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Digital transformation of the future of forestry: an exploration of key concepts in the principles behind Forest 4.0

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This paper looks at the incorporation of blockchain and Internet of Things (IoT) technologies into Forest 4.0, a sector that harnesses advanced tools such as artificial intelligence and big data for efficient and sustainable forest monitoring and management. The synergy of blockchain and IoT has gained significant attention, offering a secure and decentralized framework for data management, traceability, and supply chain oversight. The provided use cases demonstrate how these technologies improve forest practices, with insight into smart contract implementation and decentralized systems for sustainable forest management. The major findings imply that digital technologies such as blockchain, IoT, AI, WSNs, etc. can help improve forest management sustainability, efficiency and transparency, and integration of these technologies can provide significant information for decision-making and resource allocation, as well as improve supply chain transparency and sustainable forest practices.

KEYWORDS
Forest 4.0, smart forestry, digital transformation, forestry sector, sustainability, stakeholder perceptions

1 Introduction

1.1 Background

Technology innovations have had a tremendous impact on the way the industry developed. Initially with the introduction of steam engines, then with the introduction of electricity and continued after with the introduction of Information and Communication Technologies (ICT) and robotics, it became economically sustainable research in the industrialization period (More and More, 2002). In this regard, Forest 4.0 refers to the fourth industrial revolution of the forest industry (Singh et al., 2022). This transformation, often referred to as Forest 4.0, is characterized by the integration of technologies such as blockchain, the Internet of Things (IoT), wireless sensor networks (WSN), artificial intelligence (AI), etc., into forest operations (Picchi et al., 2021; Pichler et al., 2022). The purpose of Forest 4.0 is to use technology to improve the efficiency, sustainability, and profitability of the forest business, including optimizing resource use, reducing waste, improving, and facilitating decision making. Supply chain management, for example, can be performed at various stages of the supply chain, from the forest to the mill, and even beyond to the final wood product (Tzoulis et al., 2014). The integration of technologies such as Radio-frequency identification (RFID), digital survey tools, and intelligent machines into the timber supply chain improved efficiency and safety (Pichler et al., 2022). These technologies provide a wealth of data that can help better understand the impacts of management decisions on forest health, timber quality, and other aspects (Picchi et al., 2021). Intense international competition is pushing actors in wood supply chains to implement coordinated cost-saving strategies. The use of digital technologies can enable the realization of cost savings by deepening cooperation and intensifying information exchange (Kogler et al., 2021).

It is clear however, that the forest sector is still undergoing a significant transformation, driven by the advent of digital technologies and the need for sustainable forest management. The context and motivation behind Forest 4.0 lie in the need for sustainable and efficient forest management in the face of increasing pressures from global competition and environmental change. The forest sector faces multiple challenges related to the level of digital maturity, supply change issues, lack of digital competence, as well as the needs for service innovation (Holmström, 2020) and adoption of AI methods (Uddin et al., 2023). The integration of digital technologies into forest operations presents significant opportunities to tackle these challenges; as Forest 4.0 aims to reduce the negative environmental impact of forest business by encouraging sustainable forest practices, however, there are still remaining challenges that need to be overcome (Nižetić et al., 2020; Mondejar et al., 2021).

The aims of this study are to examine the feasibility of using blockchain, IoT, and AI in Forest 4.0 for sustainable forest management and conservation, through applications in the forest industry, such as monitoring and enforcement, carbon sequestration, biodiversity conservation, and community participation.

The remaining parts of this paper include the review of the literature presented in Section 2, an analysis of the technological frameworks and models in Section 3, and a detailed analysis of the use cases of Forest 4.0 in Section 4. Paper is summarized with discussion and conclusions.

2 Literature review

2.1 Forest 4.0

Forest 4.0 extends the Industry 4.0 paradigm to the forest sector, involving the digital transformation of forest operations with technologies such as IoT, AI, big data analytics and cloud computing to improve efficiency, productivity, and sustainability (Müller et al., 2019; Reitz et al., 2019; He and Turner, 2021; Molinaro and Orzes, 2022). The goal is to create a "smart forest" by interconnecting and monitoring all aspects of the ecosystem through digital technologies, including real-time forest health monitoring with sensors, AI-driven predictive modeling, and efficient resource management on digital platforms (Lausch et al., 2018; Rana and Varshney, 2021; Torresan et al., 2021; Krishnamoorthy et al., 2023). A key aspect of Forest 4.0 is the digitalization of the wood supply chain, focusing on wood tracking to improve efficiency and safety. Pichler et al. (2022) advocate the integration of RFID technology, digital survey tools, and intelligent machines into the supply chain to facilitate information flow, maintaining costs at market levels. Smart harvesting operations, as explored by Picchi et al. (2021), involve sensors and digital technologies for forest inventories, planning, and execution, enhancing sustainability through intelligent forest machines. Furthermore, Kogler et al. (2021) highlight the cost savings potential of integrated wood supply chains, emphasizing the role of digitalization in improving cooperation and information exchange.

Digital technology is gaining importance in European forest management, addressing the challenges of sustainable practices (Lazdinis et al., 2019). Forest 4.0, a novel management paradigm, uses digital tools to improve the sustainability, productivity, and resilience of forest ecosystems (Singh et al., 2022; Högberg et al., 2023). Blockchain and IoT play a crucial role in Forest 4.0, offering transformative potential for management and conservation (Monrat et al., 2019; He and Turner, 2022). The blockchain ensures secure storage of certification and traceability data, promoting transparency and integrity in forest management (zu Ermgassen et al., 2019; Kim and Huh, 2020; Ahmed et al., 2022). Real-time data from sensors, drones, and monitoring systems contribute to decision making in sustainable harvesting, fire management, and wildlife monitoring (Dainelli et al., 2021). Furthermore, IoT and blockchain help to execute carbon sequestration and biodiversity conservation programs (zu Ermgassen et al., 2019; Kim and Huh, 2020; Ahmed et al., 2022). These technologies improve sustainability, reduce costs, and foster trust among ecosystem participants, enabling effective global forest resource management.

Despite these benefits, challenges slow the widespread adoption of digital technology in forest management. The issues include lack of standards, interoperability, and high implementation costs (Baldwin, 2020; Khan et al., 2022). Legislative and governance obstacles also exist, which require changes in laws and regulations for technology adoption, with concerns about data privacy and security on blockchain networks (Aggarwal et al., 2021). Stakeholder hesitancy due to potential data exposure raises additional concerns about trust and privacy in the use of digital technology.

2.2 Artificial intelligence, blockchain, IoT and WSNs in forest management and monitoring

AI, integral to Forest 4.0, improves forest monitoring through improved precision, efficiency, and automation (Holzinger et al., 2023). Its application requires thorough consideration of the technical, economic, and ethical implications for sustainable forest management (Gabrys, 2020). Research and development efforts are crucial for exploring AI's advantages and constraints, establishing best practices, and defining standards in forestry (Ecke et al., 2022). Machine learning and computer vision process extensive data from various sources, such as satellite images, drone images, and sensor networks, providing information on forest health, biodiversity, and sustainability (Galaz et al., 2021; Ecke et al., 2022). AI automates traditional monitoring methods, improving the precision of forest inventories and ground-based observations (McKinley et al., 2017). This automation increases efficiency, reduces labor, and facilitates rapid responses to environmental concerns (McKinley et al., 2017; Sandino et al., 2018).

Unfortunately, challenges still hinder the implementation of AI. The issues include the lack of standardization, regulation and compatibility, coupled with ethical dilemmas and data protection concerns (Nishant et al., 2020). Technical hurdles such as high-quality data requirements and algorithm complexity impede widespread adoption (Nishant et al., 2020). Financial barriers, such as high costs, pose challenges for organizations and communities (Johnson et al., 2021). Questions about the precision, dependability, and ethical implications of the algorithm underscore the need for global regulatory solutions that address biases for the use of ethical AI in forest management (Bellamy et al., 2018; Kim et al., 2019; Zhang et al., 2021).

