intelligence has also become a disruptive technology, changing sectors around the world. AI has the potential to transform the process of ecosystem monitoring and decision-making in environmental management to ensure sustainability [4]. The capability of AI to handle large volumes of data, identify trends, and anticipate future trends is an opportunity to improve the monitoring of the ecosystem in a way that had never been thought of before [5]. Conventional environmental management has tended to monitor ecosystems using discrete data collection techniques, e.g., manual surveys or satellite images. Nevertheless, the volume and intricacy of environmental data, when processed through the prism of climate change, land-use changes, and the loss of biodiversity, demand more advanced tools to monitor the environment in real-time, combine different data types, and forecast changes. In this case, AI has been the leading innovator in these developments, providing intelligent solutions to handle the complexity of the world ecosystem [6].

The originality of this review lies in proposing a Three-Layer AI Integration Framework for Ecosystem Management that synthesizes fragmented research across terrestrial, aquatic, and urban ecosystems. Unlike prior reviews that focus on isolated AI applications (e.g., species identification, or deforestation detection), we provide an integrated analytical lens examining: (Layer 1) AI-enhanced data acquisition via IoT-remote sensing fusion; (Layer 2) predictive modeling for ecosystem dynamics; and (Layer 3) adaptive governance through AI-driven decision support systems. This framework enables us to identify critical gaps where AI's potential remains untapped, particularly in multi-ecosystem interoperability and real-time policy feedback loops, offering a novel contribution beyond prior literature [7,8].

Compared to the past reviews where the reviewer might have focused on particular AI applications or environmental management initiatives, this article offers an integrative analysis, looking at how AI approaches are being applied in a very broad spectrum of ecosystems, including forests and wetlands on land, as well as in the sea [9]. The paper also explores case studies of where AI has successfully been applied in practice, demonstrating practical uses and the results of such AI-powered solutions. This is an original holistic perspective of integrating the divergent strands of research in AI and environmental science, and provides a single lens of how the two can cooperate to manage the ecosystem more sustainably.

Besides, the crossroads of AI in other advanced technologies that complement and amplify its potential in environmental management are also discussed in this review. Combining AI with Internet of Things (IoT) sensors, e.g., can enable real-time and uninterrupted monitoring of environmental variables that would present a comprehensive and dynamic image of the health of an ecosystem [10]. Combined with remote sensing technology, including satellite imagery and drone surveillance, AI allows the acquisition of high-resolution data in remote areas or large areas, which increases the surveillance possibilities even more [11]. Combined with the predictive capabilities of AI, these technological solutions can provide an opportunity to detect changes in the environment early and make more informed decisions at the local, regional, and global levels [12].

Nevertheless, there are challenges connected with the use of AI in environmental management. This review is also novel in that it acknowledges the shortcomings and challenges that remain to be resolved to ensure AI achieves its potential. The quality and availability of data, especially in remote locations, are major challenges to the successful implementation of AI[4]. In addition to this, the ethical concerns of AI decisions in ecosystem management are also a concern, especially in the provision of fair and just results to communities that depend on the ecosystem services. The intricacy of ecosystems, species diversity, and the interaction of environmental factors also complicate the task of developing universally applicable AI models[13]. This review takes a critical look at these challenges, giving a reflection on the existing barriers as well as possibilities for future research.

To conclude, the originality of the presented article is based on the fact that it thoroughly examines the transformative nature of AI in the area of environmental management. This review brings together recent advances in the field of AI technology and ecosystem monitoring and decision-making to outline how AI can be used to tackle urgent environmental challenges. In a world where sustainability and the health of the ecosystem are going to be the most important factors, AI will be a highly useful tool in enhancing the accuracy and scope of environmental management. The present paper preconditions a further discussion of the opportunities of AI to build a more sustainable future, as we have to insist on a more interdisciplinary approach and the creation of AI-based solutions that can be used on a large scale to solve global environmental issues[14].

2. AI in Ecosystem Monitoring

Ecosystem monitoring plays a critical role in comprehending the health, dynamics, and transformations within the natural environment[15]. Artificial Intelligence (AI) has become a potent instrument for improving the precision, effectiveness, and magnitude with which ecosystems can be observed in recent years. The conventional mechanisms of monitoring ecosystems, such as field surveys, manual data collection, and small-scale remote sensing, are becoming increasingly ineffective in handling the increasing complexity and urgency of environmental changes. Conversely, AI technologies can provide new solutions as they are able to process large volumes of environmental information, identify trends, and deliver real-time analysis. The following section will discuss how AI is transforming ecosystem monitoring by discussing technological changes in data collection, AI models to assess an ecosystem, and actual case studies that illustrate how AI has been used in practice.

2.1. Technological Advancements in Data Collection

Collecting high-quality and high-resolution data is a key aspect of successful ecosystem monitoring. Conventionally, data could only be collected through periodic surveys or satellite remote sensing. Although these techniques have proven to be very useful, they are usually limited by space, time, and resources. With the introduction of AI-based technologies, the possibilities for environmental data collection have increased significantly, making the approaches more dynamic, accurate, and scalable[10].

The combination of AI and remote sensing technologies has been among the greatest innovations in data collection. Satellites and drones, as well as unmanned aerial vehicles (UAVs), have transformed the capacity to survey ecosystems in large and frequently inaccessible regions. The high-resolution imagery produced by these platforms is processed by AI algorithms that extract relevant information that is hard for human analysts to detect. As an illustration, AI can detect even minor changes in vegetation health, invasive species expansion, or deforestation rates at previously unimaginable speeds and levels of accuracy. This method saves much time and cost that would be incurred in the process of manual data analysis, and thus large-scale monitoring is a possibility and an efficient way to monitor data[16].

Along with remote sensing, the development of Internet of Things (IoT) devices has also improved environmental monitoring[17]. IoT sensors can be installed across multiple ecosystems and used to gather real-time data on variables such as air and water quality, soil moisture, temperature, and biodiversity indicators. This stream of data is analysed by AI algorithms to detect trends, anomalies, and new threats to the environment. An example is in aquatic ecosystems, where AI may be used to interpret sensor readings from rivers and oceans to detect changes in water temperature, salinity, and pollution levels. Monitoring enabled by IoT enables immediate reaction to environmental changes, which can improve decision-making and intervention.

