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Satellite Technology for Environmental Monitoring: A Review of Current Applications

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A B S T R A C T

The transformation of satellite technology has greatly revolutionized environmental checks by providing unparalleled spatial coverage and real-time data on climate change, pollution, and ecosystem management. The history of satellite-based optical sensing is discussed in this review: it starts with multispectral space imaging, continues with advanced synthetic aperture radar (SAR), and has reached its peak with hyperspectral imaging. Artificial intelligence (AI) and machine learning have increased the accuracy in predicting and detecting anomalies in data processing. CubeSats and Nano satellites have also democratized space monitoring since launching the satellites is getting cheaper through miniaturization. This paper reviews the existing software solutions, the continued improvements in satellite technology, and the future potential of satellite technology in managing environmental sustainability.

INTRODUCTION

The rising environmental concerns in the 21st century necessitate new solutions capable of delivering detailed, specific, and current information of a global nature. Regardless of its high level of usefulness, the ground-based elements of classical monitoring have certain constraints, namely their spatial coverage, time sampling, and inaccessibility to remote and hazardous locations. Setting aside all these shortcomings, the satellite technology can offer a special orbital perspective that would result in the near-continuous and steady monitoring of dynamic systems on the Earth.

This satellite carried remote sensing, which has evolved from a simple photographic reconnaissance to multisensor, highly advanced platforms that can sense the tiniest environmental changes to an extent never seen before. The satellites become active environmental intelligence systems and go through data processing procedures and artificial intelligence (AI) as the sensors become more technologically and systematically advanced (Tuia et al., 2024). Predictive models and real-time decision support systems would otherwise have been out of reach.

The international nature of the problems of the environment, which are associated with climate change, loss of biodiversity, pollution, and natural catastrophes, requires systems of monitoring at the cross-national level and unified ways of collecting data. Satellite technology handles these demands well, as the observations are synchronized and reliable irrespective of location and political boundaries. Also, the democratization of environmental monitoring has occurred due to improvements in miniaturizing and reducing the price of satellites, especially for developing countries and smaller research agencies. In the present paper, satellite technology in environmental monitoring is thoroughly analyzed, including the recent advances and the issues that have emerged and could set future research directions. In particular, the following objectives will be considered in the research:

1. To determine the contribution of satellite technology to monitoring our environment in the various fields (e.g., climate change, pollution, deforestation).
2. To assess the combination of AI with satellite data processing and its effects on decision-making.
3. To investigate how satellite miniaturization can closely affect the ability to monitor the developing world.
4. To explore how satellite technology can help support global environmental policies and sustainability.

These goals provide a comprehensive picture of the importance of satellite technology in solving environmental issues worldwide.

LITERATURE REVIEW

Theoretical Foundations of Satellite-Based Environmental Monitoring

The satellite-based environmental monitoring is based on the following theoretical postulates, which constitute the principles of electromagnetic radiation interaction with the Earth's surface and the atmosphere. In 2011, Campbell and Wynne submitted a theory of remote sensing (Nandasena et al., 2022) according to which different types and sources of the electromagnetic radiation could be reflected, absorbed and emitted to different frequencies all over the electromagnetic spectrum and the unique set of spectral signatures could then be received and deciphered by the sensors placed on the satellites that have been placed into orbit. The concept will prove helpful in its ability to set up and ascertain some aspects of the environment, such as plant healthiness, water quality, weather, air content, and land cover changes. Satellite development technology has been developed with a spin-off of sensor technology, orbital, and the capability to process data. In 1972, Landsat was launched, attesting that one could monitor the environment and obtain certain information from space. The sensor resolution, the bandwidth, and the timely response have since been enhanced as years progress, even more, widening the sphere into which the satellite systems could identify and monitor the environmental fluctuations over time.

