Review Article

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AI and IoT in biodiversity assessment

Abstract

The integration of Artificial Intelligence (AI) and Internet of Things (IoT) technologies has revolutionized biodiversity assessment practices in recent years. This comprehensive review explores the various applications of AI and IoT in biodiversity assessment, highlighting their contributions to data collection, analysis, and conservation efforts. The synergy between AI algorithms and IoT sensors enables real-time monitoring of species diversity, habitat health, and environmental changes, thereby enhancing our understanding of ecosystem dynamics and supporting effective conservation strategies. Key methodologies discussed include automated species identification, species distribution modeling, wildlife monitoring and tracking, ecological forecasting, environmental DNA (eDNA) analysis, and data integration and visualization. The review also addresses challenges such as data quality and standardization, ethical and privacy concerns, and the need for capacity building. Future directions emphasize advancements in sensor technology, AI algorithms, IoT networks, data integration, and public participation. This manuscript underscores the transformative potential of AI and IoT in advancing biodiversity science, promoting sustainable resource management, and safeguarding biodiversity for future generations.

Keywords: biodiversity assessment, artificial intelligence (AI), internet of things (IoT), species monitoring, habitat health, conservation strategies, machine learning, real-time data, ecological research, environmental monitoring

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Introduction

Biodiversity assessment is crucial for understanding the health and dynamics of ecosystems, guiding conservation efforts, and mitigating biodiversity loss in the face of global environmental challenges. Traditionally, biodiversity assessments relied on labor-intensive field surveys and manual data collection methods, which are often time consuming, resource intensive, and limited in spatial and temporal scope. The advent of AI and IoT technologies has revolutionized these practices by offering innovative solutions for data acquisition, analysis, and interpretation in biodiversity science.

AI, encompassing machine learning (ML) algorithms and deep learning models, excels in processing large volumes of complex data, identifying patterns, and making predictions with high accuracy.[1] IoT devices, including sensors and remote monitoring systems, provide real time data on environmental parameters such as temperature, humidity, and habitat conditions.[2] The synergy between AI and IoT facilitates automated species identification, habitat mapping, population monitoring, and ecosystem health assessment, thereby revolutionizing biodiversity research and conservation strategies.[2]

The assessment and monitoring of biodiversity are critical endeavors in understanding and conserving Earth's rich tapestry of life.[3] Biodiversity, encompassing the variety of species, ecosystems, and genetic diversity, underpins ecosystem services essential for human wellbeing, from clean air and water to food security and climate regulation. However, amid escalating anthropogenic pressures such as habitat loss, climate change, and invasive species, traditional biodiversity assessment methods face challenges in comprehensively capturing and analyzing complex ecological dynamics.

In recent years, advancements in Artificial Intelligence (AI) and the Internet of Things (IoT) have emerged as transformative tools in biodiversity science. AI, particularly through machine learning and deep learning algorithms, offers unprecedented capabilities in processing vast volumes of ecological data, identifying species, and detecting patterns that were once impractical with traditional methods.[1] Concurrently, IoT technologies, enabled by interconnected sensors and devices, provide real time environmental data acquisition across diverse habitats, enhancing spatial and temporal resolution in biodiversity monitoring.[2]

The synergy between AI and IoT presents a paradigm shift in biodiversity assessment, empowering researchers, conservationists, and policymakers with actionable insights to inform evidence-based decisions.[2] From species distribution modeling and habitat monitoring to wildlife tracking and ecological forecasting, these technologies offer scalable and cost-effective solutions to address pressing conservation challenges on a global scale.[2]

This manuscript comprehensively reviews the use of AI and IoT in biodiversity assessment, highlighting their applications, challenges, and future directions. By synthesizing current research and technological advancements, this review aims to elucidate the transformative potential of AI and IoT in advancing biodiversity science, promoting sustainable resource management, and safeguarding biodiversity for future generations.

Problem statement

To address these challenges, AI and IoT technologies offer promising solutions. AI algorithms can analyze vast amounts of data collected from various sources, such as cameras, sensors, and drones, to identify and classify different species and habitats. IoT devices can be deployed in remote locations to continuously monitor environmental conditions and gather data on biodiversity patterns. By combining AI and IoT, we can develop more efficient and accurate biodiversity assessment tools. For example, AI-powered image recognition systems can analyze camera trap data to identify and count different species, while IoT sensors can monitor changes in temperature, humidity, and other environmental factors that affect biodiversity.