The combination of AI, IoT, and remote sensing is a potent set of tools to monitor ecosystems. These technologies can be used to compile enormous quantities of data across various spatial and temporal scales, providing a more comprehensive picture of ecosystem health. In addition, the incorporation of AI ensures that such data is analysed more effectively and accurately, enabling more informed decisions in a fraction of the time required when utilising traditional methods[18].

2.2. AI-Based Models for Ecosystem Assessment

After data is gathered, AI models are essential in interpreting and analyzing the data to determine the health of the ecosystem and forecast changes in the future. AI methods, including machine learning (ML), deep learning (DL), and others, have become widespread for processing environmental data, identifying trends, and predicting ecosystem conditions[7]. Such AI models are capable of discerning more intricate connections among environmental factors, and this information can give an understanding of how ecosystems operate, which would be challenging to acquire using conventional methods.

Monitoring biodiversity has been a key area where AI-based models have been particularly useful[19]. For example, AI algorithms can be trained to identify species using audio recordings, camera trap footage, or drone videos. In tropical forests, where biodiversity is extremely high, AI models can recognize animal species based on camera trap shots, even among species that are similar to each other. The models are applicable in the monitoring of endangered species, the trend of their population, and the success of conservation. Moreover, image recognition systems powered by AI can tell when a habitat is degraded or there is an invasive species, which is important to conservation managers.

Besides monitoring biodiversity, AI models are becoming popular in the analysis of vegetation and habitat[20]. Using satellite and drone imagery, AI algorithms can assess vegetation health, detect changes in land cover, and identify areas of ecological stress. As an example, machine learning models may be used to track the distribution of wildfires, deforestation, or land-use modifications, which can be critical information for land management and conservation. Convolutional neural networks (CNNs) are a type of deep learning that has demonstrated potential in identifying patterns and objects in satellite and aerial images, which can be successfully used to classify types of land cover and detect fine-scale changes in vegetation.

The AI models are also used to forecast future ecological patterns, including the effects of climate change on the ecosystem or the invasion of invasive species[21]. These predictive models combine environmental data with climate models and other socio-economic variables to predict the future trend of ecosystems in various situations. Such models can assist policymakers and conservationists to predict environmental threats in order to implement proactive instead of reactive management strategies.

Although the current AI-based models have achieved considerable progress in their application in the assessment of ecosystems, there are still challenges. The major challenge is that developing the right models requires high-quality training data[22]. To be effective, AI models require large, diverse, and well-labeled datasets. These datasets are not available in most areas, particularly in those areas where the ecosystem is not well researched or where data collection facilities are deficient. Also, AI models may be constrained by the data that can be obtained in various ecosystems, making it challenging to develop a single set of models that can be used in all regions.

The interpretability of AI models is another issue[23]. Although machine learning models can provide a very accurate prediction, it may be challenging to gain insight into the reasoning behind the prediction. This black box issue may become an obstacle to belief and adoption, especially when AI is employed to guide policy-making. Scholars are also striving to develop more explanatory AI models that could provide a clearer picture of the processes underlying changes in ecosystems.

2.3. Case Studies and Applications of AI in Ecosystem Monitoring

Applications of AI in ecosystem monitoring practice have been shown to be successful in a few case studies across diverse environmental settings. **Table 1** summarises major case studies of AI use across various ecosystems. These case studies are helpful for understanding the potential and limitations of AI and its capacity to solve environmental problems in the real world[24].

Table 1. Applications of AI in Ecosystem Monitoring. This table summarizes key case studies of AI applications in various ecosystems and their impact on ecosystem health.

Ecosystem	AI Technology Used	Monitoring Focus	Outcome/Impact
Tropical Rainforests	Machine Learning, Remote Sensing	Deforestation, Illegal Logging	Early detection of illegal logging, proactive conservation strategies
Coral Reefs	Deep Learning, Computer Vision	Coral Bleaching, Biodiversity	Early identification of coral stress and bleaching events
Agricultural Systems	Machine Learning, IoT Sensors	Soil Moisture, Crop Health	Optimized irrigation schedules, reduced water usage
Marine Ecosystems	Neural Networks, Satellite Imaging	Fish Populations, Water Quality	Improved fishery management, pollution detection

A notable one is the use of AI to monitor forests. The use of AI in analyzing satellite images and drone footage has been applied in tropical rainforests to identify deforestation and illegal logging. In a single case study in the Amazon rainforest, machine learning algorithms were trained to detect changes in forest cover using high-resolution satellite images. These algorithms could identify cases of deforestation months earlier than they could be detected by other means, enabling conservation authorities to respond faster. Moreover, AI models have been used to assess forest health by analysing vegetation density and diversity, providing valuable insights into ecosystem stability [25,26].

Another notable use of AI in monitoring ecosystems is in marine conservation. Coral reefs are highly sensitive to environmental pressures such as rising ocean temperatures and pollution; thus, AI-based systems have been implemented to monitor them. In a study, machine learning models were applied to images and videos of underwater environments to identify indicators of coral bleaching, a condition caused by rising water temperatures. These models could detect bleaching events with high precision, and researchers could track the well-being of coral reefs and take necessary measures to save them. In marine biodiversity monitoring, machine learning models have also been applied to analyze audio recordings of underwater habitats to detect marine species and trace changes in populations [27,28].

Besides these instances, AI is also being used more in monitoring urban ecosystems. With their multifaceted environmental problems, cities need new approaches to managing air quality, waste, water, and green spaces. AI-based sensors and data analytics platforms are being deployed to track air pollution in cities, providing real-time information on particulate matter, carbon emissions, and other pollutants. The AI algorithms then analyze this data and determine pollution hotspots and forecast air quality trends. City planners can use this information to develop policies that reduce pollution and improve people's health [29].