Blockchain technology, with its potential to improve traceability and transparency between value chains, is gaining attention in various sectors, including forest management (Zeadally and Abdo, 2019; Lobovikov et al., 2021; Molinaro and Orzes, 2022). In Forest 4.0, the blockchain offers a secure, decentralized platform to store and manage critical forest management information (Molinaro and Orzes, 2022). A key advantage of blockchain in forest management lies in its ability to establish a tamper-proof ledger for certification and traceability data (Pan et al., 2019; Vilkov and Tian, 2019). This ledger can include information on the origin, transportation, and management techniques of forest products, promoting transparency and integrity. Another example of using blockchain across the forest value chain is the implementation of the digital product passport in the furniture sector (Dalipi et al., 2024). The application of blockchain can enforce regulations, deter illegal activities such as logging, and support conservation initiatives (Kiptum, 2021). In addition, blockchain helps in the execution of carbon sequestration and biodiversity conservation programs by tracking and verifying credits and offsets (Bose et al., 2019; Wang et al., 2020).

However, there are unsolved obstacles to the widespread adoption of blockchain in forest management. Issues such as lack of standardization, compatibility, and high implementation costs pose challenges (Lima, 2018; Kouhizadeh et al., 2019; Prewett et al., 2020). Legislative and governance adjustments are often necessary considering concerns about data privacy and security in blockchain networks (Zhang et al., 2019). Addressing these hurdles is crucial to realize the full potential of blockchain in advancing sustainable forest management.

IoT technologies (Yunana et al., 2021) play a crucial role in Forest 4.0, providing valuable information on forest health, improving safety and efficiency, and automating forest management (Nitoslawski et al., 2019). However, challenges must be addressed, including technical, financial, privacy, security, and ethical considerations (Yadav et al., 2020), to ensure a responsible and effective implementation (Zhao et al., 2023). A key benefit of IoT in forest management is the collection and analysis of real-time data, with sensors monitoring environmental parameters such as temperature, humidity, and soil moisture (Krishnamoorthy et al., 2023). This information informs decisions about planting, harvesting, and conservation. In addition, IoT helps to detect animals, providing crucial insights into forest ecosystem richness and health. Safety and efficiency are improved by real-time monitoring of equipment and personnel in remote or hazardous areas, reducing response times to emergencies and minimizing risks (Reitz et al., 2019). Furthermore, the IoT automates and optimizes processes such as harvesting and planting trees, improving operational efficiency (Salam, 2019).

Despite these advantages, barriers to the adoption of IoT in forest management persist (Lakhwani et al., 2018). Issues such as the lack of device standardization (Saleem et al., 2018) and high implementation costs pose challenges. Privacy and security concerns arise due to the sensitive nature of data, which requires careful preservation (Frustaci et al., 2017). Ethical considerations include the responsible and sustainable use of IoT technologies in the collection of wildlife and forest data (Atlam and Wills, 2019). Overcoming these challenges is crucial for the successful and responsible integration of IoT into Forest 4.0.

Wireless Sensor Networks (WSN; Jino Ramson and Moni, 2017) are integral to Forest 4.0, utilizing numerous low-power sensors to wirelessly interact and share data with central nodes (Kandris et al., 2020). They play a crucial role in improving forest management operations by providing real-time data on health, conditions, and environmental factors such as temperature, humidity, and soil moisture levels (Alsayyari et al., 2017; Jino Ramson and Moni, 2017; Zhang et al., 2017). This information informs decision making for activities such as planting, harvesting, and conservation. WSNs also contribute to safety and efficiency by monitoring equipment and personnel in remote or hazardous areas, offering real-time location and status updates to mitigate emergencies and reduce risks (Damaševičius et al., 2023).

However, challenges remain to be solved toward the implementation of WSN in forest management (Yang et al., 2019). Technical limitations, such as restricted wireless communication range, and concerns about data privacy and security, pose obstacles (Yue and He, 2018; Li, 2019). Financial barriers, including high investment and implementation costs, further complicate widespread adoption. Initiatives should begin with small-scale experimentation before expanding or standardizing. Ethical considerations surrounding data collection from wildlife and forests must be addressed to ensure a responsible and sustainable use of WSN technologies (Ergunsah et al., 2022). Comprehensive studies are still essential to develop practical solutions for the successful application of WSN in forest management (Kumar et al., 2019).

3 Concept behind the Forest 4.0

Forest 4.0 involves a wide range of multifaceted and interconnected concepts, from digital technologies such as IoT and AI to forestry practices such as forest management and conservation. Figure 1 shows a mind map for such concepts applied in the Forest 4.0 domain. **Forest management** concept is the overarching framework for the use of digital technologies in the forest sector, as it includes the conservation and sustainable development of forests and the management of forest health, biodiversity, and deforestation. **Digital technologies** are the key enablers of Forest 4.0, as they include big data analytics, IoT,

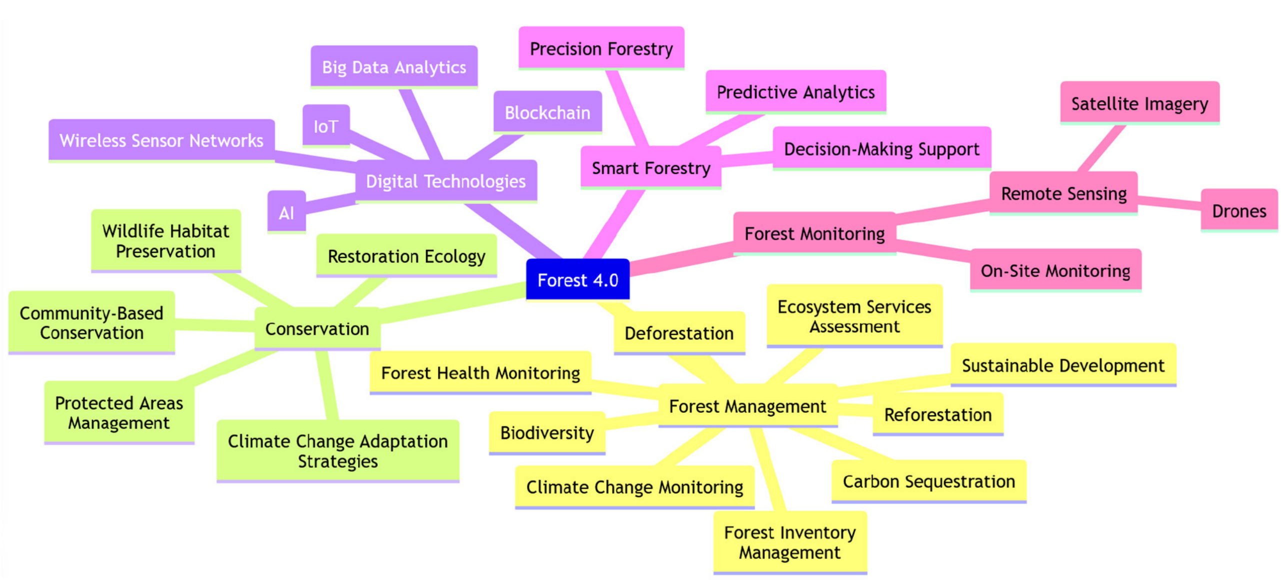

FIGURE 1
Mindmap of Forest 4.0. *Synthesized by authors of the paper*.