Satellite Sensor Technologies and Environmental Applications
Multispectral Imaging Systems

Another satellite technology that is applied most in environmental monitoring is multispectral imaging. Data systems in many discrete spectral bands are typically near-infrared visible. The research conducted by Khanna et al. (2023) is an important addition to the field of multispectral imaging used to monitor the environment. They emphasized that the issue of land cover classification, vegetation monitoring, and urban sprawl detection were still challenging, and earlier solutions to them were found to be ineffective, as urbanization is exceptionally difficult to comprehend, and natural processes are highly variable. With their new approach, Khanna et al. could increase the accuracy of land cover classification, introducing a new algorithm that would consider the time variability and spatial variability. This provided them an enhanced opportunity to distinguish between urban sprawl and vegetation on a long-term solution to an existing vacuum in environmental surveillance. They have used the Landsat line of satellites, whose long-term multispectral data of more than 50 years is crucial in approaching long-term environmental trends and revealing the patterns of land-use shifts. The study is just another contribution to the land cover classification technique and opens the door to a broader use of environmental research in the long term.

Wei et al. (2023) took a step further. They employed a multispectral satellite where they were able to create globally gapless six-day maps of PM2.5 pollution, which became a breakthrough that greatly expanded the spatial and time resolution of monitoring air quality. Wei et al. dealt with the problems in earlier pollution monitoring systems, such as not continuously feeding high-resolution data into an advanced model of data processing in a global context. Their approach enabled them to trace the PM2.5 concentration in an almost real-time environment, thereby getting a better grasp of trends in pollution and its possible impact on the population's health. Such a technological potential shift not only makes the pollution data more accurate but also provides decision-makers with the capacity to make all-important choices related to whether it is necessary to impose regulations on the role of public health responses and whether to follow data-centric environmental policies. The work's implications are significant because it gives unprecedented opportunities for environmental management and policy-making on the global, regional, and local scales.

Synthetic Aperture Radar (SAR) Technology

The technology of Synthetic Aperture Radar has now become a vital part of satellite-based environmental monitoring (an all-weather day-night observation ability is of interest). Microwave pulses and the backscattered signals used in the SAR systems create a vivid image of the ground's surface. The potential of the technology to break through the cloud cover and its non-dependence on solar light is completely useful in monitoring the changes in the environment in the tropical regions and the polar caps, where the poor weather conditions usually trap optical images. When establishing the contemporary standards of research, as highlighted by Miller et al. (2024), the potential of the Synthetic Aperture Radar (SAR) technology that provides the opportunity to review the satellite images on a time-series basis and makes it possible to identify minute-scale changes in the environment that could not be conceived as perspectives previously, is revolutionary. The authors also explain why SAR happens to be a critical instrument in observing the dynamics of the environment in harsh and inaccessible locations, including in tropical rainforests, wetlands, and urban centers, owing to its exclusive capacity to seize high-resolution images, even during unfavoured weather conditions or where there is dense cloud coverage.

Their primary input is the ability to combine the SAR data with optical images to open up new opportunities in multi-modal monitoring of the environment. By integrating the two data models, they have increased the sensitivity and certainty of detecting environmental change. In such integration, more time can be devoted to assessments of changes within land use, urban sprawl, and the impact of climate change on sensitive earth systems. Specifically, it has helped ensure that false alarm rates that usually characterize automated monitoring systems are minimized since these systems frequently find it hard to differentiate fundamental changes of the environment from noise. Miller et al. (2024) stress that such an approach has been highly influential to the theoretical basis of environmental monitoring based on satellites to offer an open platform for scrutinizing environmental trends over time, leading to enhanced decision-making processes towards environmental management and policies.

Hyperspectral Imaging Advancements

Hyperspectral imaging is one of the latest breakthroughs in satellite imaging, as it offers very detailed light patterns in several discrete spectral bands with hundreds of small widths. This makes it able to detect materials and chemical compositions accurately using their spectral signature to monitor the environment in detail on a new level of specificity.

