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Research Article

The Potential of IoT for Efficient Environmental Management: An Exploration of IoT Technologies for Precise Monitoring and Resource Management

Ruslan Ovcharenko[1], Vita Reznichenko[2], Serhiy Kyrylenko[3], Ievgen Akhromkin[4], Yurii Forkun[5]

[1] Doctor of Public Administration, Associate Professor, Professor, Department of Public Administration, Educational and Scientific Institute of Management, Economics and Finance, Interregional Academy of Personnel Management, Kyiv, Ukraine.

[2] PhD in Agriculture, Associate Professor, Department of Geoponics, Agro-technical Faculty, Central Ukrainian National Technical University, Kropyvnytskyi, Ukraine.

[3] PhD in Economics, Associate Professor of the Department of Entrepreneurship and Trade, West Ukrainian National University, Ternopil, Ukraine.

[4] Doctor of Economic Science, Professor, Departments of Economic Security, Public Management and Administration, Zhytomyr Polytechnic State University, Zhytomyr, Ukraine.

[5] PhD, Associate Professor, Associate Professor of the Department of Software Engineering, Faculty of Information Technologies, Khmelnytskyi National University, Khmelnytskyi, Ukraine.

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ABSTRACT

Introduction: Given the global environmental pollution, depletion of natural resources, and climate change issues, it is crucial to prioritise stabilising the environmental situation and implementing the concept of sustainable development. In this context, using an efficient environmental monitoring system in conjunction with the fundamentals of environmental management and incorporating modern information technologies is considered a powerful tool for environmental conservation.

Objectives: This research aims to analyse the potential of Internet of Things (IoT) technologies for effective monitoring and resource management with precision aimed at improving environmental productivity.

Methods: The research process employed general methods such as generalisation, systematisation, abstraction, analysis, synthesis, and concretisation.

Results: The study analysed mechanisms for ensuring sustainable development by implementing environmental innovation activities. The functionality of environmental monitoring was identified, and trends in its implementation using IoT were analysed. During the research, software for developing an effective environmental monitoring algorithm was analysed, and the principles of its functioning were determined. The dynamics, issues, and prospects of resource management with precision were substantiated. It has been demonstrated that utilising IoT for effective monitoring enables the tracking of dynamics and identification of potential problems. The aggregated data format is suitable for further analysis.

Conclusions: These research findings can be applied to optimise Ukraine's environmental development strategy by implementing precision resource management, environmental conservation elements, and innovative city management systems.

Keywords: information systems, IoT, IoT technologies, sustainable development, environmental monitoring, digitalisation, resource management, ecology, energy efficiency, environmental and economic modeling, sustainable use of resources, development of coastal destinations, marine areas.

INTRODUCTION

In today's globalised and integrated world, accessible and effective communication is crucial. The Internet of Things (IoT) enables rapid data transmission between devices, real-time data processing, and effective decision-

making. The impact of IoT technologies is also evident in environmental management, providing innovative opportunities for using IoT technologies to monitor theen vironmentandmanageresourceswithprecision.

The research problems concerning the essence of environmental management in modern concepts, the methodology of precision resource management, and the dynamics analytics in the investigated area have received considerable attention from contemporary scholars. Specifically, in the national scientific field, the specifics of implementing environmental management through modern technologies as an objective necessity for improving resource conservation have been studied [12], [16]. The possibilities of using innovative eco-technologies as part of circular economy processes are explored [2], [13], and the potential of ecological optimisation of the use of exhaustible resources is analysed [1], [10].

Among the contemporary scientific works dedicated to the scientific development of the issues of environmental innovation activity and the study of the impact of IoT technologies on environmental management, the research of scholars Horbal et al. [4] and Kovalenko [15], stands out, which details the analytics of the digitised environmental monitoring process and identifies the role of IoT technologies in resource management. Additionally, based on the research experience of countries that have specific achievements in the effective use of digitised environmental innovation potential in the context of sustainable development, several scholars Illiashenko et al. [7], Kosovych [14]. highlight relevant opportunities for adapting IoT capabilities for effective environmental management in Ukraine.

However, the question of implementing practical successful experience in implementing an effective IoT system for precise monitoring and resource management in the delineated aspect has yet to be studied sufficiently. Therefore, there is a need to intensify the interest of scholars and managers in studying the possibilities of using IoT for effective monitoring and resource management with precision.