These case studies show that AI has broad potential for monitoring ecosystems across various environmental conditions. They, however, also point to the limitations of the AI solution in larger areas, the ability to combine various data sources, and the credibility and validity of AI predictions. In addition, effective partnerships among researchers, conservationists, and local communities, and the creation of data-sharing frameworks that enable the integration of multiple monitoring tools and data sources often determine the success of AI applications [14].

3. AI-Driven Decision-Making for Sustainable Environmental Management

With the world facing mounting environmental issues such as climate change, habitat loss, and resource depletion, the need to implement effective and adaptable decision-making models has gained momentum. The traditional environmental management methods, although useful, tend to be quite reactive and have difficulty capturing the complexity, dynamism, and interconnectedness of ecosystems. The implementation of Artificial Intelligence (AI) in decision-making can transform environmental governance by providing information-driven insights, predictive capabilities, and optimisation algorithms that can help decision-makers address environmental problems proactively, fairly, and effectively [30]. This part discusses the opportunities for AI to transform decision-making in environmental management, with particular emphasis on AI-based predictive models, resource management optimisation algorithms, and the incorporation of AI into policy and planning procedures.

3.1. AI Models for Predictive Decision Support

Predictive decision support is one of the most revolutionary uses of AI in the field of environmental management [31]. AI models, particularly those based on machine learning (ML) and deep learning (DL), have demonstrated exceptional capabilities in forecasting environmental changes, assessing the impact of various management strategies, and providing actionable insights to policymakers and conservationists. The application of these predictive models is very diverse, with applications in climate change impacts on ecosystems, as well as in the spread of invtowardpecies or the direction taken by an ecosystem towards degradation. **Table 2** summarises AI-based predictive models applied in environmental management to predict the effects of biodiversity and climate change.

Table 2. AI-Based Models for Predictive Decision Support in Environmental Management. This table outlines predictive AI models and their applications to environmental challenges.

Model Type	Application Area	Environmental Challenge Addressed	AI Techniques Used
Climate Change Impact	Biodiversity Forecasting	Predicting species vulnerability to climate change	Machine Learning, Deep Learning
Wildfire Prediction	Forest Management	Wildfire spread prediction and risk assessment	Neural Networks, Data Mining
Flood Risk Assessment	Urban Planning, Disaster Management	Predicting flood events and impacts	Regression Models, Decision Trees
Invasive Species Spread	Ecological Monitoring	Forecasting the spread of invasive species	Random Forest, SVM

AI-driven predictive models come in especially handy in controlling complex systems where human intuition might not be enough to fully harness the dynamics. As an illustration, to forecast the effects of climate change on biodiversity, it will be necessary to combine various variables, including changes in temperature, precipitation, and land-use changes. When trained on past data, machine learning models can be used to analyze these factors and produce predictions of how ecosystems will react to future climate conditions. Such forecasting abilities enable environmental management to be more proactive, and thus, decision-makers can put in place mitigation mechanisms to ensure that adverse changes can be avoided. An example is the vulnerability of a particular species to climate change, which can be predicted using machine learning algorithms to prioritize conservation efforts in the most vulnerable areas [32].

Another promising area for AI-driven predictive decision support is disaster management. Applied to the wildfire scenario, such machine learning algorithms can be used to examine past fire data, weather conditions, and vegetation states to determine the probability of occurrence of a wildfire and its spread in the future. The information may be utilized to support emergency response plans, resource allocation, and land-use planning to mitigate the risk of wildfires. In the same manner, AI models can predict the frequency and severity of natural disasters, including floods, hurricanes, and droughts, and thus more successful disaster preparedness and risk management can be achieved [33].

The predictive capabilities of AI also relate to monitoring and managing the health of ecosystems. Indicatively, some AI models can forecast the proliferation of an invasive species depending on environmental factors and interactions between the species. By predicting the spread of invasive species under various conditions, AI can assist conservationists in taking specific control actions and reducing the ecological footprint. Moreover, predictive models may be used to determine regions where ecosystems tend to be in a degraded state, and this may be addressed early enough to conserve critical ecosystem services like carbon sequestration, water purification, and biodiversity conservation [5].

Although AI is promising in terms of predictive decision support, issues of accurate model development and deployment continue to be challenges [34]. Availability and quality of data are one of the major concerns. Predicting anything with AI models requires large, high-quality datasets, which are unavailable in many cases. It is more so in areas where ecosystems are poorly known or where there is a lack of data-collection infrastructure. Besides, although AI models can make predictions using past trends, the fact that the future environment is uncertain can confound the predictions, including the unpredictability of human actions or the multifaceted interactions occurring in an ecosystem.

3.2. Optimization Algorithms for Resource Management

The other outstanding contribution of AI to sustainable environmental management is that it is able to assist in the optimization of resource allocation. With the ever-growing global population and the need to have a larger supply of natural resources, the efficiency and sustainability in managing resources have been one of the most critical issues of environmental governance. AI-based optimization algorithms provide novel approaches to resource management of essential resources like water, energy, land, and biodiversity [35]. **Table 3** estimates the different AI optimization algorithms and how effective they are in resource management, especially in agriculture and land use.

Table 3. Comparison of AI Optimization Algorithms in Resource Management. This table compares different AI optimization algorithms and their applications in resource management for agriculture and land use.

Algorithm	Resource Management Area	Optimization Goal	Strengths	Limitations
Genetic Algorithms	Water Management	Optimize irrigation schedules	Effective in handling complex constraints and adaptable	Computationally intensive, requires significant data
Linear Programming	Land Use Planning	Maximize land-use efficiency for agriculture	Simple to implement, efficient	Cannot handle non-linear problems
Reinforcement Learning	Energy Management	Optimize energy distribution in smart grids	Self-learning, dynamic adaptation	Requires large amounts of data and slow convergence
Simulated Annealing	Forest Management	Optimize forest conservation strategies	Can escape local minima and is flexible	Sensitive to initial conditions

In water management, AI algorithms can manage the allocation and utilization of water in agriculture, cities, and natural systems optimally [36]. Weather forecasts, soil moisture sensors, and irrigation systems can be used to analyze data in machine learning to identify the most efficient watering schedules, reduce water waste, and optimize agricultural productivity. Equally, AI can streamline water storage and distribution in cities, which can be used to ensure that water is utilized effectively and fairly. In areas where there is a lack of water, AI-generated forecasts can predict water scarcity and assist in the decision-making process concerning water rationing and distribution to ensure that the most urgent needs are satisfied.