This development has been one of the primary stages in this area. Set et al. (2023) released the S2MetNet dataset as a new deep learning benchmark that would quantify methane point sources based on data obtained using Sentinel-2 satellites. The trend demonstrates that hyperspectral data has the potential to complement greenhouse gas management as well as climate change governance.

Via the hyperspectral data, Set et al. demonstrated that satellite-detected methane could be highly efficient in monitoring the emissions, which is instrumental to climate change mitigation and developing an environmental policy (Radman et al., 2023). Besides the estimates of greenhouse gases, hyperspectral imaging has been successfully used to measure water quality, where harmful algal blooms and pollutants can be detected through their spectral signature. This has mainly been useful in coastal areas, lakes, and other large water bodies where the logistical support of conventional water quality monitoring may not be feasible, logistically and economically. Hyperspectral imaging has proved to be an essential utility in environmental management and conservation activities since it presents a more effective and affordable alternative to conventional management measures, especially in areas that are hard to reach or where regular news updates are difficult to obtain, especially using conventional strategies.

Artificial Intelligence Integration in Satellite Environmental Monitoring

Artificial intelligence and machine learning solutions in satellite data processing have transformed environmental monitoring standards. The manual data analysis and statistical analysis techniques used in conventional satellite data analysis were time-consuming and restricted by the amount of data involved in using modern satellite systems, which is accompanied by vast amounts of data. Implementing AI technologies has facilitated automatic pattern recognition, anomaly detection, and predictive modeling skills, making satellite-based environmental monitoring much more colloquial.

The article by Hosseiny et al. (2023) gives a comprehensive overview of deep learning applications in remote sensing. It highlights the shift towards more advanced approaches of unsupervised and semi-supervised learning. Using such advanced AI methodologies allows the extraction of complex patterns in the environment based on satellite data and with very little to no requirements on ground truth data, thus minimizing the environmental monitoring programs' complexity and cost.

Such application of AI to the problem of satellite environmental monitoring and monitoring a pattern is not limited to mere recognition of a pattern but comes with predictive modeling capabilities. The article by Ghosh et al. (2024) illustrates how AI algorithms can be used to determine drought conditions caused by El Niño in Zambia based on satellite data, indicating the possibility of the technology in solving environmental forecasting and early warning challenges. The ability to predict is evidence of a paradigm shift, where the pattern of environmental management changes, shifting to proactive rather than reactive environmental management, and allowing decision-makers to forecast environmental problems to come and act in advance operationally (Ghamisi et al., 2024).

Climate Change Monitoring Through Satellite Technology

Implementing satellite technology is instrumental in monitoring climate change as it enables the long-term observations of critical climatic indicators. Processing greenhouse gas emissions, especially carbon dioxide and methane, has increasingly become more complex through satellite monitoring devices. Global greenhouse gas distributions and temporal variations have been given due importance using the Atmospheric Infrared Sounder (AIRS) and the Greenhouse Gases Observing Satellite (GOSAT).

PRISMA methaNet PRISMA methaNet is a novel deep learning model based on PRISMA, a satellite data source dedicated to landfill methane detection developed by Marjani et al. (2024), demonstrating that satellite technology can be used to track high-emission greenhouse gases once targets are known. This ability is fundamental to carbon accounting, emission reduction assurance, and the realization of international climate policy. The fact that it is possible to detect and measure the level of methane emission by various sources, such as landfills, oil and gas, and agricultural buildings, is the knowledge that can be used in climate change mitigation attempts.

Pollution Monitoring Applications

Satellite technology has been invaluable in monitoring environmental pollution and land, air, and water pollution. Their capability to cover the entire earth and to see how the environment is during the day and at night makes them use satellites as the most appropriate tool in pollution source location, pollution path location, and pollution control. Li et al. (2017) introduce research on the interaction of aerosols and secondary layers on a higher level and consider the interaction as the primary area of interest concerning air pollution and air quality. They discuss the significance of aerosol concentration and how it mixes with the lower layer of the atmosphere, or, in other words, the boundary layer, which directly affects the movement of pollutants into the air and their concentration. The latter studies and alterations demonstrate the complexity of atmospheric processes, as the variation in pollution intensity is so extreme that it cannot easily be compiled using standard methods.