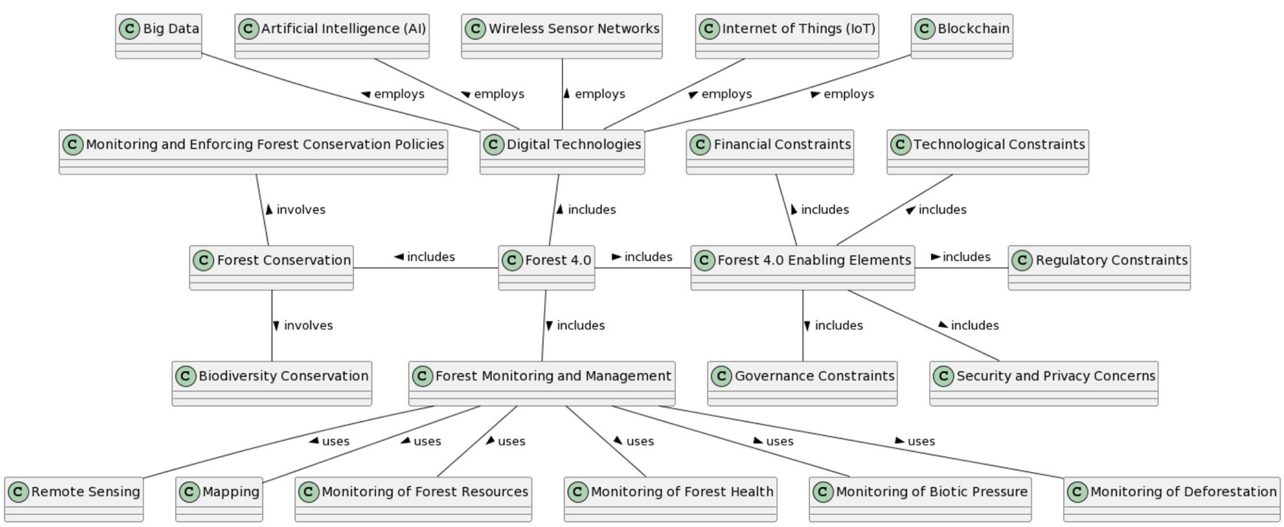

FIGURE 2
Conceptual taxonomy of Forest 4.0. *Synthesized by authors of the paper*.

WSN, AI, and blockchain, which can be used to support decision-making, improve forest management efficiency and accuracy, and provide valuable data and insights into forest conditions. **Smart forestry** concept refers to the use of digital technologies to enhance the management of forests. It includes precision forest, predictive analytics, decision-making support and assessment of ecosystem services, which can help organizations make better informed decisions, reduce the impact of environmental challenges and threats, and improve the sustainability of forests. **Forest monitoring** concept refers to the use of remote sensing, drones, satellite imagery, and *in-situ* monitoring to assess the health and conditions of forests.

We suggest inextricably linking the main elements in the Forest 4.0 domain, as effective use of digital technology in the forest sector requires a comprehensive and integrated approach to forest management that takes into account the interaction of these concepts and their interdependence.

Forest 4.0 can also be defined using a conceptual taxonomy of a classification and categorization of the different concepts and technologies that comprise the Forest 4.0 paradigm. Blockchain, the Internet of Things, wireless sensor networks, AI and big data are all examples of the digital technologies used in Forest 4.0. Forest Monitoring and Management includes the use of digital technologies to monitor and manage forests, such as remote

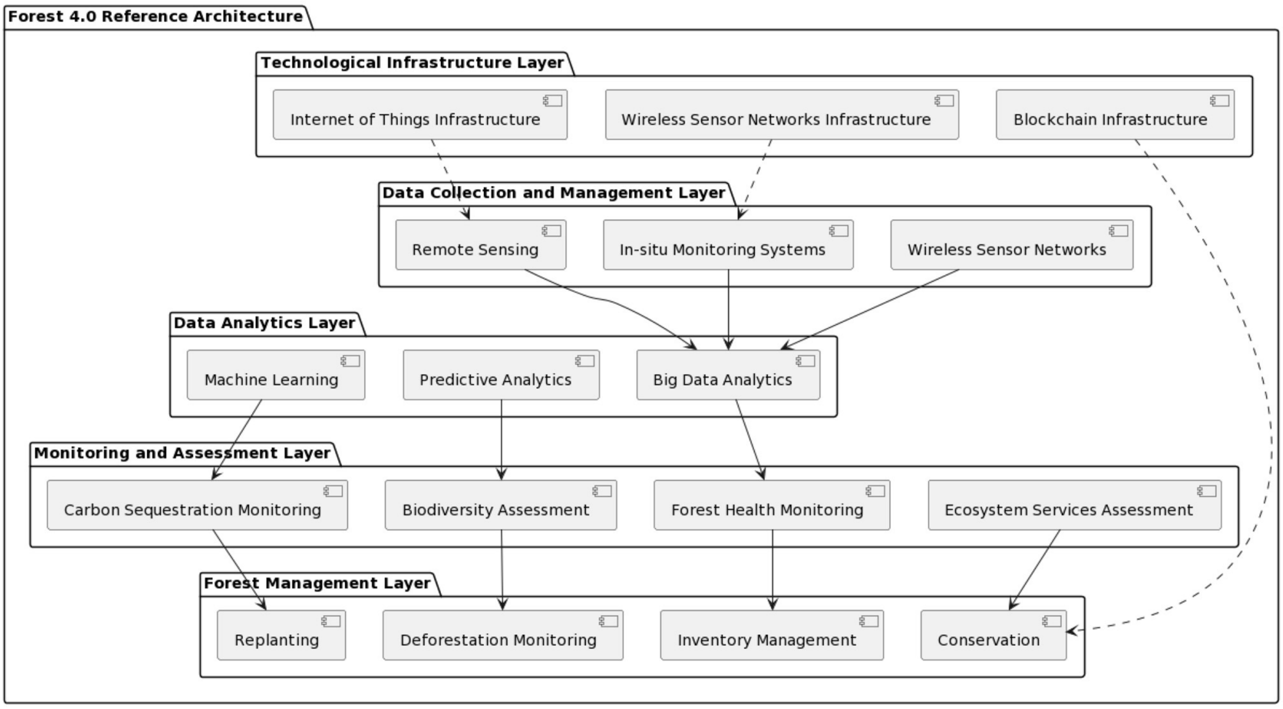

FIGURE 3
A Forest 4.0 reference model. *Synthesized by authors of the paper*.

sensing, mapping, and monitoring of forest resources, as well as monitoring of forest health, biotic pressure, and deforestation. Forest conservation is concerned with forest conservation, including monitoring and enforcing forest conservation policies, carbon sequestration, and biodiversity monitoring. Forest 4.0 Enabling elements comprise the enabling elements required for effective Forest 4.0 adoption, such as technological, financial, regulatory, and governance constraints, as well as security and privacy concerns.

This taxonomy (see Figure 2) provides an understanding of the different ideas and technologies used in Forest 4.0 while also emphasizing their interdependence and links. By categorizing these concepts and technologies, researchers and practitioners can better understand the Forest 4.0 paradigm and how it can be used to improve forest management and conservation.

A Forest 4.0 reference model (see Figure 3) explains the composition of a multilayered approach that includes advanced digital technologies such as blockchain, IoT, AI and big data to create a smart and sustainable forest management system. Data Collection and Management Layer is responsible for gathering and handling data from diverse sources such as in-situ monitoring systems, remote sensing, and wireless sensor networks. The Data Analytics layer uses big data analytics to derive insights from the data acquired in the Data Collection and Management layer and helps to make a decision-making assistance by utilizing approaches such as predictive analytics and machine learning. Monitoring and Assessment Layer monitors and assesses the health of forests, biodiversity, carbon sequestration, and ecosystem services using data analytics findings. It can also help decision making by visualizing and analyzing outcomes. The Forest Management Layer incorporates the Monitoring and Assessment Layer's outputs to assist forest management tasks such as inventory management, deforestation monitoring, replanting, and conservation. The technological infrastructure layer provides the underlying technological infrastructure to support the other levels of the architecture, such as wireless sensor networks, the Internet of Things, and the blockchain.

3.1 Reference architecture

A proposed reference architecture for Forest 4.0 (see Figure 4) includes the following components:

- A smart forest monitoring and management system, which involves the use of IoT, wireless sensor networks, artificial intelligence, and big data for real-time forest monitoring and optimized management practices (Torresan et al., 2021).
- The traceability and Compliance System, based on blockchain technology, ensures safe and transparent forest product tracking, promoting legal and sustainable trade to improve governance in the forest sector (Dddder and Ross, 2017).
- A predictive analytics and Decision Support System, driven by machine learning, helps in forest management decision making, including early warning systems for forest fires, pests, diseases, forest growth issues, and forest resources optimization (Hefeeda and Bagheri, 2007; Zhang et al., 2008; De Meo et al., 2013; Mongus et al., 2018).