These technologies can also help to expand the scope of biodiversity assessment. Traditional methods often focus on a limited number of species or habitats, but AI and IoT can enable us to study a wider range of biodiversity indicators, including genetic diversity and ecosystem health.

AI and IoT have the potential to revolutionize biodiversity assessment by overcoming the limitations of traditional methods. By improving accessibility, efficiency, accuracy, and scope, these technologies can provide valuable insights for conservation efforts and sustainable resource management.

Methodologies of biodiversity assessment using AI & IoT

Advancements in Artificial Intelligence (AI) and the Internet of Things (IoT) have revolutionized biodiversity assessment, offering novel methodologies to monitor and understand ecosystems.[4] These technologies enable the collection of vast amounts of ecological data and its analysis at unprecedented scales and resolutions. Below are key methodologies utilized in AI and IoT applications for biodiversity assessment.

Species identification and classification

Machine learning algorithms: AI based algorithms such as convolutional neural networks (CNNs) and random forests are trained on large datasets of species images or sounds to classify species accurately from field recordings or camera traps.

IoT sensors: Deployed sensors capture environmental data (e.g., temperature, humidity) and species-specific cues (e.g., bird calls, animal tracks), which are processed using AI algorithms for real time species identification.[2]

AI driven image recognition and pattern recognition techniques enable automated species identification from camera trap images, drone footage, and acoustic recordings. Convolutional Neural Networks (CNNs) and deep learning algorithms trained on large species databases can accurately classify species and distinguish between similar looking organisms, facilitating rapid biodiversity surveys and monitoring programs.[1]

Applications

1. **Wildlife monitoring and conservation**

a) AI-enabled camera traps and acoustic sensors monitor endangered species, supporting population assessments and adaptive management strategies.[5]

b) Real-time data analytics inform conservation interventions, mitigating human-wildlife conflicts and preserving biodiversity hotspots.[3]

2. **Citizen science initiatives**

a) Mobile applications and crowdsourcing platforms engage citizen scientists in species identification and data collection.

b) AI algorithms analyse crowdsourced data to validate species records, expanding ecological knowledge and supporting large-scale biodiversity surveys.

3. **Ecosystem health assessment**

a) Automated species identification monitors biodiversity indicators, detecting ecosystem changes and assessing the impacts of environmental stressors (e.g., climate change, habitat fragmentation).[3]

b) Long-term data trends support evidence-based conservation policies and adaptive management practices for resilient ecosystems.[4]

Species distribution modeling (SDM)

Data integration: AI techniques integrate diverse datasets, including satellite imagery, climate models, and species occurrence records, to predict species distributions and habitat suitability.[6]

IoT enabled environmental monitoring: Continuous data streams from IoT sensors provide fine-grained environmental variables that improve the accuracy and reliability of SDM outputs.[2]

Habitat mapping and monitoring: IoT enabled sensors and satellite imagery coupled with AI algorithms allow for high resolution habitat mapping and monitoring. AI models process multispectral and hyperspectral data to delineate habitat boundaries, detect land cover changes, and assess habitat fragmentation, providing insights into ecosystem dynamics and biodiversity hotspots.[7]

Applications

1. **Conservation planning**

a) **Habitat suitability maps:** SDM identifies critical habitats and priority areas for conservation, informing protected area design and management.[4]

b) **Species recovery programs:** Predictive models guide reintroduction efforts and habitat restoration initiatives for endangered species.

2. **Climate change impact assessment**

a) **Range shifts:** SDM forecasts potential shifts in species distributions under various climate scenarios, aiding in the development of adaptive management strategies.[6]

b) **Vulnerability assessments:** AI models evaluate species' vulnerability to climate change, supporting the prioritization of conservation actions.

3. **Invasive species management**

a) **Early detection:** SDM predicts potential invasion hotspots, facilitating early detection and rapid response measures.

b) **Risk assessment:** Models assess the ecological and economic risks posed by invasive species, guiding resource allocation for control efforts.

Wildlife monitoring and tracking

GPS and radio telemetry: IoT devices like GPS collars and radio tags track individual animals, collecting movement data used to study behavior, migration patterns, and habitat use.