The article aims to analyse the potential impact of Internet of Things technologies on environmental management to improve resource management within sustainable development.

LITERATURE REVIEW

The results of the analysis of interdisciplinary vectors in contemporary research indicate significant interest among scholars in the issue of exploring the potential of information technology innovations and their practical implementation to realise environmental sustainability principles.

Numerous scientific studies have reflected various aspects of the researched problem and its individual aspects. Specifically, contemporary works highlight aspects of the environmental management concept using innovative technologies, including IoT and artificial intelligence [19], [31]. The functionality of environmental monitoring in the modern resource management system is analysed [23], algorithms for targeted investments in practical, innovative environmental projects are studied [6], and modern technological solutions in the outlined concept are explored [28].

Furthermore, some scholars have conducted analytics on IoT for effective monitoring and resource management with precision, minimising destructive environmental impact, and preventing climate change [25]. In recent works, the paradigm of the researched phenomenon in the context of implementing the potential of digital technologies into environmental management systems is positioned as a priority for sustainable economic development [29]. The conceptual horizons of the researched problem are expanded in the works of scientists [17], [21], who are involved in developing models of effective environmental management based on digital optimisation of data collection, accumulation, and analysis to form efficient management decisions regarding resource utilisation.

However, the issues of practical implementation of the potential of IoT technologies for effective monitoring and resource management with precision mostly remain beyond the scope of attention in contemporary scientific research or are insufficiently explored. It accentuates the necessity for an expanded study of the subject of this research.

METHODS

Various interdisciplinary scientific research methods were used during the research process, including analysis, synthesis, abstraction, induction, and deduction. The methods of analysis and synthesis were applied to identify the main opportunities for using IoT for effective monitoring and resource management with precision. The study used

the inductive method to formulate predictive directions for developing the investigated process. Additionally, the deductive method was used to identify directions for forming an innovative concept of the impact of IoT technologies on the modern environmental management system. The research applied the abstraction method to extract theoretical generalisations, identify vital categories and concepts, and conclude the priority vectors of development of the researched phenomenon.

It followed the principles of complexity and a systematic approach to scientific research. This approach facilitated the analysis of the research subject as a complete system with interconnections and interdependencies.

RESULTS

Environmental concerns are among the most pressing issues of our time. Information technologies are now recognised as a powerful toolkit for preventing, protecting, preserving, and regenerating the environment. However, it is worth noting that digitised tools can hurt the environment if their use is not adequately controlled.

Information technologies, such as the Internet of Things (IoT), are becoming more prevalent in all areas of society and are a powerful tool for productivity. The quality of a country's scientific, technical, industrial, and socio-economic potential, as well as the overall standard of living of the population, will be determined by the level of information literacy in the younger generation. To achieve modern, innovative optimisation of measures aimed at mitigating the negative consequences of anthropogenic impact on the natural environment and intensifying environmental regeneration, new approaches to environmental monitoring and resource management are necessary [16], [12]. This concept encompasses a variety of cutting-edge digital methods and tools that significantly improve process accuracy, reduce the risk of human error, and enable unrestricted implementation of necessary options across space and time.

Monitoring, essentially, constitutes a comprehensive system of observations, data collection, accumulation, analysis, and systematisation of information regarding the parameters of the surrounding environment. When successfully implemented, it enables practical assessment and prediction of the dynamics of environmental indicators and the development of corresponding well-founded recommendations for making efficient managerial decisions.

Overall, the functioning of the environmental monitoring system is based on a set of essential principles, including objectivity and reliability, multilevel and complexity, systematicity and openness, and the promptness of informing responsible authorities. Additionally, effective environmental monitoring requires coherence in normative-methodological and program-technical provisions.

The priority of current issues in implementing the system of environmental monitoring studies is conditioned by the fact that the existing environmental monitoring system operates in isolation, failing to provide a comprehensive assessment of indicators of the natural environment and the utilisation of resource potential. It hampers the further forecasting of environmental dynamics and the adoption of optimal decisions in the management field regarding optimising natural resource utilisation in specific locations [7], [14].

When studying the impact of Internet of Things (IoT) technologies on environmental management, it is essential to understand how modern information technologies affect environmental sustainability and minimise destructive processes in the natural environment. Environmental monitoring and modelling are highly functional in this context and form the basis for precise resource management. The current state of information technology allows for the creation of computer models to analyse and predict ecosystem changes. Modern digital tools, including artificial intelligence, provide access to in-depth research on various environmental aspects, such as climate change, forest regeneration dynamics, and water resource distribution.