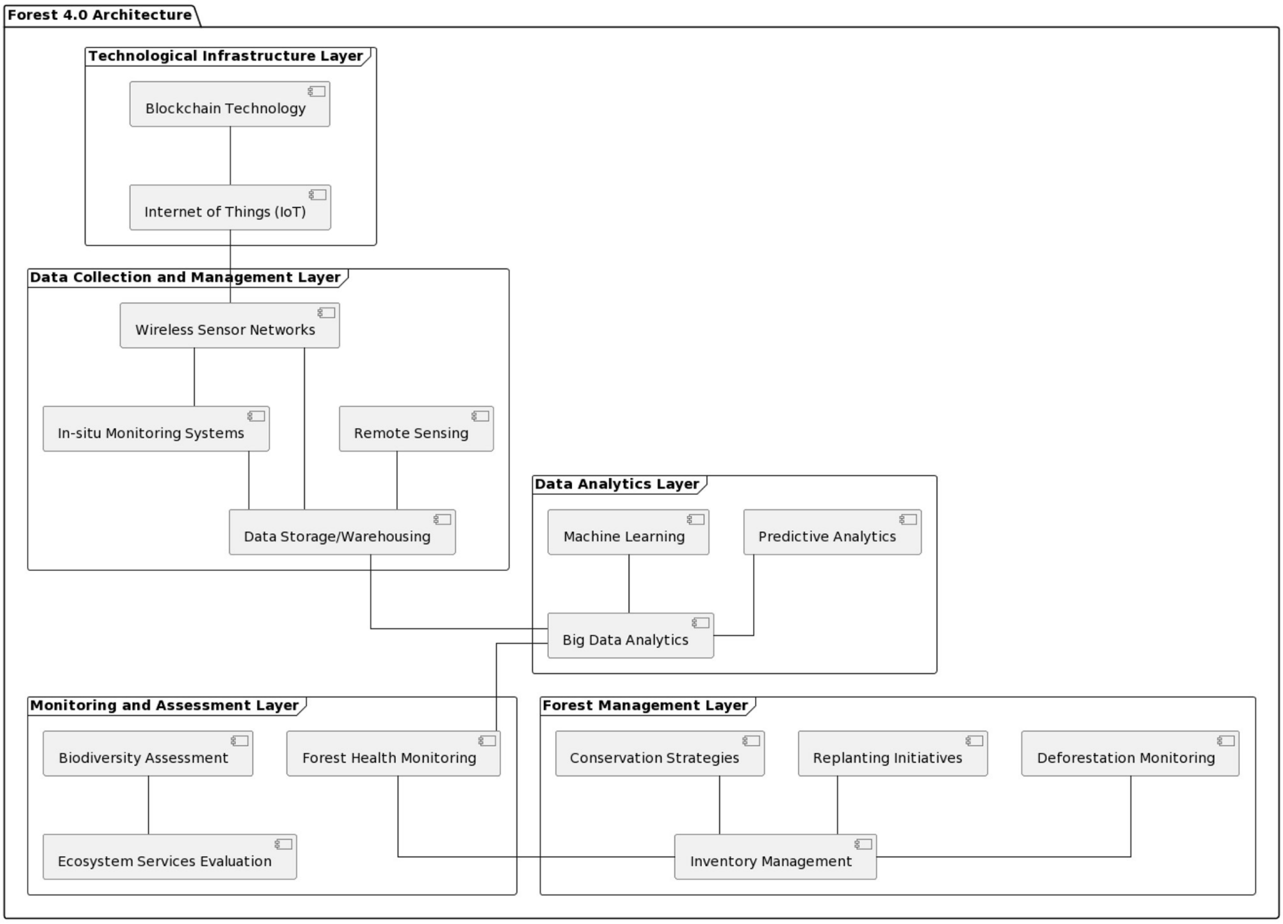

FIGURE 4
Reference architecture of Forest 4.0. *Synthesized by authors of the paper*.

- The forest resource management system integrates data for an end-to-end view of forest resources, supporting planning, execution, and monitoring. It includes tools for resource allocation, budgeting, and activity tracking (Johnson and Geldner, 2019).
- A stakeholder engagement and collaboration platform provides a secure platform for forest stakeholders to exchange information and collaborate, fostering a collective approach to forest management (MacDicken et al., 2015).

3.2 Deployment model

A Distributed Deployment Model for Forest 4.0 was developed (Figure 5) to use key digital technologies, including blockchain, IoT, and AI (Bécue et al., 2021), at various levels of forest management: local communities, state / private forest managers and international organizations (Friedman et al., 2020). Each level is assigned specific tasks based on its experience and resources. This deployment model helps optimize the strengths of different management levels, enhancing the robustness and efficiency of the system. For example, local communities use IoT sensors for real-time forest health monitoring, while forest departments employ AI algorithms to analyze sensor data and predict potential threats, or, for example, international organizations use blockchain to secure data storage.

4 Uses cases of Forest 4.0

4.1 Carbon sequestration

Carbon sequestration, capture, and storage of atmospheric carbon dioxide (CO_2), is critical for climate mitigation (Yen and Wang, 2013; Pais et al., 2020). Example state-of-the-art Forest 4.0 applications in carbon sequestration uses advanced technologies such as AI and remote sensing to accurately measure and enhance the carbon storage capabilities of forests (Güler, 2024). Using high-resolution satellite imagery and LiDAR data, these applications can create detailed 3D models of forest biomass (Xu et al., 2021), allowing for precise quantification of carbon stocks (Araujo et al., 2023). In Forest 4.0, digital technologies enhance this process by providing real-time data on forest carbon stocks. Modern sensors and IoT devices collect vital information on tree growth, mortality, and biomass. Machine learning algorithms analyze growth patterns

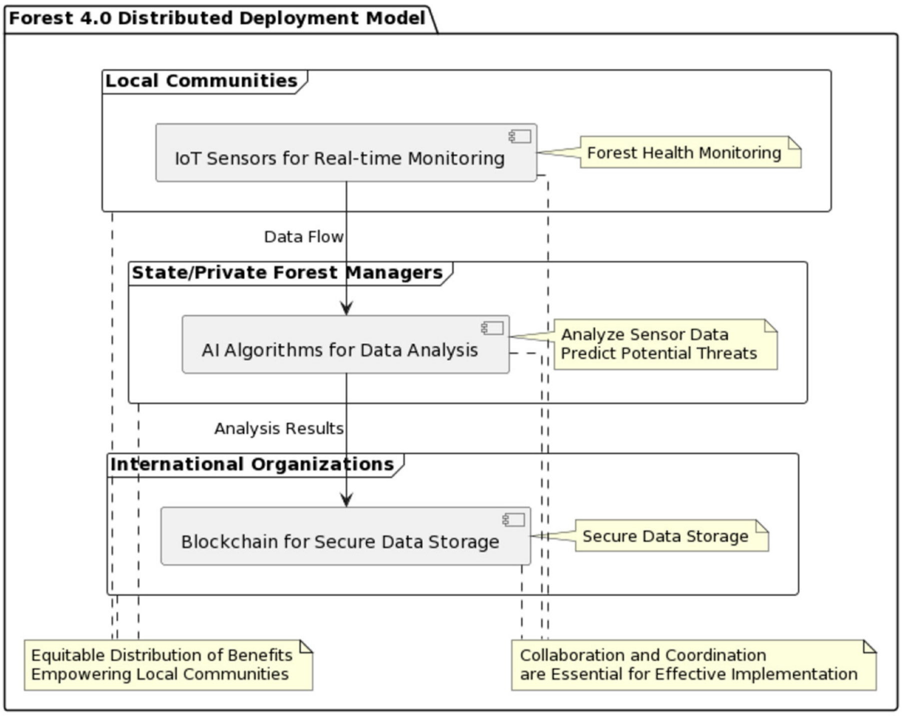

FIGURE 5
Deployment model of Forest 4.0. *Synthesized by authors of the paper*.

and predict future carbon sequestration potential, while IoT-enabled sensors provide real-time data on forest health and environmental conditions (An, 2024). Aerial and satellite images offer a comprehensive view of forest cover, helping to monitor changes and estimate carbon emissions from deforestation (DeFries et al., 2007). Blockchain can be used to create a decentralized system (see Figure 6) to track and verify carbon credits from sequestration (Kotsialou et al., 2022), increasing transparency and deterring fraud. This incentivizes investment in forest conservation and carbon sequestration.