AI data processing: Machine learning algorithms analyze movement patterns and habitat preferences derived from IoT collected data, providing insights into species ecology and conservation needs.[8]

Population dynamics and behavior analysis

AI powered analytics analyze movement patterns, social behaviors, and population dynamics of wildlife populations based on GPS tracking data and sensor networks.[8] Machine learning algorithms

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predict species distribution models (SDMs), population trends, and ecological niches, aiding in wildlife conservation strategies and adaptive management practices.[9]

Applications

1. **Population monitoring**

a) **Abundance estimation:** Using AI to analyse camera trap images and estimate population sizes of various species.

b) **Behavioural studies:** Monitoring daily and seasonal activities, feeding habits, and social interactions of wildlife to understand behavioural ecology.[10]

2. **Habitat use and migration patterns**

a) **Habitat preference:** Identifying critical habitats and resources used by different species through spatial analysis of tracking data.

b) **Migration routes:** Mapping migration corridors and identifying stopover sites for migratory species using GPS and satellite tracking data.

3. **Human-wildlife conflict mitigation**

a) **Early warning systems:** Implementing IoT-based early warning systems to alert communities about the presence of potentially dangerous wildlife.[2]

b) **Conflict hotspot mapping:** Analysing spatial data to identify areas with frequent human-wildlife conflicts and develop targeted mitigation strategies.[7]

4. **Conservation planning and management**

a) **Protected area management:** Using tracking data to inform the design and management of protected areas, ensuring they encompass critical habitats and migration routes.[11]

b) **Species reintroduction:** Monitoring the success of species reintroduction programs by tracking the movements and survival of released individuals.

Ecological forecasting

AI models for predictive analysis: Utilizing historical data and real-time IoT inputs, AI models forecast changes in biodiversity patterns, population dynamics, and ecosystem responses to environmental stressors (e.g., climate change, habitat fragmentation).

IoT enabled data collection: Continuous monitoring through IoT devices enables adaptive management strategies based on AI driven forecasts, supporting proactive conservation interventions.

Applications

1. **Climate change adaptation**

a) Ecological forecasts predict species responses to climate variability, facilitating proactive conservation planning and habitat restoration efforts.

b) AI-driven climate models assess the vulnerability of endemic species and ecosystem resilience to changing environmental conditions.

2. **Invasive species management**

a) AI algorithms monitor invasive species' spread and ecological impacts, guiding early detection and rapid response strategies.

b) Predictive modelling identifies high-risk areas for invasive species establishment and prioritizes mitigation interventions.

3. **Ecosystem services assessment**

a) Ecological forecasting evaluates ecosystem functions (e.g., pollination, carbon sequestration) and their contributions to human well-being.

b) AI-based economic valuation informs policy decisions and sustainable development practices for maintaining ecosystem services.

Environmental DNA (eDNA) analysis

IoT sensors and AI algorithms facilitate eDNA sampling and analysis to detect species presence through environmental samples such as soil, water, and air.[5] AI based bioinformatics tools interpret eDNA sequences, identify species signatures, and assess biodiversity in aquatic and terrestrial ecosystems, offering noninvasive methods for species monitoring and ecosystem health assessment.

Applications

1. **Biodiversity inventory**

a) **Species detection:** Using eDNA to detect the presence of rare, elusive, or invasive species in various habitats, providing comprehensive biodiversity inventories.

b) **Habitat monitoring:** Monitoring changes in species composition over time to assess the health and stability of ecosystems.[2]

2. **Conservation management**

a) **Protected area assessment:** Evaluating the effectiveness of protected areas by comparing eDNA data from within and outside these regions.[11]

b) **Restoration projects:** Tracking the success of habitat restoration efforts by monitoring the reappearance of target species through eDNA analysis.

3. **Invasive species monitoring**

a) **Early detection:** Implementing eDNA analysis for the early detection of invasive species to enable rapid management interventions.[9]

b) **Impact assessment:** Assessing the impact of invasive species on native biodiversity by analyzing changes in eDNA signatures over time.

4. **Water quality monitoring**

a) **Aquatic biodiversity:** Using eDNA to assess the biodiversity of aquatic ecosystems and monitor water quality by detecting indicator species.

b) **Pollution impact:** Evaluating the impact of pollution on aquatic life by tracking changes in eDNA signals corresponding to sensitive species.