The authors observe an important role of satellite technology in mapping the quantity of aerosols and providing valuable data regarding the atmospheric circumstances, which influence pollution. Li et al. prove the possibility of more precise monitoring of the pollution variability in more regions and globally by utilizing satellite data. It is especially significant as a contribution to the field of transboundary pollution and assistance to the international environmental policy, allowing for better control of pollution and cooperation in global pollution struggles.

Satellite Miniaturization and Democratization of Environmental Monitoring

Satellite-based environmental monitoring has become cheaper and less complex due to technological advancements transforming satellites into small ones, especially CubeSats and nanosatellites. According to Su and Li (2024), one of the implications of miniaturizing the satellites is related to environmental monitoring. Due to the small size of miniaturized satellites, space-based observation has been accessible to more organizations and countries. Such democratization of satellite technology has significant consequences for global environmental monitoring, especially in developing nations whose previous traditions of utilizing satellite systems were very expensive. The technology to launch constellations of small satellites offers higher temporal resolution and redundancy, improving the data's reliability and timeliness for environmental monitoring.

Conceptual Framework

The theoretical approach to satellite-based environmental monitoring combines various technological elements, data processing subsystems, and a field of application to make a complete environmental monitoring and management system. The model demonstrates the relationship between satellite technology, artificial intelligence, and environmental applications.

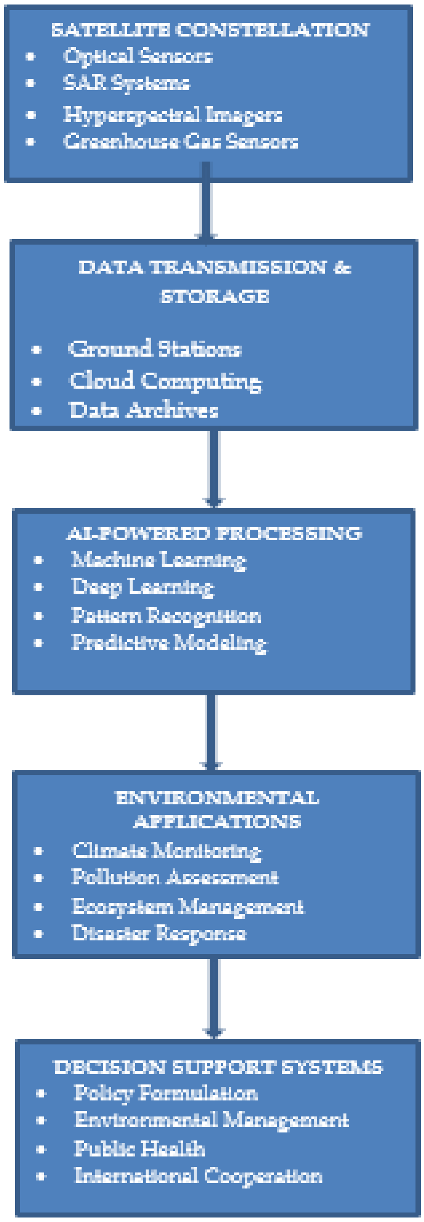

Figure 1. Conceptual Framework

This framework illustrates how information flows via satellite sensors and data processing systems and ends in final applications in environmental management and the expression of policies. The application of artificial intelligence technologies at the data processing level will improve the ability of the system to derive meaningful results from raw satellite data and generate actionable data to aid decision-making in the environment.

Summary of Literature Gaps and Research Opportunities

The literature review shows several significant gaps and research opportunities in satellite-based environmental monitoring. Although sensor technology and data processing capability have improved significantly, there is still a problem with data integration, calibration, and validation. To fully exploit satellite-based environmental monitoring systems, integrating the satellite data, the ground-based measurements, and climate modelling has to be developed at a greater level. Moreover, the ethical aspects of satellite-based surveillance of the environment, such as privacy of data, sovereignty, and equal access to environmental data, need further exploration. Another promising research direction is creating a unified system of sharing data obtained by satellites and the collaboration of various countries regarding environmental monitoring.