4.2 Biodiversity monitoring

Digital technology in biodiversity monitoring offers rapid and accurate collection and real-time analysis of extensive forest-related data. Examples of Forest 4.0 applications include a combination of remote sensing, big data analytics, and AI to track and analyze the variety of species within forest ecosystems (Raihan, 2023). Sensors placed in the forest can monitor environmental factors such as temperature, rainfall, and soil moisture, helping to assess species populations and their changes over time (Pimm et al., 2015; Salle et al., 2016). Automated systems using drones and camera traps capture images and videos, which are then processed by machine learning algorithms to identify species and monitor their populations (Petso et al., 2022). Genetic analysis and environmental DNA (eDNA) sampling provide additional layers of data, enabling the detection of even elusive or nocturnal species (Beng and Corlett, 2020). Such data are invaluable for evaluating ecosystem health, identifying conservation needs, and employing conservation initiatives. AI further enhances monitoring by automatically identifying and counting species in forest imagery data (Silvestro et al., 2022). The diagram (Figure 7) represents a high-level architecture of a Biodiversity Monitoring System.

4.3 Sustainable forest management

Forest 4.0, built on sustainable forest management principles (Sheppard and Meitner, 2005), uses digital technologies, including IoT sensors, wireless networks, and blockchain, for real-time forest monitoring and effective management (Sharma and Verma, 2022). Sample applications on Sustainable forest management in the context of Forest 4.0 involves integrating digital technologies to balance ecological, economic, and social objectives (Bastos et al., 2024). Precision forestry techniques utilize GIS, remote sensing, and IoT sensors to optimize timber harvests, ensuring minimal environmental impact and promoting regeneration (Venanzi et al., 2023). Big data analytics support decision-making by predicting the outcomes of various management strategies, while blockchain technology ensures transparency and traceability in logging activities (He and Turner, 2021). The deployment of sensors in forests captures data on temperature, soil moisture, light intensity, and air quality, transmitted to a central server via Zigbee (Safaric and Malaric, 2006) or LoRaWAN (Ertürk et al., 2019; Osorio et al., 2020; Almuhaya et al., 2022). The often employs machine learning and AI for data analysis, pattern detection, and real-time alert or recommendation generation. For example,

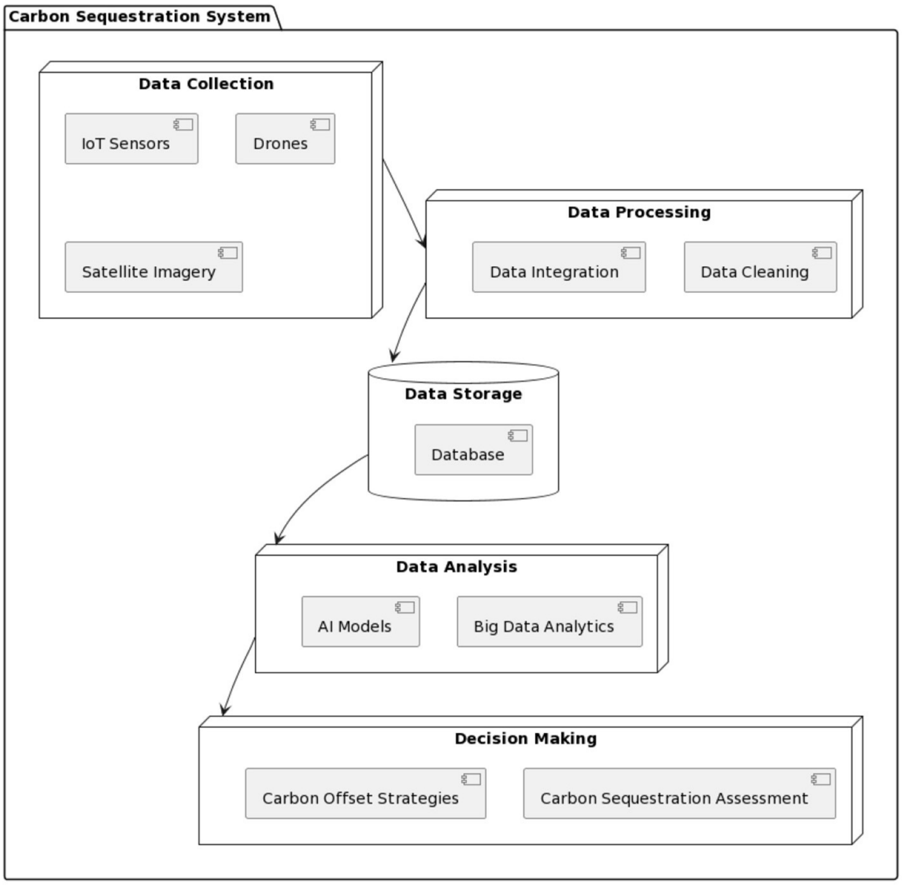

FIGURE 6
Architecture of carbon sequestration system. *Synthesized by authors of the paper*.

a significant decrease in soil moisture can trigger suggestions for additional water sources to prevent drought conditions. Blockchain ensures data integrity, security, and transparency, allowing secure access and verification by stakeholders, such as forest managers and conservationists. It also manages rights and duties, ensuring sustainable forest use in compliance with regulations. Beyond monitoring, the system aids in carbon sequestration, biodiversity tracking, and enforcement, quantifying carbon footprints, and providing evidence for certification. It also monitors endangered species, habitats, and migration patterns. The diagram in Figure 8 illustrates how IoT, Wireless Sensor Networks (WSN), blockchain and AI contribute to real-time monitoring, decision-making, and policy compliance in sustainable forest management and conservation.

4.4 Carbon credits tracking

Carbon tracking in smart forests, facilitated by Forest 4.0, uses digital technologies to accurately monitor carbon sequestration (Sterck et al., 2021; Bowditch et al., 2022), contributing to the design of carbon credit systems, the management of greenhouse gas emissions and the combating of climate change (Corbera et al., 2010; Haites, 2018). Carbon credits tracking applications are revolutioning Forest 4.0 through the use of blockchain technology and smart contracts, which ensure transparency and security in carbon trading markets (Marke et al., 2022). Some of applications use blockchain to secure and decentralized monitor carbon credits, integrating IoT, wireless sensor networks, and blockchain for data collection, analysis, and storage (Saurabh and Dey, 2021). Wireless sensors measure forest characteristics by transferring data through the IoT to a blockchain-based database. Machine learning analyzes the data, offering insight for sustainable forest management. Advanced sensors, data analytics and remote sensing technologies provide accurate and verifiable measurements of carbon sequestration, essential for issuing and validating carbon credits (Smith et al., 2020). Blockchain records every transaction, from the issuance of credits based on verified carbon sequestration to their sale and transfer, reducing fraud and double-counting risks (Marchant et al., 2022). Key characteristics here include carbon sequestration rates, tree growth metrics such as height, diameter, and canopy cover, as well as biomass accumulation. Soil carbon content and tree health indicators such as leaf chlorophyll content and vitality are also tracked. The composition of the forest, which includes the diversity, distribution and age distribution of species of trees, is monitored along with environmental conditions such