This approach also facilitates effective pollution control processes. Next-generation information systems allow for monitoring environmental pollution levels, identification of pollution sources, and prompt response to them. Additionally, they serve as a foundation for collecting, analysing, and visualising reliable environmental data. This process uses sensors and data collection systems to monitor air, water, soil quality, and biodiversity.

The digitisation of environmental management involves interacting with stakeholders. Technologies can optimise collaboration with nature conservation organisations and environmental projects, facilitating collecting,

accumulating, and analysing data on environmental conditions. This contributes to the adoption of well-founded managerial decisions for environmental preservation.

Environmental monitoring is a promising vector for implementing the Internet of Things (IoT) concept. IoT solutions with functionality enabling environmental analysis and mitigation of the negative anthropogenic impact have been developed and successfully tested. Specifically, specialised sensors, integrated into practical functionality, continuously accumulate informational data, based on which necessary decisions and measures are formulated and implemented to counteract negative trends and phenomena in the natural environment. Individually tailored environmental sensors and mobile applications are effectively and promptly used to retrieve information from sensors. Typically, the functionality of these devices is implemented through Wi-Fi, GPS, and Bluetooth.

In particular, the Air Quality Egg sensor is a successful example of practical IoT utilisation for monitoring air quality parameters and the BigBelly device for waste management. Both mentioned tools are promising for application in Ukraine to stabilise the environmental situation [28].

The IoT functionality has proven to be an effective positive tool for influencing the environmental situation, but its full potential has not yet been fully explored. It is obvious that the use of IoT capabilities for effective monitoring and management of resources with accuracy ensures the fulfilment of primary tasks of monitoring and management activities in the environmental sphere, namely:

- introducing an automated system for collecting, accumulating, analysing and summarising information data on quantitative and qualitative indicators of the state of the environment and resource potential through the creation of a digital data bank;

- practical assessment of indicators and parameters of natural resource potential, which creates the basis for precise regulation of the resource use process;

- reliable identification of sources of environmental pollution and the extent of anthropogenic impact;

- forecasting the dynamics of environmental indicators;

- developing and implementing sound decisions on rational environmental management and sustainable development.

Implementing an IoT-based environmental monitoring system aligns with leading pan-European approaches to environmental management. Adopting and effectively utilising this approach will create favourable conditions for Ukraine's international cooperation in greening activities and ensure alignment of the national environmental protection system with globally integrated requirements.

When studying the use of IoT for precise resource monitoring and management, it is essential to focus on its general principles of operation. Typically, environmental parameters are monitored using a hardware-software tool based on microcontrollers. A controller is a miniature computer with specific inputs and outputs that operate according to a pre-written program.

The controller enables numerous peripheral devices and has extensive functionality due to its various interfaces and internet connectivity. Furthermore, it typically includes a dedicated interface for connecting a camera to capture photos and videos. The schematic diagram of the system resembles an algorithm (Fig. 1). It consists of a series of devices with corresponding sensors and the data collected from all devices are sent to the controller.

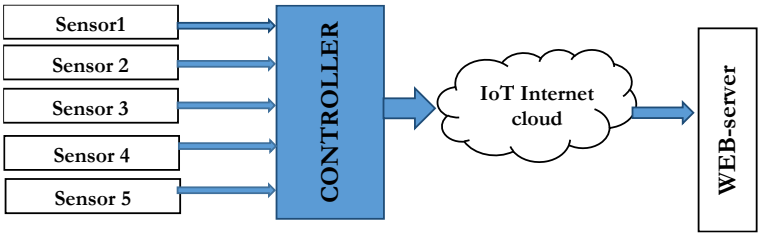

Figure 1. Common Block Diagram of an Automated Environmental Monitoring System

Analysing the algorithm depicted in Fig.1, it is worth noting that the device consists of several sensors for measuring programmed environmental parameters. Information from the sensors is sent directly to the controller, after which the system processes the received data and accumulates it in a particular file, which is then transmitted to the IoT. Cloud computing technology is applied to efficiently monitor the data obtained in the global network, which ensures the presence of a personal local server. This approach is currently widespread and accessible. Cloud computing involves assigning a separate IP address, allowing the monitoring of information dynamics from any location [17], [21]. Using target software developed for individualised controllers enables the implementation of operational functionality with arrays of information data obtained from sensors, such as filtration or calculation of specified indicators.