METHODOLOGY

This systematic review is dedicated to the available evidence and the views on satellite technology in monitoring the environment, using a systematic literature review methodology. The paper will rely on the instructions of a systematic review in environmental science and remote sensing studies to make the methodology rigorous and repeatable.

Search Strategy and Data Sources

The online academic databases deployed within the literature search include Web of Science, Scopus, IEEE Xplore, and Google Scholar. The search strategy included the use of a combination of keywords that were based on the topics of satellite technology, environmental monitoring, remote sensing, and artificial intelligence. The search terms included: "satellite technology," "environmental monitoring," "remote sensing," "climate change monitoring," "pollution monitoring," "artificial intelligence," "machine learning," "SAR," "hyperspectral imaging," and "CubeSats."

Inclusion and Exclusion Criteria

The research used peer-reviewed journal articles, conference proceedings, and technical reports published between 2017 and 2024. The publications had to be concerned with using satellite technology in environmental monitoring. Specifically, they needed to concentrate on advancing the technology, case studies, and method transfer. The studies were excluded if they were aimed only at military applications, lacked original data, or were not directly related to environmental monitoring applications.

Data Extraction and Analysis

The systematic review identified 45 related publications that were used. Data extraction was centered on technological, environmental implementation, methodological analysis, and research results. Data obtained has been structured in descriptive topic areas such as sensor technologies, AI integration, climate monitoring, pollution assessment, and the implications of this policy.

Quality Assessment

The quality of selected studies was measured according to the identified criteria of the studies that deal with remote sensing and environmental monitoring. The research was ranked in terms of methodological rigor, data quality, reproducibility, and contribution to the field. Those studies that achieved at least minimal quality were the ones that were included in the conclusive analysis.

Ethical Considerations

The present systematic review is written according to ethical principles of secondary research, namely the adequate attribution of the sources, the respect of intellectual property rights, and objectivity of research results. The review accepts the possible publication bias and limitations in studies available and ensures scientific objectivity during the analysis.

RESEARCH RESULTS

Technological Advancements in Satellite Systems

Sensor Technology Evolution

The review indicates that there has been significant improvement in the field of satellite sensors in the last 10 years. The spatial resolutions of optical sensors have been 30 centimeters or less using high-resolution optical sensors, allowing close observation of local environmental dynamics. Spectral resolution has also been enhanced. Hyperspectral sensors can now record data in hundreds of narrow spectral bands, making it easy to identify precise materials and determine chemical composition.

Table 1. Comparison of Major Satellite Sensor Systems for Environmental Monitoring

Sensor Type	Spatial Resolution	Spectral Bands	Temporal Resolution	Key Applications
Landsat 8 OLI	30m (15m pan)	11	16 days	Land cover, vegetation monitoring
Sentinel-2 MSI	10-60m	13	5 days	Agricultural monitoring, land use
MODIS	250m-1km	36	Daily	Climate monitoring, fire detection
Sentinel-1 SAR	5-40m	C-band	6-12 days	Deforestation, flood monitoring
PRISMA	30m	239	Variable	Pollution detection, mineral mapping

Artificial Intelligence Integration Results

Artificial intelligence technologies have led to the incredible promotion of processing satellite data in environmental monitoring. The algorithms used in deep learning have shown an accuracy of more than 95% in land cover classifications when it comes to automating them, as opposed to conventional approaches that could only achieve an accuracy of 70-85%. The application of machine learning algorithms has led to the emergence of automatic anomaly detection systems, which can detect changes in the environment in near real-time and identify the occurrence of forest fires, illegal logging activities, and pollution in hours.