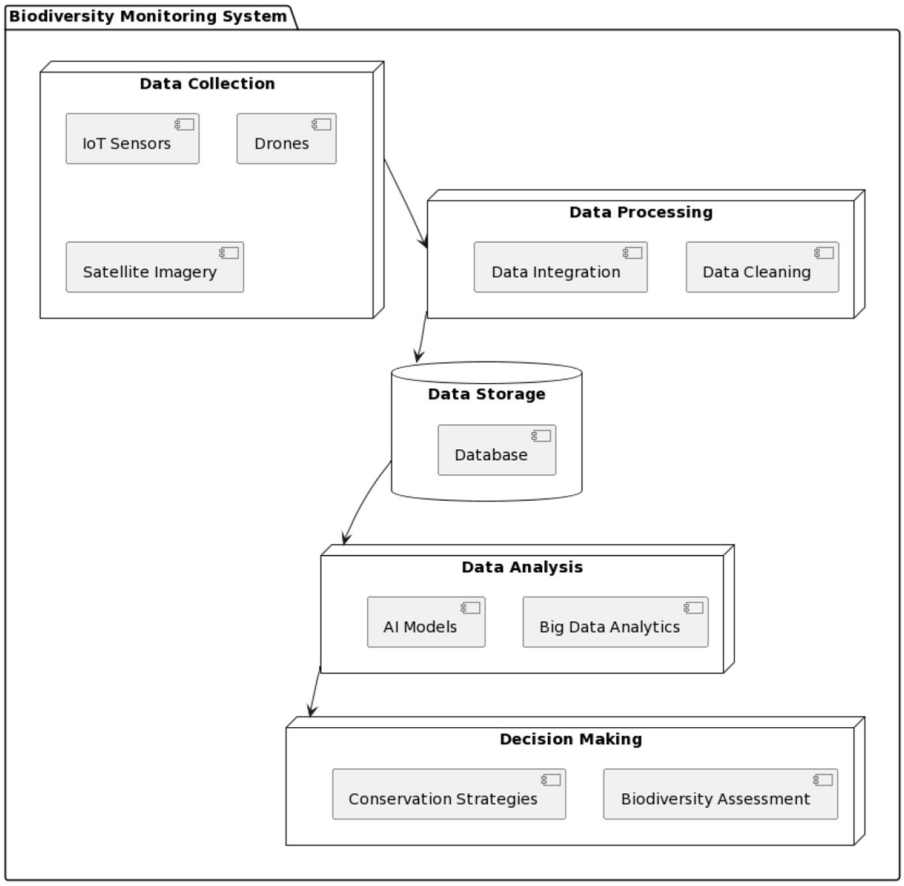

FIGURE 7
Architecture of Biodiversity Monitoring System. *Synthesized by authors of the paper*.

as temperature, humidity, rainfall, and soil moisture levels. In addition, land use changes are observed, including deforestation and reforestation rates, land cover, and land use patterns. Carbon emissions from forest fires and management activities, as well as biodiversity metrics such as the presence and abundance of various flora and fauna species, are further critical components. Forest density, ecosystem services such as water filtration and habitat provision, and air quality, including greenhouse gas concentration, are also typically measured (Bussotti and Pollastrini, 2017). The concept architecture of the system includes modules for data collection, storage, processing, analysis, and reporting (see Figure 9).

4.5 Supply chain tracking

The process of tracking the movement of forest products from forest to consumer, known as supply chain tracking in smart forest management (Feng and Audy, 2020), involves various stakeholders: forest managers, loggers, transportation firms, processors, and merchants. Supply chain tracking applications in forestry has been significantly enhanced by the application of IoT, blockchain, and big data analytics. These technologies provide end-to-end visibility of timber and forest products from harvest to final sale. Blockchain technology, an example of a supply chain tracking system in smart forests (Cueva-Sánchez et al., 2020), establishes an immutable record of transactions and product movements. Each transaction is recorded as a block in the chain, creating an unalterable travel record that ensures compliance with legal, environmental, and social requirements (Felipe Munoz et al., 2021). Forest 4.0 improves transparency of the wood and paper supply chain, using blockchain to secure, decentralized, and tamper-proof provenance tracking from sustainably managed forests (Gonczol et al., 2020; Hoeben et al., 2023). Figure 10 illustrates this high-level architecture of the supply chain tracking system.

RFID technology (Björk et al., 2011) involves the attachment of RFID tags to forest products for real-time tracking, providing data on location, temperature, and other details. Additional technologies, including the Internet of Things (Zhao et al., 2011), wireless sensor networks (Jino Ramson and Moni, 2017), and artificial intelligence (Sharma et al., 2022; Shivaprakash et al., 2022), improve supply chain monitoring in smart forests. These technologies contribute new data and insights, improving decision

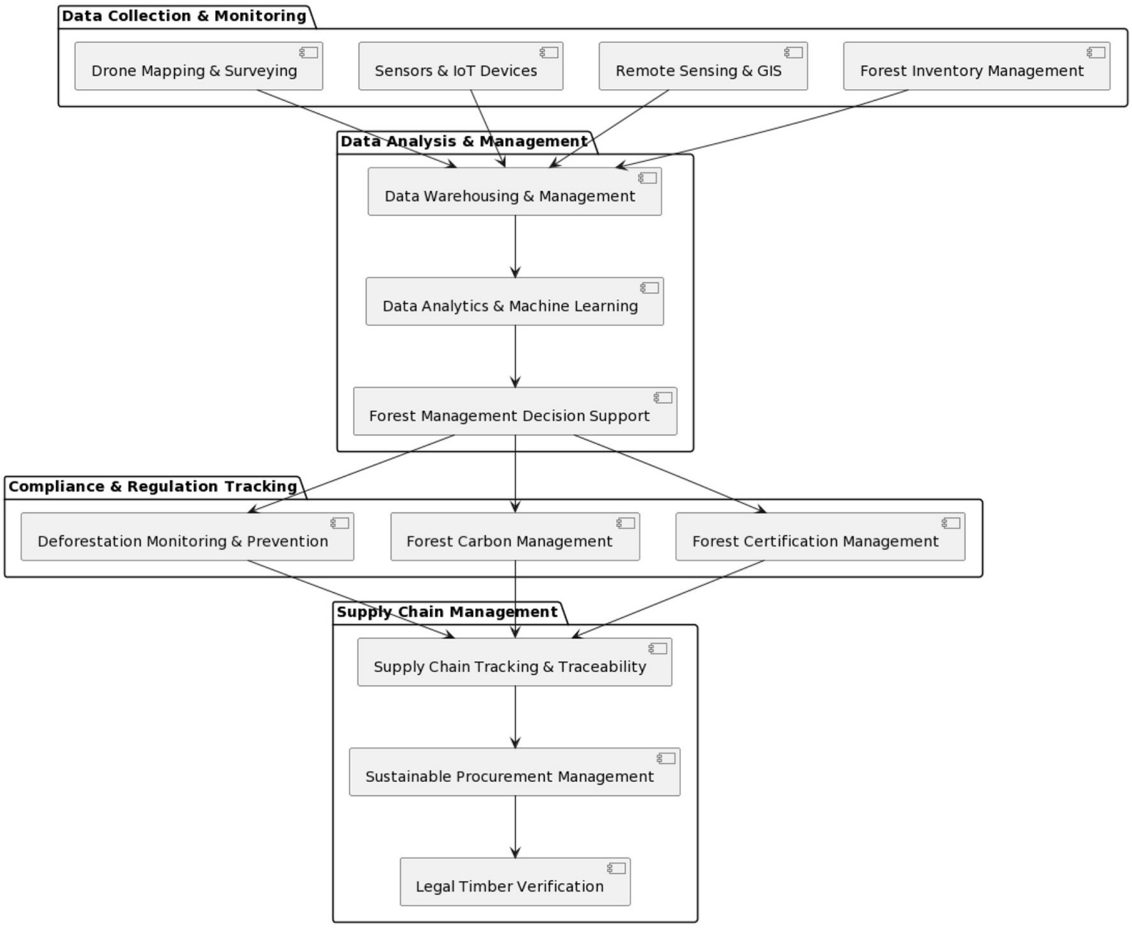

FIGURE 8
Architecture of sustainable forest inventory management system. *Synthesized by authors of the paper*.

making and mitigating risks such as illegal logging and conflicting timber trafficking (Pichler et al., 2022).