Data integration and visualization

AI driven data fusion: Integrating multisource data (e.g., satellite imagery, ground surveys, and IoT sensor data) using AI techniques facilitates comprehensive biodiversity assessments and ecosystem monitoring.

Visualization tools: AI powered data visualization platforms transform complex biodiversity data into interactive maps, graphs, and dashboards accessible to researchers, policymakers, and the public.

Visualization tools and techniques

1. **Geospatial visualization**

a) **GIS platforms:** Utilizing Geographic Information Systems (GIS) platforms (e.g., ArcGIS, QGIS) to map species distributions, habitat types, and environmental variables.

b) **Heat maps and density plots:** Creating heat maps and density plots to visualize species abundance and distribution patterns over space and time.

2. **Interactive dashboards**

a. **Web-based dashboards:** Developing web-based interactive dashboards that allow users to explore biodiversity data through customizable maps, charts, and graphs.

a) **Real-time monitoring:** Implementing dashboards that provide real-time updates from IoT sensors, enabling continuous monitoring of biodiversity metrics.[3]

3. **3D and virtual reality (VR) visualization**

a) **3D mapping:** Employing 3D mapping techniques to visualize complex ecological landscapes and species interactions in three dimensions.[7]

b) **VR environments:** Creating VR environments for immersive exploration of biodiversity data, enhancing understanding and engagement among stakeholders.

4. **Temporal visualization**

a) **Time-series analysis:** Using time-series analysis tools to visualize changes in biodiversity over time, highlighting trends, cycles, and anomalies.

b) **Animation and simulation:** Developing animations and simulations to depict dynamic ecological processes and potential future scenarios based on predictive models.

Challenges and considerations

***Data quality and standardization*:** Ensuring IoT data accuracy and consistency is crucial for reliable AI analysis and biodiversity assessments.[12]

***Ethical and privacy concerns*:** Addressing ethical implications of AI and IoT use in wildlife monitoring, including data privacy, animal welfare, and indigenous knowledge rights.[5]

Capacity building: Promoting technical skills and capacity among stakeholders for effective AI and IoT adoption in biodiversity science and conservation.[13]

These methodologies illustrate the diverse applications of AI and IoT in biodiversity assessment, highlighting their potential to enhance ecological understanding, inform conservation strategies, and mitigate anthropogenic impacts on global biodiversity.

Experimental and theoretical methods

Experimental methods

1. **Camera trap deployment**

a. **IoT-enabled cameras:** Deploy cameras equipped with IoT connectivity to transmit data in real-time or periodically.

b. **AI-powered analysis:** Use AI algorithms to analyze captured images for species identification, behaviour analysis, and population estimation.

c. **Data validation:** Compare AI results with expert verification to assess accuracy and refine models.

2. **Sensor networks**

a. **Environmental monitoring:** Deploy networks of sensors to measure temperature, humidity, precipitation, and other environmental factors.

b. **AI-driven analysis:** Use AI to correlate environmental data with biodiversity patterns and predict habitat suitability.

c. **Real-time alerts:** Implement real-time alerts for significant changes in environmental conditions that may impact biodiversity.

3. **Drone surveys**

a) **Aerial imagery:** Use drones equipped with high-resolution cameras to capture aerial images of study areas.

b) **AI-based image analysis:** Employ AI algorithms to analyze images for land cover classification, habitat mapping, and species detection.

c) **3D modeling:** Create 3D models of landscapes to assess habitat connectivity and fragmentation.

4. **Acoustic monitoring**

a) **Bioacoustics sensors:** Deploy acoustic sensors to record soundscapes.

b) **AI-driven analysis:** Use AI to identify species-specific vocalizations and estimate population densities.

c) **Habitat characterization:** Correlate acoustic data with habitat characteristics to assess biodiversity patterns.

5. **Citizen science**

a) **Mobile apps:** Develop mobile apps that allow citizens to contribute data, such as species observations and environmental conditions.

b) **AI-assisted identification:** Incorporate AI-powered image recognition into apps to assist users in identifying species.

c) **Data validation:** Implement quality control measures to ensure data accuracy and reliability.