Energy management has also seen the application of AI, especially in integrating renewable energy [37]. As more and more energy is produced and distributed by renewable sources like solar and wind, which are unpredictable and change with the weather conditions, AI can be used to optimize energy generation and delivery. With machine learning, it is possible to predict changes in energy demand and supply, which can be used to balance the grid and minimize the use of fossil fuels. Moreover, AI may be applied to optimise the work of smart grids, which allows making real-time changes to the flow of energy, minimising waste, and ensuring that energy is used efficiently.

AI optimization algorithms in land-use planning could be used to balance the conflicting needs of land, i.e., urban development, agriculture, and conservation [38]. The machine learning models can be trained to analyze several variables, such as land productivity, biodiversity, and environmental sensitivity, in order to identify the most sustainable land-use patterns. For example, AI models can identify areas of high ecological value that need to be conserved and suggest land-use adjustments with low environmental impact. This method would enable policymakers to make evidence-based decisions that are supportive of economic growth and environmental sustainability.

Another field where AI-based optimization has come in handy is biodiversity conservation. In wildlife management, AI models may be used to optimize the distribution of resources for conservation activities, e.g., to better understand where to put a protected region or how to invest in the preservation of a species. By analysing factors, including the quality of habitat, species distribution, and the risk of species extinction, AI can assist in prioritising conservation efforts that will most effectively influence biodiversity. Moreover, AI can help to optimize the use of the areas under protection, making sure that resources are distributed over those areas that need the most attention and reducing human-wildlife conflicts [39].

Although AI-based optimisation algorithms promise to be highly useful for resource management, there are challenges in their application. The trade-off of various objectives is one of the key issues. As an example, in land-use planning, there might be a conflict among agricultural production, urban development, and conservation [40]. The AI models should take into account these conflicting goals and assist decision-makers in overcoming the pitfalls of environmental, economic, and social balance. Also, optimisation algorithms are sensitive to data correctness, up-to-date data, and the feasibility of combining data from multiple sources.

3.3. AI in Policy and Planning

The introduction of AI in policy and planning systems can transform environmental management [41]. Conventional policymaking tends to rely on expert judgment, historical statistics, and qualitative evaluations when making decisions. Although these approaches have worked well with policymakers, they may not be able to explain the complexity and interconnectedness of environmental problems. AI offers an opportunity to make policy decisions more evidence-based, transparent, and responsive to changing conditions.

AI-powered decision support systems (DSS) are one of the key innovations in this area [42]. These systems combine AI models and data from numerous sources, including satellite images, sensors, and socio-economic data, to provide policymakers with real-time information on the environmental state. DSS can assist policymakers in detecting new environmental problems, evaluating the performance of existing policies, and determining the potential consequences of various policy interventions by processing complex datasets with AI. In one instance, AI models can recreate the impacts of various land-use policies on biodiversity, carbon emissions, and economic development, enabling decision-makers to select a policy that maximises environmental and social well-being.

The capability of AI to model complex systems and simulate the effects of various scenarios is one of the benefits of AI in policy and planning. For example, AI may be employed to model the impacts of climate change on agricultural output, water, and food security, enabling policymakers to develop strategies to mitigate climate change and safeguard vulnerable societies [43]. Likewise, the impact of various urban planning strategies on air quality, transportation, and energy consumption can be simulated using AI, enabling cities to create more sustainable and habitable urban environments [44].

Transparency and accountability in environmental governance are also very important requirements that AI supports. AI can help policymakers make decisions based on objective, evidence-driven information rather than political factors or vested interests by enabling them to access real-time data and predictive models. Moreover, AI can positively affect population participation in the policy-making process by providing citizens with access to environmental data and decision-making tools. As an example, AI-based platforms might enable local communities to check the air and water quality, deforestation, or the efficacy of conservation programs, providing them with a chance to engage more actively in environmental regulation [14].

Nonetheless, the introduction of AI into policy and planning also raises relevant ethical and governance issues. Making AI-based decision support systems transparent and accountable is a challenge. Some AI models have a black-box quality, and it may be challenging to know how policymakers and the public make decisions. The quest to enhance the interpretability and transparency of AI models is essential to ensuring that the use of AI in decision-making is trusted and acceptable to society. Also, AI should be applied in a manner that promotes justice and equality, especially in responding to environmental justice. It is possible that AI-led policies will favour select communities or industries over others and increase disparities, especially when the data upon which AI models are trained is skewed or incomplete [45].

3.4. Challenges and Limitations

Though AI has demonstrated great potential in environmental decision-making, a number of issues and restrictions have to be overcome to allow its wider deployment. The availability and quality of data are one of the major challenges. AI models need to operate on large and high-quality datasets, but in most areas, environmental data is scarce, patchy, or old. This is a vexing issue, especially in regions where ecosystems are not well researched or those that have little monitoring facilities [46].

Complexity of ecosystem dynamics is another challenge. AI models are usually based on simplified assumptions and might not be able to fully reflect the complexity of natural systems. Ecosystems are very dynamic, and most of the interacting variables are hard to predict their future behavior with a high degree of accuracy. Additionally, AI models tend to be constrained by access to credible data concerning particular environmental variables, which may cause prediction uncertainty [47].

Also, the ethical aspects of AI-driven decision-making should be taken into account. With the increasing penetration of AI in environmental governance, the question has been raised about how fair, transparent, and accountable AI-based policies are. It is necessary to have strong governance structures that can ensure that AI is utilized in a manner that enhances environmental justice and equity. This involves making sure the AI models are trained with diverse and representative datasets or making sure that AI-driven decision-making processes will not disproportionately hurt vulnerable populations or ecosystems [48].