4.6 Deforestation monitoring

Application on Deforestation monitoring are starting to become more precise and proactive with the adoption of advanced Forest 4.0 technologies (Gao et al., 2020). High-resolution satellite imagery and AI-driven analytics allow for real-time detection of deforestation activities, providing early warnings and enabling swift action. Using digital technology, such as the Internet of Things (IoT), blockchain, and AI, improves the accuracy and efficiency of these efforts (Pahari and Murai, 1999; Tucker and Townshend, 2000; Shimabukuro et al., 2019; Alzubi and Alsmadi, 2022). Forest 4.0 facilitates real-time tracking of deforestation, using IoT sensors and blockchain to create a secure and tamper-proof data repository (Chowdhury, 2006; Achard et al., 2007; Perbet et al., 2019). Wireless sensors in forests capture environmental data, while high-resolution satellite imagery, processed by machine learning, identifies deforested areas. Local populations and rangers contribute through smartphone apps, reporting deforestation incidents (da Luz et al., 2014). Drones equipped with multispectral cameras survey large forest areas, identifying changes in vegetation cover and land use (Nuwantha et al., 2022). A centralized dashboard integrates data from wireless sensors, satellites, and mobile apps, allowing real-time monitoring and rapid response to deforestation. The blockchain ensures secure data management (Taskinsoy, 2019; Mechik and von Hauff, 2021), making manipulation impossible. AI algorithms analyze data for trends and provide real-time warnings, empowering forest managers to take proactive measures. Figure 11 depicts such a high-level architecture of the Deforestation Monitoring system.

5 Discussion and conclusions

Forest 4.0, with its potential to address industry challenges, offers substantial scalability (Verkerk et al., 2020). It holds promise for improving forest resource management and monitoring on a large scale through real-time data, increased transparency, efficiency, and support for sustainable practices. However, Forest 4.0 scaling faces challenges, including the need for investment

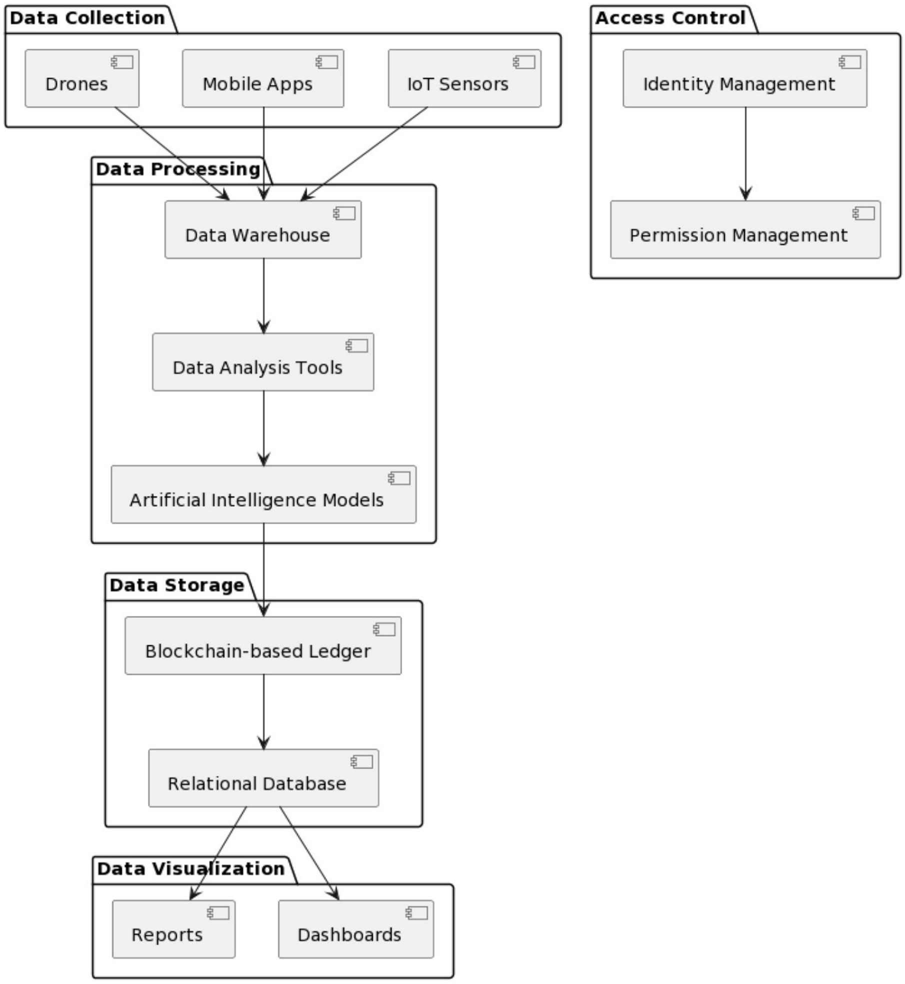

FIGURE 9
Architecture of carbon tracking system. *Synthesized by authors of the paper*.

in technical infrastructure, the establishment of standard data management protocols (Duncanson et al., 2019), and training for practitioners and policy makers. Collaborative efforts with governments, the commercial sector, civil society, and academic institutions are essential to overcome technical, financial, and institutional challenges to scaling (Weiss et al., 2021). The potential for scalability in Forest 4.0 is significant, requiring collaborative efforts to ensure effective implementation and acceptance among all stakeholders (Marchi et al., 2018).

Successful integration of digital technology in Forest 4.0 for effective forest management requires addressing regulatory and governance challenges (Cashore and Stone, 2012; Dlamini and Montouroy, 2017). A multi-stakeholder strategy is crucial, necessitating the establishment of international standards, legal frameworks, and governance models (Tegegne et al., 2016). The adoption process is complex and requires a comprehensive approach to overcome governance and regulatory constraints (Bernhard et al., 2020). To maximize the benefits, roles, and obligations for parties involved in digital technology management must be clearly defined. Financial barriers also add up to the costs associated with the adoption and implementation of digital technologies in forest management (Müller et al., 2019). Furthermore, Forest 4.0 must support sustainable forest management by identifying areas that need attention and promoting eco-friendly practices. Real-time data on forest conditions aid in the adoption of practices that reduce the impact of human activities on forest resources (Zhang et al., 2022). In essence, Forest 4.0 revolutionizes forest management and conservation through real-time data provision, enhanced accountability, and the promotion of sustainable practices.

Forest 4.0, which uses digital technologies such as blockchain, IoT, wireless sensor networks, AI, and big data, has transformative implications for forest management and conservation (Zhang et al., 2022). Enhanced data management and decision making (Prato, 2019) are key benefits. By providing real-time data on forest resources and conditions, Forest 4.0 empowers managers and policy makers to make well-informed decisions (Zhang et al., 2022). In addition, it promotes openness and accountability in forest management through technologies such as blockchain, ensuring secure and accessible information for stakeholders, thus