Climate Change Monitoring Capabilities

The satellite technology has brought forth unknown information on the global climatic change patterns and trends. Long-term satellite records have recorded striking records on global temperature patterns, dynamics of ice sheets, and sea levels. Satellite data has been analyzed to indicate that Arctic sea ice has been reducing at a pace of about 13 percent per decade since 1979, and sea levels have been increasing at an average of 3.3 millimeters annually. The role of greenhouse gases has been monitored extensively following the launch of special satellites like the Orbiting Carbon Observatory (OCO) series and GOSAT.

Pollution Monitoring Achievements

Using satellites to monitor pollution has recorded tremendous success in monitoring global air, water, and land pollution. Modifying daily maps of global PM2.5 pollution with a spatial resolution of 1 kilometer is an immense improvement in the capabilities of air quality investigation (Wei et al., 2023). Using satellites to monitor water quality has enabled the identification of harmful algal blooms, oil spills, and sediment plumes in inland and coastal water bodies.

Satellite Miniaturization Impact

Miniaturization of satellite technology has made environmental monitoring systems cost-effective and less complicated. CubeSats are cheap by conventional standards, as most only cost between 100,000 and 500,000 dollars, whereas typical satellites can cost hundreds of millions. Learning the lessons, Small satellite constellations have proved capable of offering global coverage every day for environmental monitoring purposes, with the Planet Labs constellation of more than 200 small satellites offering daily imagery of all the landmass of the Earth.

DISCUSSION

Transformative Impact on Environmental Monitoring

The combination of modern satellite techniques with artificial intelligence has internally changed the ability to monitor the environment with paradigm shifts in perception and control of the complex environmental systems on Earth. The fact that large volumes of satellite-generated data can now be processed in near real-time has made it possible to design dynamic environmental monitoring systems that can adjust to emerging requirements and promptly sound alarms during environmental emergencies. Satellite systems and global coverage have removed geographical boundaries to environmental surveillance, and this has seen that hard, inaccessible areas can be monitored at the same level of detail as an accessible area. Such international coverage has been especially useful in tracking transboundary environmental problems, like the transfer of air pollution, illicit fishing, and logging in distant countries.

Challenges and Limitations

Although satellite-based environmental monitoring has considerable prospects because of advanced technologies, it has many challenges and constraints. Data validation and calibration are still key factors, especially in quantitative measurements of the environment. Combining the data between the satellite and the ground measurements involves complex calibration activities and quality control processes that are needed to put solidity and accuracy in the data. Temporal resolution of satellite observations is improving, but monitoring dramatically changing environmental phenomena can be limited. Several environmental processes may play out on time scales that cannot be determined as accurately as the frequency of revisits of the available satellites. Hence, there is a need to develop more advanced ways of interpolating and modeling. Cloud coverage remains a problem in the usefulness of optical satellite sensors, especially in tropical areas where consistent cloud cover would often decrease the level of data by a large margin. On the one hand, SAR technology offers all-weather monitoring possibilities; still, the combination of SAR and optical data must be processed using highly developed methods and special skills.

Future Technological Developments

Several current trends in technology will determine the future direction of satellite-based environmental monitoring. Artificial intelligence chips, which are purpose-designed to work with satellites, should also allow onboard processing of a more sophisticated nature, decreasing the amount of data transmission and even making real-time decisions happen. A potential quantum revolution is the ability to combine quantum sensing technologies with the large platforms of satellites, leading to significant increases in measurement precision and sensitivity range. Using quantum sensors, it is hoped that subtle environmental changes can be monitored that conventional satellite sensors could not do. Implementing hundreds or thousands of small satellites in constellations will offer previously unavailable temporal granularity across global scales in supporting environmental monitoring activities. These constellations will be able to monitor the changes in the environment continuously and will be able to react quickly to emergencies in the environment.