The cloud storage functionality is typically performed by a cloud service (platform). Data transmission to the cloud allows for accumulating information in a secure and accessible location, forming optimal conditions for further analysis on various platforms or devices [25].

The outlined functional concept of an automated environmental monitoring system enables integration into scalable IoT networks and the development of a complex of hardware and software tools for collecting and aggregating IoT data. The architectural composition of the concept is implemented in the form of a complex set of hardware and software tools for collecting and aggregating IoT data using various sensors, a central controller, and cloud storage. The generated data can be viewed via a web interface from any location. The developed system allows for prompt response to environmental conditions, providing a basis for tracking dynamics and identifying potential issues, with the aggregated data format suitable for further analysis, including intelligent analysis. The proposed tools are considered suitable for use in innovative city management systems. Thus, combining information technology and ecology contributes to intensifying the implementation of sustainable development principles, promoting environmental protection and regulating its impact by forming precision resource management concepts.

DISCUSSION

In order to achieve the expected outcomes of researching the potential implementation of Internet of Things (IoT) technologies on environmental management during the transformation period of socio-economic processes, it is necessary to consider the findings of scholars regarding critical concepts. It should be noted that the multifactorial process of developing capabilities and directions for implementing digital projects of environmental innovations and technologies has led to divergent approaches in structuring their functionality and the level of prospective feasibility.

Certain contemporary scholars focus on the significance of cloud technologies for efficient environmental monitoring and resource management with precision. In this context, it is worth highlighting researchers [8], [27] who pay particular attention to the necessity of developing the multifunctionality of monitoring systems, which would expand the spectrum of IoT technology's influence.

Meanwhile, several scholars [24] focus on analysing the fundamental principles of natural resource utilisation, considering them vital factors contributing to enhancing energy security and preventing destructive impacts on the natural environment. By doing so, they create various opportunities for developing energy infrastructure and sustainable economic growth. Several contemporary researchers [18] argue that innovations based on modern technological capabilities, and even harnessing the potential of artificial intelligence, are vital tools to support environmental sustainability. According to these scholars, innovative technologies protect natural resources from degradation and regenerate resource potential.

The issues related to the use of artificial intelligence and cloud technologies for efficient monitoring and management of resources with precision are outlined in the works of several scholars [26], whose research focuses on developing and practically implementing modern approaches to innovative environmental activities. At the same time, many contemporary scholars [20] are convinced that the priority of environmentally oriented innovative activities lies in the implementation of modern digital technological solutions and information resource capabilities. These scholars interpret the concept of innovative environmental activities as a necessary precondition for positive dynamics in the socio-economic development of society.

Despite the considerable spectrum of scientific developments on the researched issue, aspects of using IoT for efficient monitoring and resource management with precision in the context of the basic principles of sustainable development require further in-depth research.

CONCLUSION

As a result of the research, the possibilities of using Internet of Things (IoT) technologies for effective monitoring and management of resources with precision aimed at improving ecological productivity were analysed. During the research, mechanisms for ensuring sustainable development through ecological innovation activities were analysed, the functionality of environmental monitoring was identified, and trends in its implementation through IoT were analysed.

Partially analysed during the research was the software for developing a practical algorithm for environmental monitoring and the principles of its functioning. The dynamics, issues, and prospects of resource management with precision were substantiated. It was demonstrated that IoT for effective monitoring allows tracking dynamics and identifying potential problems, while the format of aggregated data is suitable for further analysis.

In the work process, the conviction was formed that priority directions for developing the researched sphere are implementing a series of measures within a unified national development strategy. The proposed concept reflects the variability of effective use of the potential of ecological innovation activities in optimising Ukraine's socio-economic development, which is relevant to implementing elements of a sustainable climate course and intensifying the efficiency of renewable energy resource utilisation.

Ecological innovation activity in the modern economic environment of developed countries is seen as an effective tool for optimising the ecological and socio-economic environment, positioning itself as one of the pillars for achieving full implementation of sustainable development principles. This approach can address the problem of reducing the consumption of exhaustible resource potential, ensuring preventive protection and regeneration of the environment, and stimulating the profitability of economic entities' activities. Implementing principles for ecologizing economic and production activities under an effective system of economic and managerial incentives for implementing innovative ecological solutions will enable the realisation of a practical concept of rational natural resource management.

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