Theoretical methods

1. **Machine learning algorithms**

a) **Species identification:** Develop deep learning models (e.g., convolutional neural networks, recurrent neural networks) to accurately identify species from images, sounds, or genetic data.

b) **Habitat mapping:** Employ machine learning techniques to classify land cover and map habitats based on remote sensing data.

c) **Population modelling:** Use statistical models and machine learning to predict population dynamics and assess conservation status.

2. **Data fusion**

a) **Multi-sensor data:** Combine data from different sources (e.g., cameras, sensors, drones) to obtain a more comprehensive understanding of biodiversity.

b) **AI-driven integration:** Develop AI algorithms to integrate and analyze diverse data types effectively.

3. **Spatial analysis**

a) **GIS integration:** Integrate AI and IoT data with Geographic Information Systems (GIS) to analyze spatial patterns and relationships.

b) **Habitat connectivity:** Assess habitat connectivity and fragmentation to identify critical areas for conservation.

4. **Ethical considerations**

a) **Privacy and data security:** Develop ethical guidelines for data collection, storage, and sharing to protect sensitive information.

b) **Biodiversity ethics:** Consider the potential impacts of AI and IoT technologies on biodiversity and develop responsible practices.

By combining these experimental and theoretical methods, AI and IoT can provide powerful tools for biodiversity assessment, conservation, and sustainable management.

Case studies

AI based camera trapping in conservation areas

The use of AI enabled camera traps in conservation areas such as national parks and wildlife reserves has revolutionized wildlife monitoring and population assessments.[5] AI algorithms automatically analyze camera trap images, identify individual animals, and estimate population densities, providing valuable data for conservation management and antipoaching efforts.[9]

IoT driven marine ecosystem monitoring

IoT sensors deployed in marine environments collect real-time data on water quality, temperature, and marine biodiversity. AI algorithms process sensor data to monitor coral reef health, detect invasive species, and assess marine ecosystem resilience to climate change, informing marine conservation strategies and sustainable fisheries management.[4]

Challenges and limitations

1. **Data quality and consistency**

a) **Sensor accuracy and reliability:** IoT devices, such as environmental sensors and camera traps, can vary in accuracy and reliability. Inconsistent data can lead to erroneous conclusions about biodiversity trends.[12]

b) **Data standardization:** Different data sources and formats can complicate data integration efforts. Establishing and adhering to standardized data formats and protocols is essential for seamless data integration and analysis.

2. **Scalability and performance**

a) **Handling large data volumes:** The volume of data generated by IoT devices and AI algorithms can be immense, requiring robust data storage and processing capabilities. Scalability of infrastructure is crucial to manage and analyze this data efficiently.

b) **Computational resources:** Advanced AI algorithms, such as deep learning models, require substantial computational resources. Ensuring adequate infrastructure and optimizing algorithms for performance is necessary to handle real-time data processing and analysis.[1]

3. **Technical expertise and training**

a) **Skill gaps:** The effective use of AI and IoT in biodiversity assessment requires specialized knowledge in both technology and ecology. Bridging the skill gap through training and capacity-building initiatives is essential.

b) **User-friendly interfaces:** Developing intuitive and user-friendly interfaces for data collection, analysis, and visualization tools can enhance accessibility for researchers, conservationists, and policymakers.

4. **Data privacy and security**

a) **Sensitive data protection:** Biodiversity data, particularly when linked to geographic locations, can be sensitive. Ensuring data privacy and implementing robust security measures to protect against unauthorized access is critical.

b) **Ethical considerations:** The use of genetic data, such as environmental DNA (eDNA), raises ethical questions regarding data ownership, sharing, and potential misuse. Establishing clear guidelines and ethical frameworks is necessary.

5. **Environmental impact**

a) **Sensor deployment:** The deployment of IoT devices in natural habitats can have unintended environmental impacts, such as disturbances to wildlife. Minimizing the ecological footprint of these technologies is important.

b) **Energy consumption:** IoT devices and data processing centres consume energy. Implementing energy-efficient technologies and practices can mitigate their environmental impact.

6. **Cost and resource allocation**

a) **Funding and resources:** The deployment and maintenance of AI and IoT systems require significant financial investment. Securing sustained funding and resources is crucial for long-term biodiversity monitoring programs.

b) **Cost-benefit analysis:** Conducting cost-benefit analyses to evaluate the return on investment for AI and IoT technologies in biodiversity assessment can guide resource allocation decisions.