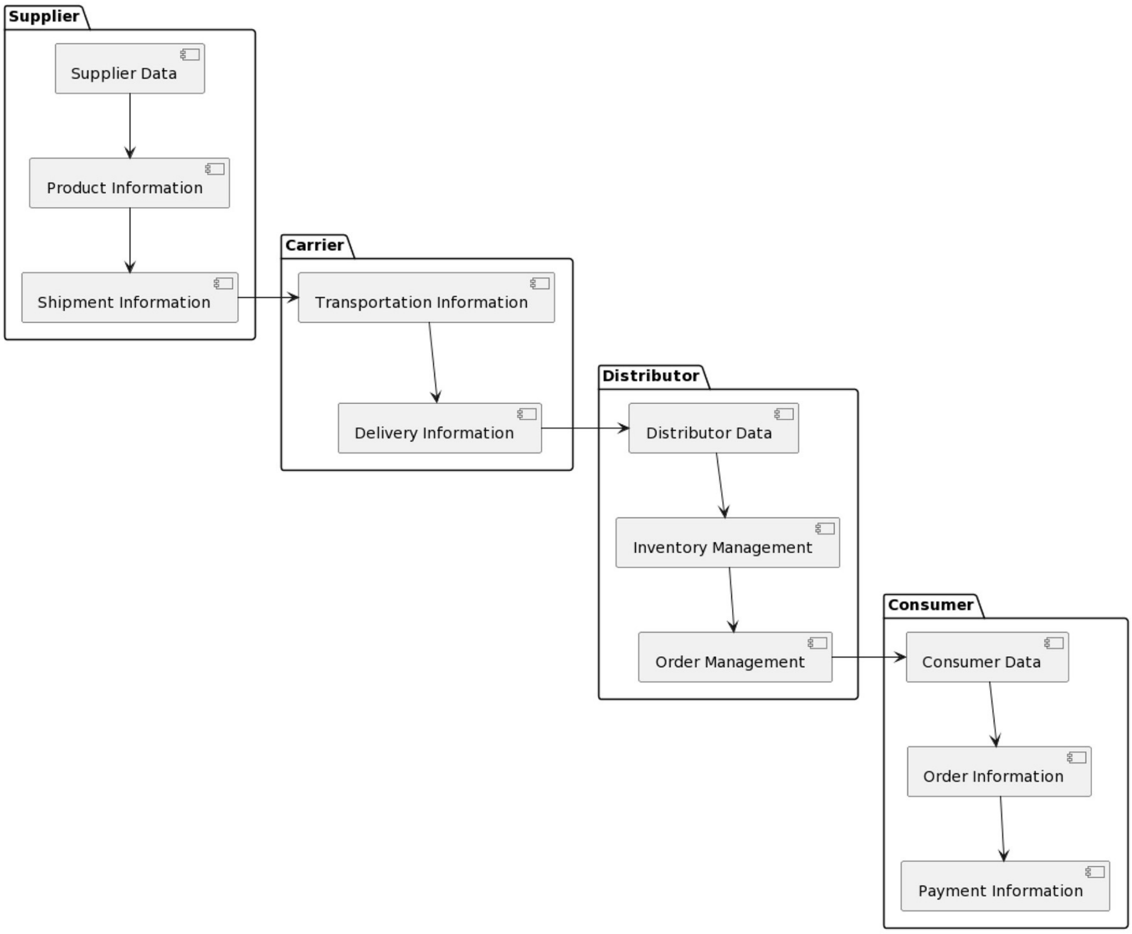

FIGURE 10
Architecture of supply chain tracking system. *Synthesized by authors of the paper*.

promoting trust and collaboration while mitigating corruption risks (Liubachyna et al., 2017).

The adoption of digital technologies in forest management, including Forest 4.0, faces a number of technical barriers that must be addressed to ensure their successful implementation (Holzinger et al., 2022). The problems of standardization and interoperability in digital technology pose significant obstacles in the forest sector. This hinders seamless data flow among stakeholders, leading to redundant efforts (Scholz et al., 2018). Addressing this challenge requires the development and implementation of international guidelines for the integration of digital technology into forest management. Inclusive decision making involving local communities and indigenous people, who possess valuable knowledge of the forest, is essential for the effective and sustainable use of digital technologies in Forest 4.0. A global perspective, exemplified by technologies such as blockchain, emphasizes the need for widespread adoption and coordinated regulation between regions, particularly in areas less digitized like the supply chain (Dilyard et al., 2021). Data privacy and security pose another set of critical challenges in the implementation of digital technologies within Forest 4.0 (Jagatheesaperumal et al., 2021). The integration of blockchain and IoT in forest management, involving sensitive data and transactions, requires robust legislative and technical frameworks to protect this information. These data include details about the ownership and transactions of forest assets, along with personal information about the parties involved in the management process (Bettinger et al., 2016).

The major findings imply that digital technologies such as blockchain, IoT, AI, WSNs, etc. can help improve forest management sustainability, efficiency and transparency, and integration of these technologies can provide significant information for decision-making and resource allocation, as well as improve supply chain transparency and sustainable forest practices (Torresan et al., 2021). Forest 4.0 uses examples and real-world applications that illustrate the potential of these technologies to improve forest resource management and monitoring. Furthermore, the use of blockchain and IoT in forest management could open up new avenues for more secure and effective data handling (He and Turner, 2021).

Future research should focus on creating and testing novel ways to increase forest management sustainability and efficiency. The use of innovative digital technology in forest management

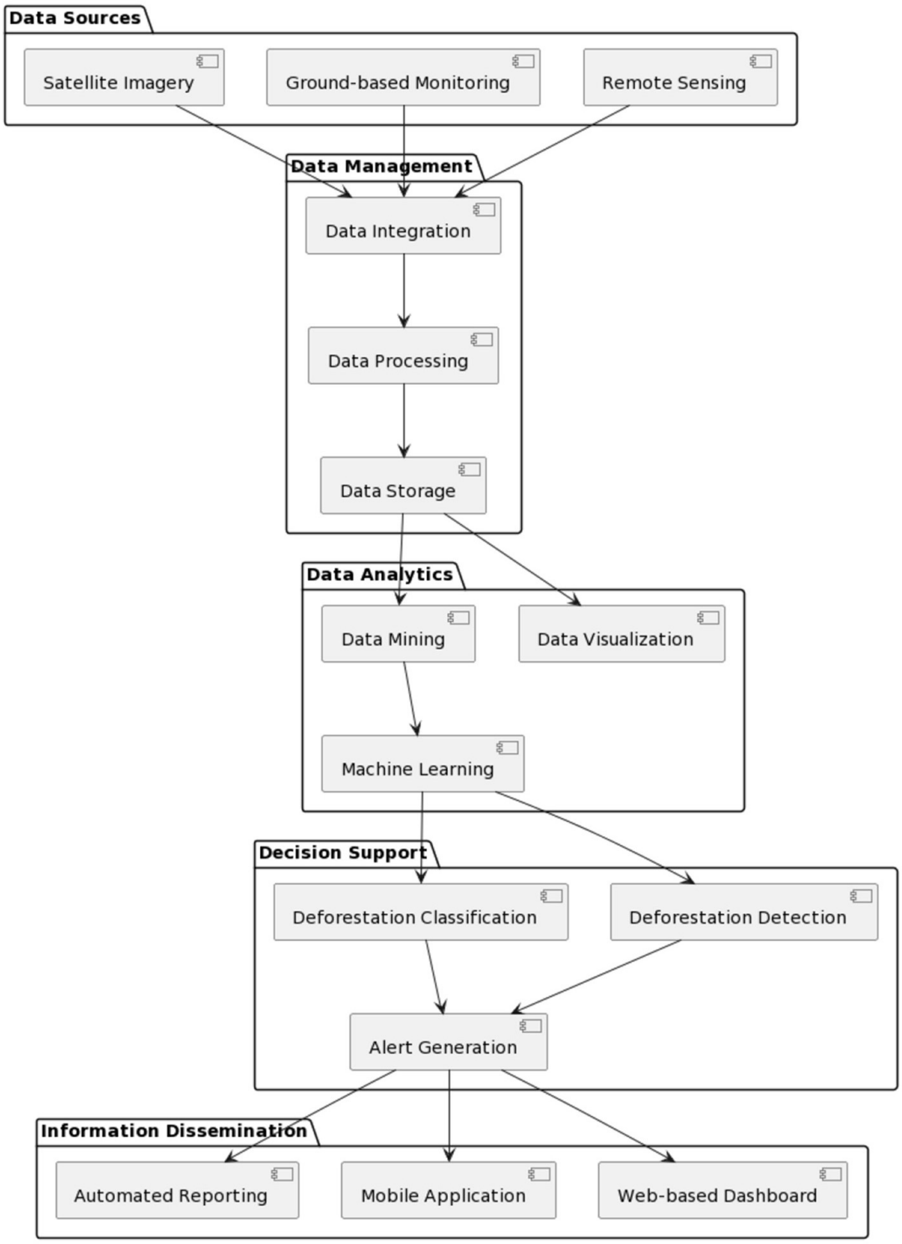

FIGURE 11
Architecture of deforestation monitoring system. *Synthesized by authors of the paper*.

and bioeconomy is a once-in-a-lifetime opportunity to improve the sustainability, efficiency, and transparency of the industry, and policy makers and practitioners must collaborate to capitalize on these innovations for the benefit of forests and society (Jankovský et al., 2021).

Author contributions

RD: Conceptualization, Formal analysis, Investigation, Validation, Visualization, Writing – original draft. GM: Formal analysis, Validation, Writing – review & editing. AK: Formal analysis, Writing – review & editing. RM: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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