4. Challenges and Limitations in AI-Driven Environmental Management

With the growing importance of Artificial Intelligence (AI) in environmental management, it is essential to critically scrutinise the restrictions and issues that prevent its full potential. Though AI may have great potential for monitoring the ecosystem, optimising resources, and informing policy, there are major challenges that must be overcome to make it effective and widely applicable in the environmental field. These obstacles span data quality, the complexity of environmental systems, ethical issues, technological constraints, and barriers to expanding the application of AI-based solutions [49]. Learning about these issues is important to create more resilient, sustainable, and ethical AI systems in the environmental management domain.

4.1. Data Quality and Availability

Data is at the heart of AI's success in environmental management. Artificial intelligence (AI) models, especially machine learning (ML) and deep learning (DL) models, need large quantities of high-quality data to operate effectively [50]. Nevertheless, the absence of high-quality, precise, and complete datasets is one of the most important issues of AI-driven environmental management. The information required to build AI models and make decisions is usually a diverse range of data, such as satellite data, remote sensing data, sensors utilized in the ecosystem, field surveys, and citizen science projects. All of these data sources have limitations and discrepancies that can severely affect the effectiveness and accuracy of AI-based solutions.

The inconsistency in environmental data across regions and ecosystems is one of the most important problems in environmental data [14]. In most regions across the world, particularly in remote or underdeveloped regions, there is a lack of environmental data, or the data is old. Monitoring systems, particularly in low-income countries, may not have the necessary infrastructure to collect and process large volumes of data. Moreover, the data can be gathered at arbitrary times, which is problematic in terms of real-time monitoring and predictive modeling. To illustrate, in biodiversity monitoring, the lack of detailed information on species distribution or ecosystem well-being in some regions can be a barrier to creating effective AI models for informed conservation decisions.

Further, the variety of environmental data is another challenge [51]. Environmental data is usually unstructured or heterogeneous, with different formats, e.g., satellite images, sensor data, audio files, and text notifications. AI models, in particular those based on deep learning, demand structured information that can be processed efficiently. Although recent developments in AI methods, including natural language processing (NLP) and computer vision, have enabled processing of some unstructured data, these methods remain unable to handle complex, multimodal data sources. The absence of a unified data format also makes unifying data across sources more challenging, making it hard to construct unified and comprehensive AI models.

Although there may be data collection infrastructure, the quality of data may be affected in many instances by errors, sensor failures, or human bias in data collection, even in areas where data collection infrastructure has been established. For example, in wildlife surveillance using camera traps, AI models might not be able to recognise the species correctly when the images are out of focus, low quality, or in awkward poses. On the same note, satellite images, although effective, have a weakness: cloud cover that hampers viewing of land or water bodies. Inaccuracies in data can result in incorrect predictions or suboptimal decision-making, undermining the potential benefits of AI in environmental management[52].

To resolve these data quality and availability issues, a better data collection system, a more comprehensive monitoring network, and a uniform data format are necessary[53]. Moreover, it is important to invest in research to enhance data validation, sensor technologies, and to fill data gaps to make AI models reliable in environmental contexts. **Table 4** provides a summary of the key obstacles to AI applications in environmental management, especially when it comes to data quality and ecosystem complexity.

Table 4. Challenges in AI-Driven Environmental Management. This table outlines the primary challenges and potential solutions for AI deployment in environmental contexts.

Challenge	Description	Impact on AI Applications	Potential Solutions
Data Quality and Consistency	Inconsistent data across regions and outdated datasets	Reduced accuracy of AI predictions and limited generalizability	Improved data collection, standardization of formats
Ecosystem Complexity	Interconnected ecological processes difficult to model	Models may oversimplify ecosystem dynamics, leading to inaccurate forecasts	Hybrid modeling approaches, multi-scale models
Bias in AI models	Biased training data leading to inequitable decisions	AI systems may prioritize certain stakeholders or ecosystems	Use of diverse, representative datasets, and fairness audits
Lack of Data Infrastructure	Limited sensor networks and data access in remote areas	Difficulty in scaling AI solutions and a lack of real-time data	Investment in sensor technologies and global data-sharing networks

4.2. Complexity of Ecosystem Dynamics

Ecosystems are highly interconnected, complex, and dynamic. These are composed of several interacting parts, such as flora, fauna, microorganisms, soil, air, and water, which are affected by external factors, such as climate, human activity, and natural events. This is one of the biggest challenges in AI models, which usually simplify their assumptions to make predictions. Although AI can detect trends in big data sets, it is hard to capture the total diversity of interactions and feedback in ecology[54].

As an illustration, AI models that are created to forecast changes in biodiversity would not be able to take into consideration the entire complexity of ecological interactions[13]. The species in an ecosystem are not solitary objects; they relate to each other in a complex manner, in terms of predation, competition, and symbiosis. Also, human actions, including farming, urbanization, and deforestation, have far-reaching and generally unforeseeable impacts on ecosystems. Even AI models that use machine learning might not be able to represent these complexities and nonlinear interactions that cause changes in the ecosystem.

More so, ecosystems have continuously evolved, usually as a reaction to both natural and human-induced factors. This renders it difficult to come up with AI models that are capable of forecasting future ecosystem conditions, particularly in the long run. As an example, climate change is changing the weather patterns, sea levels, and the distribution of species on Earth. Although AI models can forecast certain factors of climate change, the long-term and cascading impacts of these changes on ecosystems are not well understood. This renders AI hard to offer credible forecasts in areas of high uncertainty, and consequently, complicates the procedure of making decisions on the basis of these forecasts[47].