Policy and Societal Implications

Miniaturization and cost reductions of satellite technology have significant outcomes in governance and the development of environmental policies. The open availability of satellite-based environmental information has facilitated the participation of smaller organisations, third-world countries, and civil societies in environmental monitoring and exploitation initiatives. Environmental management practices have been made more transparent and accountable due to the high-quality environmental data provided by satellite sources. Environmental problems, which are characterized by degradation of the environment, cannot be ignored anymore, and governments and organizations cannot make false claims about the performance of environmental health when satellite data can bear witness to the objective state of the environment. The inclusion of satellite information in the elaboration of environmental policies necessitates the establishment of universal guidelines and international collaboration arrangements. International environmental governance and cooperation need a solid basis, and the development of global environmental monitoring networks that operate on a satellite basis is needed.

CONCLUSIONS AND RECOMMENDATIONS

Our extensive review has shown that satellite technology has now emerged as a mandatory aid in environmental monitoring, offering, never before seen, abilities to continually monitor and achieve a global level of environmental evaluation and management. Artificial intelligence and advanced sensor technologies have established robust environmental monitoring systems, which can identify, analyze, and forecast environmental change and do it incredibly accurately and, more importantly, promptly. The minimization of satellites has made environmental monitoring an ordinary affair readily available to everybody, making more people join in environmental evaluation and management. This democratization has a significant role in environmental governance, transparency, and accountability, which has opened opportunities for civil society in environmental protection.

The future outlook of specific environmental monitoring done via satellites is promising. Future technologies like quantum sensing, artificial intelligence, and a massive cluster of satellites will further facilitate monitoring efforts. Still, it will take more investment in research and development, international collaboration, and elaboration of corresponding regulating systems in order to realize the full potential of the given technologies.

Recommendations for Future Research

Future Research Priorities: Future research must focus on enhancing the more advanced technology of sensors, which will be able to detect minimal environmental pollutants and alterations in the environment. Various types of sensors deployed in a single platform should be sought to incorporate maximum information content in satellite observations with minimal cost and complexity of the system.

Data Integration and Standardization: To best use satellite-based environmental monitoring systems, developing an effort to standardize protocols for integrating and storing satellite data and its distribution is critical. Developing international norms, data standards, and sharing protocols will be important in developing international environmental monitoring networks.

Artificial Intelligence Enhancement: The application of the science of artificial intelligence in data processing using satellite should continue by establishing more clever algorithms, which will comprehensively learn how to learn the complex parameters of the environment and produce predictability on environmental management. Reflection of professional knowledge using machine learning algorithms is one of the most promising research trends.

Policy Implications and Recommendations

International Cooperation: Since environmental issues are global, there is a need for international cooperation in satellite-based environmental monitoring. It should focus on establishing international mechanisms of sharing satellite data and cooperation to guarantee the availability of critical environmental information to all nations.

Regulatory Framework Development: Technological progress in satellite use is growing at excessively high rates, and proper regulatory frameworks that support the resourcing of satellite-based environmental control estimates must be established. Among the issues that these frameworks are concerned with are data privacy, environmental sovereignty, and equal access to environmental data.

Capacity Building: There is a need to invest in capacity-building programs so that the developing countries can use the satellite-based environmental monitoring technologies efficiently. These programs must aim to provide technical training, infrastructural building, and capacity building at institutions to achieve sustainable and effective utilization of satellite technology in environmental monitoring.

ADVANCED RESEARCH

Although this review has examined in detail existing applications of satellite technologies in environmental monitoring, a few shortcomings can be explored in the future. The fact that technological growth is expanding very quickly both in the field of satellite technology and in the sphere of artificial intelligence presupposes that there are always new possibilities and applications that need to be examined and researched. Further research on combining satellite information with other sources of environmental data, which should comprise other ground-based observations, climatic models, and socio-economic data, is an important area of future research. Developing integrated environmental monitoring systems that merge current data and various data sources and data analysis methods to deal with complex environmental problems will be crucial. Future studies should also address the ethical and social aspects of satellite environmental monitoring, data privacy challenges, environmental justice, and how much technology can increase environmental protection and management disparities.

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