7. **Data integration and interoperability**

a) **Heterogeneous data sources:** Integrating data from diverse sources, including IoT devices, satellite imagery, and field observations, can be challenging. Developing interoperable systems and frameworks is essential for effective data integration.[7]

b) **Data quality assurance:** Ensuring the quality and reliability of integrated data through rigorous validation and verification processes is critical for accurate biodiversity assessment.

8. **Policy and regulatory frameworks**

a) **Regulatory compliance:** Navigating regulatory requirements for data collection, storage, and sharing, particularly across different jurisdictions, can be complex. Ensuring compliance with local, national, and international regulations is necessary.

b) **Policy support:** Advocating for policies and regulations that support the use of AI and IoT in biodiversity assessment can facilitate their adoption and integration into conservation efforts.

9. **Societal and cultural considerations**

a) **Community engagement:** Engaging local communities and stakeholders in biodiversity monitoring initiatives can enhance data collection efforts and ensure that technological interventions are culturally appropriate.

b) **Equity and inclusion:** Ensuring equitable access to AI and IoT technologies for biodiversity assessment, particularly in resource-limited settings, is important for inclusive conservation efforts.

10. **Uncertainty and model limitations**

a) **Model accuracy:** AI models, such as species distribution models (SDMs), are based on assumptions and may have limitations in accuracy.[12]

Future directions

The future of AI and IoT in biodiversity assessment holds immense promise for advancing ecological research, conservation science, and environmental management Future directions in this field will likely focus on several key areas:

1. **Advancements in sensor technology**

a) **Miniaturization and mobility:** Development of smaller, more mobile sensors that can be deployed across diverse and challenging environments will enhance data collection capabilities.

b) **Multi-sensory integration:** Combining various types of sensors (e.g., visual, acoustic, chemical) to capture comprehensive data about ecosystems will improve the accuracy and depth of biodiversity assessments.

2. **Enhanced AI algorithms**

a) **Deep learning and neural networks:** Continued advancements in deep learning techniques will improve species identification, behaviour analysis, and ecological modelling.

b) **Edge computing:** Implementing AI algorithms directly on IoT devices (edge computing) will enable real-time data processing and immediate response actions, reducing the need for constant connectivity and large data transfers.

3. **Scalability and network connectivity**

a) **Expanding IoT networks:** Increasing the scale and coverage of IoT networks, including satellite-based IoT, will allow for global biodiversity monitoring and assessment.

b) **Interoperability standards:** Developing standard protocols for data exchange between different IoT devices and platforms will facilitate broader integration and collaboration.

4. **Big data and cloud computing**

a) **Data management platforms:** Establishing advanced cloud-based platforms for storing, managing, and analyzing large volumes of biodiversity data will enhance accessibility and collaborative research.[9]

b) **AI-driven analytics:** Leveraging AI for sophisticated data analytics and visualization will provide deeper insights into ecological patterns and trends.

5. **Citizen science and community engagement**

a) **Public participation:** Engaging citizen scientists through user-friendly IoT devices and AI-powered apps will expand data collection efforts and raise public awareness about biodiversity conservation.

b) **Educational initiatives:** Developing educational programs and tools to teach the public and students about the use of AI and IoT in biodiversity assessment will foster a more informed and involved community.

6. **Predictive and prescriptive analytics**

a) **Ecological forecasting:** Utilizing AI to predict future changes in biodiversity and ecosystem health based on current and historical data will support proactive conservation strategies.

b) **Automated decision support:** Implementing AI systems that can provide prescriptive recommendations for conservation actions based on real-time data will enhance decision-making processes.[3]

7. **Policy and ethical considerations**

a) **Data privacy and security:** Addressing concerns related to data privacy and security, especially when involving sensitive ecological data, will be crucial for ethical AI and IoT deployment.

b) **Regulatory frameworks:** Developing and implementing regulatory frameworks that govern the use of AI and IoT in biodiversity assessment will ensure responsible and sustainable practices.

8. **Interdisciplinary collaboration**

a) **Cross-sector partnerships:** Encouraging collaboration between ecologists, technologists, policymakers, and other stakeholders will drive innovative solutions and comprehensive biodiversity assessments.

b) **Global initiatives:** Participating in international initiatives and projects aimed at leveraging AI and IoT for biodiversity conservation will promote knowledge sharing and global ecological stewardship.