In addition, the spatial and temporal scales of ecosystem processes are diverse, which is also problematic for AI models that require analyzing data at different scales[55]. Ecosystem processes are driven by various levels of resolution, including local, site-based processes, such as soil fertility, and global processes, such as patterns of ocean circulation. Trained AI models using a dataset at a single scale (spatially or temporally) can be poor predictors at different scales. A case in point is that a model created to forecast forest health in one area might not apply to another forest ecosystem that has different species makeup, soil types, and climatic conditions. This spatial and temporal heterogeneity of ecosystem processes requires the creation of flexible and adaptable AI models that can respond to these changes.

To overcome these issues, AI models should be more flexible and complex, with more ecological processes and feedback loops included. Further developments in hybrid modeling, including machine learning with conventional ecological models, can offer a more holistic perspective of ecosystem dynamics[56]. Also, further studies are required to develop AI models that can integrate data collected across various scales and account for existing uncertainty in ecosystem processes.

4.3. Ethical and Societal Implications

With AI being introduced into environmental management, it is essential to focus on the ethical and societal aspects of AI implementation. Among the main issues is the possibility of bias in AI models, which can arise from biased training data or algorithms that favour some outcomes over others. When biased AI models are used in the context of environmental management, unfair or inequitable decisions might be made, especially when these decisions affect marginalized or vulnerable communities [57].

An example of this is the use of AI in decision-making in land-use planning or resource allocation that may favor richer or more influential actors and disregard the interests of indigenous people or low-income groups that depend on natural resources the most [58]. This may further exacerbate existing environmental injustices and widen disparities in access to resources, including clean water, air, and land. It is thus vital that AI systems are designed in an equitable way to prevent such outcomes.

Furthermore, AI-based environmental policies may have unforeseen effects, especially when they prioritise certain environmental outcomes over others. As an illustration, AI models to optimise water consumption may favour agricultural productivity at the expense of the local population or ecosystem, thereby causing water shortages in the risk zone. In the same vein, AI-based optimization of land-use patterns to achieve economic development may cause the destruction of natural habitats, which will further contribute to the loss of biodiversity. One should therefore ensure that AI systems factor in a large number of stakeholders and results, including social, economic, and environmental [59].

The other ethical issue is the possibility of loss of human agency in environmental decision-making. With the increasing involvement of AI systems in decision-making, the threat of excluding human judgment and values in favour of algorithmic recommendations is present [60]. This may result in a technocratic style of environmental regulation, in which decisions are made exclusively on data-driven insights, without regard for human values, cultural backgrounds, or local understandings. To prevent this, it is important that AI-based decision-making practices are transparent and subject to human control and responsibility. **Figure 1** shows the ethical implications of AI use in decision-making in environmental management, including fairness, transparency, and privacy.

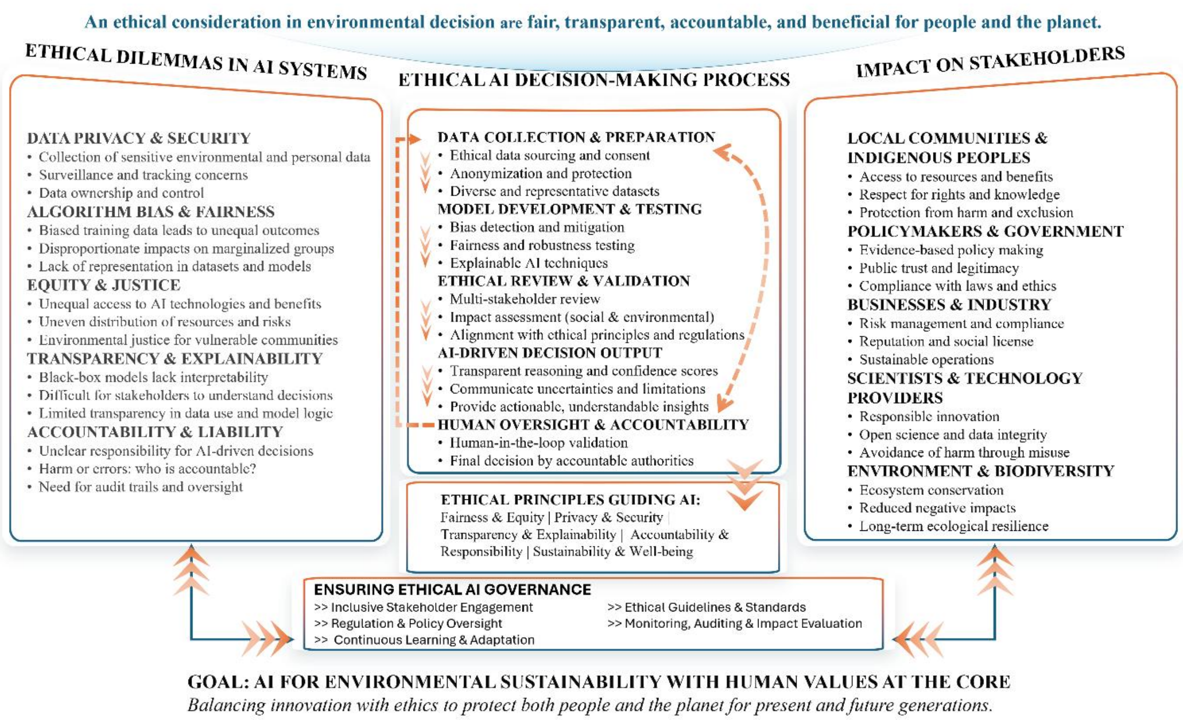

Figure 1. AI Ethical Considerations in Environmental Decision-Making. This figure highlights key ethical issues, such as bias, transparency, and privacy concerns, associated with AI systems in environmental governance.

Besides these issues, there is also concern about data privacy and surveillance due to the extensive use of AI in environmental management[61]. AI-based monitoring systems, such as those used to track deforestation or biodiversity, may rely on large-scale data collection, and people and communities may be concerned about their privacy. For example, in regions where AI is employed to monitor wildlife or land-use changes, one may have concerns about local populations being tracked or sensitive data being collected without their knowledge. To address these ethical issues, it is necessary to establish robust data governance systems that ensure privacy, transparency, and accountability.

4.4. Technological and Operational Barriers

Although AI has improved, there are still considerable technological and operational obstacles that must be overcome to achieve its extensive use in environmental management. The absence of infrastructure to implement AI solutions on a scale is one of the most urgent issues[62]. In most areas, especially in the developing world, the required data collection systems, sensor networks, and computing resources are not available. Setting up such infrastructure may be prohibitively expensive, so governments, NGOs, and other stakeholders may not be able to implement AI-based solutions.

The other operational hurdle is the integration of AI into current environmental management systems. Environmental monitoring systems have been set up by many countries and organizations, and these systems are typically not interoperable among various sectors. The implementation of AI in such systems requires a lot of coordination among stakeholders and the creation of standard data formats and protocols. Also, the implementation of AI-based solutions can be associated with the need for special skills and expertise, which are sometimes not available in local communities or governmental agencies[63].

Moreover, it is feared that AI solutions are not scalable. Although AI has been shown to be effective in small-scale applications or pilot projects, these solutions are difficult to extend to larger areas or ecosystems. For example, AI models designed to track biodiversity in one national park might not be readily applicable to another park with different species, climatic conditions, and threats. This is because there are no standardized methods of using AI in environmental management, so it is hard to repeat successful pilot projects at scale[63].

5. Insights and Future Directions

With the world confronting unprecedented environmental threats, the integration of Artificial Intelligence (AI) into environmental management is a promising frontier for advancing sustainability and ecosystem conservation. AI has great potential to solve urgent environmental problems on the planet, whether through real-time monitoring of ecosystems, resource allocation optimisation, or policy creation. The present review has discussed the potential of AI in different areas of environmental management, including environmental monitoring and biodiversity, predictive decision-making, and policy planning[64]. Nevertheless, as noted throughout this paper, the journey towards full utilisation of AI in environmental management is fraught with obstacles along the way to achieving the technology's full potential.

5.1. Insights

The most prominent impact of AI in environmental management is that it is able to process and analyze large volumes of environmental data to produce insights that would not have been possible to acquire using conventional methods. The use of AI-based technologies, including remote sensing, drones, and IoT sensors, has transformed ecosystem monitoring by enabling more efficient data collection and analysis. **Figure 2** shows the AI process of ecosystem surveillance, beginning with data gathering and continuing with data examination and decision-making. AI can help monitor ecosystems in real time by automating data processing and pattern recognition, enabling early identification of environmental stressors such as pollution, habitat degradation, and climate change impacts. These abilities render AI an invaluable resource in local and global initiatives to preserve biodiversity and ecosystem services[65].

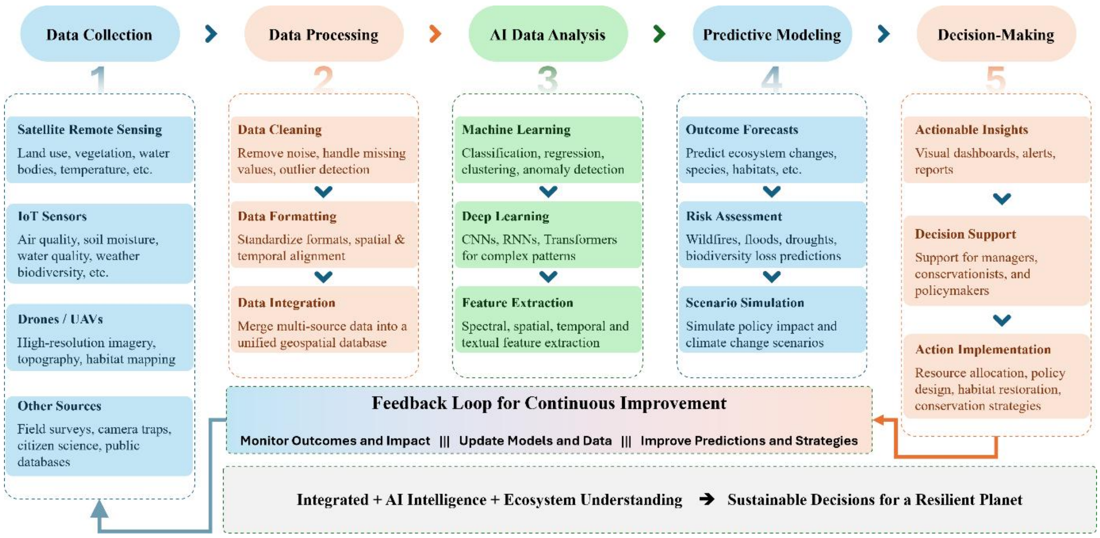

Figure 2. AI Workflow for Ecosystem Monitoring and Decision-Making. This figure demonstrates the stages of ecosystem monitoring and how AI processes data into actionable insights for decision-making.

Moreover, AI has been very promising in predictive decision support, which assists decision-makers in making predictions regarding the possible environmental conditions in different scenarios [66]. Invasive species spread, the effects of climate change on biodiversity, and the future of ecosystems are being predicted with machine learning models. The optimization algorithms that AI can power are allowing more efficient utilization of natural resources, such as water, land, and energy, in resource management. The mentioned capabilities are especially essential because the world has to deal with excessive consumption and resource depletion, which means that AI helps to make sure that resources are used in a sustainable way.

The introduction of AI in policy and planning operations has also increased its application in the field of environmental governance [67]. Through its ability to offer decision-support tools, AI can assist policymakers in coming up with evidence-based policies that would strike a balance between the needs of economic development and the conservation of natural resources. With AI-powered systems, environmental systems can be better modeled, and land-use planning, conservation strategies, and climate change adaptation decisions are made more informed. Additionally, AI can enable more people to be involved in environmental governance by making environmental information and decision-making tools available to citizens in real time.

Nonetheless, there are issues that accompany the popularisation of AI in environmental management. The most significant constraints, including data quality and availability, the complexity of ecosystem processes, and the ethical issues AI applications raise, should be addressed to enable AI to achieve its potential [68]. Moreover, operational issues, such as integrating AI into the current environmental management framework and scaling AI applications, remain an impediment to successful implementation.