9. **Long-term monitoring programs**

a) **Sustainable funding:** Securing long-term funding and resources for continuous biodiversity monitoring programs will ensure the sustainability and effectiveness of AI and IoT applications.

b) **Adaptive management:** Implementing adaptive management strategies that utilize real-time data for ongoing assessment and refinement of conservation actions will improve outcomes.

10. **Integration with other emerging technologies**

a) **Genomics and biotechnology:** Combining AI and IoT with genomics and other biotechnological advances will enable more precise and detailed biodiversity assessments at the genetic level.

b) **Augmented and virtual reality (AR/VR):** Utilizing AR and VR technologies to visualize biodiversity data and ecosystems in immersive ways will enhance research, education, and public engagement.[14]

Recommendations

The integration of Artificial Intelligence (AI) and Internet of Things (IoT) technologies represents a transformative advancement in the field of biodiversity assessment.[4] These technologies provide innovative and efficient solutions for data acquisition, processing, and analysis, which are crucial for understanding the complex dynamics of ecosystems and guiding conservation efforts. AI algorithms, such as machine learning and deep learning models, excel in processing large volumes of complex data, identifying patterns, and making accurate predictions. Concurrently, IoT devices, including sensors and remote monitoring systems, offer real-time data on environmental parameters, enabling continuous and comprehensive monitoring of species diversity, habitat health, and environmental changes.[3] The synergy between AI and IoT facilitates automated species identification, habitat mapping, population monitoring, and ecosystem health assessment. These advancements significantly enhance our ability to conduct rapid biodiversity surveys, monitor ecological changes, and develop adaptive management strategies to mitigate biodiversity loss and promote conservation.[9] Despite the numerous benefits, the integration of AI and IoT in biodiversity assessment also presents challenges, including data quality and standardization, ethical and privacy concerns, and the need for capacity building among stakeholders. Addressing these challenges requires interdisciplinary collaboration, robust regulatory frameworks, and ongoing technological innovation. Looking ahead, the future directions for AI and IoT in biodiversity assessment are promising. Continued advancements in sensor technology, enhanced AI algorithms, expanded IoT networks, and improved data integration and visualization tools will further refine our ability to monitor and conserve biodiversity. Additionally, greater public participation through citizen science initiatives and the integration of AI and IoT with other emerging technologies will expand the reach and impact of biodiversity conservation.[4,14–16]

Conclusion

The traditional methods of biodiversity assessment, reliant on labour-intensive field surveys and manual data collection, are struggling to keep pace with the escalating threats to global biodiversity. However, the emergence of Artificial Intelligence (AI) and Internet of Things (IoT) technologies present a paradigm shift in this field. This review comprehensively explored the applications of AI and IoT in biodiversity assessment, highlighting their methodologies, potential, and challenges. AI algorithms excel at processing vast ecological data sets, identifying species, and detecting patterns. IoT devices provide real-time environmental data acquisition, enhancing the spatial and temporal resolution of biodiversity monitoring.

The fusion of AI and IoT offers a powerful toolkit for researchers, conservationists, and policymakers. These technologies can be utilized for species identification and classification, species distribution modelling, wildlife monitoring and tracking, ecological forecasting, and environmental DNA analysis. Additionally, AI-driven data integration and visualization tools transform complex data into user-friendly formats, facilitating informed decision-making. There are, however, challenges to overcome. Data quality and standardization, ethical considerations, capacity building, and ensuring scalability and performance are all crucial aspects that need to be addressed. Furthermore, navigating complex policy and regulatory frameworks, alongside societal and cultural considerations, requires a multifaceted approach.

The future of AI and IoT in biodiversity assessment is bright. Advancements in sensor technology, enhanced AI algorithms, improved scalability and network connectivity, and the utilization of big data and cloud computing will further revolutionize this field. Engaging citizen scientists and fostering interdisciplinary collaboration will be instrumental in achieving this goal. Ultimately, by embracing AI and IoT technologies and addressing the associated challenges, we can move towards a future of more effective biodiversity assessment, promoting sustainable resource management and safeguarding the Earth's irreplaceable tapestry of life.

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Conflicts of interest

The author declares that there are no conflicts of interest.

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