5.2. Future Directions

Although AI has already made great strides in environmental management, future applications are even more promising, as emerging technologies and interdisciplinary approaches present new opportunities. The next round of research and development in AI should focus on a few key areas to maximise the technology's potential.

5.2.1. Improving Data Infrastructure and Quality

The quality of the data, its completeness, and standardisation are the key factors in the success of AI in environmental management [69]. The insufficiency of data, especially in remote or unsupervised areas, is one of the highest priorities for AI systems. Subsequent research ought to focus on building stronger data collection facilities, especially in underserved regions. Governments, international organisations, and NGOs can be instrumental in financing and sponsoring large-scale environmental data-gathering initiatives, especially in areas where ecosystems are most susceptible to climate change and human activities.

Also, data quality should be enhanced to ensure the quality of AI-based models [69]. The development of sensor technologies, including remote sensing satellites and IoT sensors, will enable more frequent, more accurate data, enhancing the accuracy of AI predictions. More comprehensive datasets (including a wider range of environmental variables) are also needed. By combining these datasets with available environmental monitoring systems, it will be possible to develop more robust and accurate AI models to monitor ecosystem health.

5.2.2. Advancing AI Models for Ecosystem Complexity

The complexity of ecosystems has been one of the challenges in implementing AI in environmental management [70]. Since ecosystems are highly dynamic and influenced by numerous interacting variables, it is not easy to create AI models that accurately predict their behaviour. The future of AI models should prioritise greater incorporation of ecological processes, such as complex feedback mechanisms and nonlinear interactions that govern ecosystems.

Such complexities can be overcome by conducting research on AI that applies hybrid models that integrate machine learning with traditional ecological models. By combining the power of AI to analyse big data with ecological models of ecosystem processes, researchers can develop more precise models that explain these processes. Moreover, multi-scale and multi-disciplinary approaches could enable AI models to operate across varying spatial and temporal scales and provide a more comprehensive picture of an ecosystem's behaviour [71].

5.2.3. Enhancing Model Interpretability and Transparency

With the increasing integration of AI models into environmental decision-making, it is essential to make them interpretable and transparent. Many AI models, particularly deep learning models, are black boxes, so users find it hard to know how their decisions are made. Within the context of environmental management, this lack of transparency may erode trust in AI systems and impede their use [72].

To counter this, future AI research needs to focus on developing more explainable models that provide explicit answers about how predictions are made [73]. Particularly relevant in environmental applications are explainable AI (XAI) techniques, which strive to enhance the transparency and understandability of machine learning models. To illustrate, when making decisions related to biodiversity monitoring, decision-makers need to comprehend the rationale of AI predictions regarding species populations to respond accordingly. Offering stakeholders a better understanding of AI decision-making will help build trust and acceptance of AI-driven environmental policies.

5.2.4. Ensuring Ethical AI Implementation

There will be a growing role for ethical concerns as AI becomes more involved in environmental management. The main issue is to make sure that AI-based decisions are reasonable, fair, and will not disproportionately negatively affect vulnerable populations or ecosystems. Specifically, the systems developed to implement AI should be designed without biases that could lead to the unfair allocation of environmental resources or benefits [74].

Further research should focus on developing moral codes for AI use in environmental management. Such guidelines need to be focused on the principles of transparency, inclusiveness, and fairness, so that AI systems can take into account the needs of various stakeholders, such as marginalized communities and indigenous populations that tend to be the most impacted by environmental changes. Additionally, AI systems must be designed to advance environmental justice by ensuring that AI-backed policies and activities are fair and do not exacerbate existing disparities [75].

Moreover, the privacy issues surrounding AI-based environmental surveillance must be addressed. With the growing dependence of AI systems on mass data collection, especially through IoT sensors and remote sensing technologies, the threat of surveillance and information abuse grows. The design and implementation of AI systems should prioritize the protection of the privacy of individuals and local communities and should be carried out in a responsible and informed manner in terms of data collection [14].

5.2.5. Addressing Operational and Technological Barriers

Although AI can revolutionise the field of environmental management, it still faces serious challenges to large-scale adoption, especially in infrastructure, scalability, and expertise. A large portion of the world, particularly the developing world, is not technologically equipped to implement AI-based solutions on a global scale. Future studies ought to focus on creating low-cost, scalable AI applications that can be easily integrated into existing environmental management systems, especially in low-resource contexts [10].

Operational issues, including the integration of AI into current monitoring systems, should also be resolved. Environmental management systems also tend to operate in silos, and there is a lack of integration in data collection across different sources and departments. Data formats, protocols, and systems standardisation will be vital in enabling AI models to access and process data from various sources. In addition, the creation of open-source AI tools and platforms will contribute to the democratization of access to AI technologies to enable a wider spectrum of stakeholders to benefit from AI-based environmental management [76].

Capacity-building and training programs will also play a crucial role in breaking down the technology barrier. With the ongoing development of AI technologies, the demand to hire skilled professionals capable of designing, implementing, and supporting AI systems in environmental settings is increasing. The next step is to create educational courses and training to cultivate AI prowess in the environmental arena, so that professionals are prepared to address AI implementation issues in environmental management.

6. Conclusions

To sum up, AI offers radical potential for the advancement of environmental management and sustainability. AI can help solve some of the most urgent environmental issues the planet faces by improving ecosystem monitoring, streamlining resource utilisation, and informing evidence-based policies. Nonetheless, a successful application of AI in environmental management involves numerous challenges, such as data quality, ecosystem complexity, ethical issues, and technological barriers.

The further evolution of AI-based solutions will be determined by the ability to solve these issues through interdisciplinary cooperation, investment in data infrastructure, and the formation of ethical and governance systems. In this way, AI can significantly contribute to ecosystem sustainability, the sustainable management of resources, and environmental justice. The use of AI in environmental management is bound to grow in the coming decades, and new possibilities will be available to save and protect the natural world and offer it to future generations.

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