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A COMPREHENSIVE OVERVIEW OF MODERN ENVIRONMENTAL MANAGEMENT SOFTWARE

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Abstract. *Effective environmental management is becoming increasingly important due to the anthropogenic impact on ecosystems and their components. Environmental Management Systems (EMS) are essential for heavy industries, helping to reduce the human footprint on the environment and optimize the use of natural resources. This paper examines various types of EMS, their characteristics, architecture, and computational models. Key functions of these systems include monitoring and data collection, data analysis and processing, compliance management, incident and deviation management, planning and goal setting, as well as communication and reporting. EMS address tasks related to environmental auditing, reporting, and managing environmental risks of production processes. Various systems on the market offer unique solutions for different industries. Successful implementation examples include companies like BASF and Valspar, which have saved significant resources by integrating EMS into their production processes. The conclusions highlight the importance of EMS for sustainable development and environmental safety, as well as the need for their continuous updating and adaptation to new challenges.*

Keywords: *Environmental monitoring, Environmental control, Environmental pollution, Environmental risk management, Sustainable natural resource management, Environmental Management Systems, Compliance Management, Sustainability, Industrial Impact Reduction*

Introduction. In a world where environmental issues deteriorate the quality of environmental components, impact human livelihoods, and threaten a significant portion of biodiversity, the need for effective environmental monitoring gains new significance and importance. Anthropogenic influence significantly alters the state of ecosystems through pollution, resource depletion, and climate change. In this context, Environmental Management Systems (EMS) become not just a contemporary trend but a necessity for industrial operations. EMS are essential for conducting environmental audits, management, and planning of environmental programs and activities aimed at reducing the anthropogenic load on the environment. EMS also serve as tools for manufacturers to improve compliance with environmental legislation and standards regarding atmospheric emissions, aquatic ecosystem discharges, and the efficiency of treatment facilities, soil cover, and areas adjacent to industrial sites. Economic activities must be controlled to minimize the anthropogenic impact on all environmental components. Compliance with environmental legislation and regulatory standards of economic activity is mandatory for all businesses in Ukraine and the European Union countries. The implementation of EMS allows companies not only to appear "green" but to truly reduce their impact on the environment, optimize resource use, and save costs (Ikram, 2019). However, selecting and implementing an appropriate system is a complex process that requires a deep understanding of the characteristics and capabilities of various EMS. This article aims to provide an overview of modern EMS, highlight their key features, and explore development prospects and examples of successful implementation and use of such systems in practice. It is crucial to seek and implement existing tools tailored to the conditions of Ukraine, considering current realities and existing environmental-economic risks.

Materials and Methods. The study of Environmental Management Systems (EMS) employed a comprehensive approach, encompassing the analysis of scientific literature and official documents to identify the main types of systems and their characteristics. The research also included the examination and evaluation of various EMS offerings available in the market to determine their functional capabilities and target segments. A comparative analysis was conducted to identify the advantages and disadvantages of each system. An essential part of the study involved investigating practical examples of successful EMS implementation by major companies such as BASF and Valspar, aiming to analyze their experiences and determine the key factors contributing to successful outcomes. The results of this research are aimed at identifying the main development trends of EMS and uncovering potential directions for further system improvements. The conclusions of the study can serve as a foundation for developing recommendations on the selection and implementation of EMS across different industrial and agricultural sectors.

Results and Discussion. The study revealed various methods and structures for environmental control and management of economic activities affecting environmental components. By analyzing different EMS implementations, the research identified key strategies and practices that contribute to effective environmental management. The comparison of multiple EMS offerings highlighted specific strengths and weaknesses, enabling the identification of best practices and areas for improvement. Practical examples from companies like BASF and Valspar demonstrated how comprehensive EMS frameworks can lead to significant reductions in environmental impact, improved compliance with regulations, and enhanced operational efficiency. These findings underscore the importance of a tailored approach to EMS implementation, considering the unique needs and contexts of different industries. The discussion elaborates on the critical factors that drive successful EMS adoption, including stakeholder engagement, continuous monitoring and evaluation, and the integration of innovative technologies. Overall, the results emphasize that effective EMS structures are crucial for mitigating the negative impacts of industrial activities on the environment. The insights gained from this research provide valuable guidance for businesses aiming to enhance their environmental performance and ensure sustainable operations.

Types of Systems and Their Features. Environmental Management Systems (EMS) exist in various forms, each with unique characteristics designed to meet the specific needs of enterprises.

Standard EMS are represented by international standards such as ISO 14001, which establish general requirements for environmental management. These systems help organizations structure their environmental programs, set objectives, and track outcomes (Virazindzhe, 2018). Standard EMS provide a unified approach to managing environmental aspects, facilitating the integration with other management systems. They also contribute to improving the environmental policies of enterprises and can significantly reduce costs through the rational use of natural resources and the implementation of energy-efficient production technologies (Zavertaliuk, Naumovska, 2024).

Modular EMS consist of separate modules, each focused on a specific area of environmental management, such as waste management, emissions control, or resource conservation. The modular structure allows organizations to select the components that best meet their needs and gradually expand the system over time. Modular EMS offer flexibility and adaptability, enabling easy modifications or updates in line with evolving environmental goals and strategies. They also promote more targeted and efficient resource use, as each module can be optimized for specific tasks (see Fig. 1).

Predictive EMS utilize data and analytics to anticipate future environmental challenges and risks. They integrate modeling and forecasting tools to aid organizations in planning and taking preventive measures. Predictive EMS can enhance resource optimization, risk reduction, and resilience to future environmental changes. They also enable more informed decision-making based on data and trend analysis.

Each type of EMS has its advantages and features, making them suitable for different organizational needs and contexts. The choice of a particular system depends on various factors, including the size of the organization, industry, geographical location, and specific environmental goals and strategies.

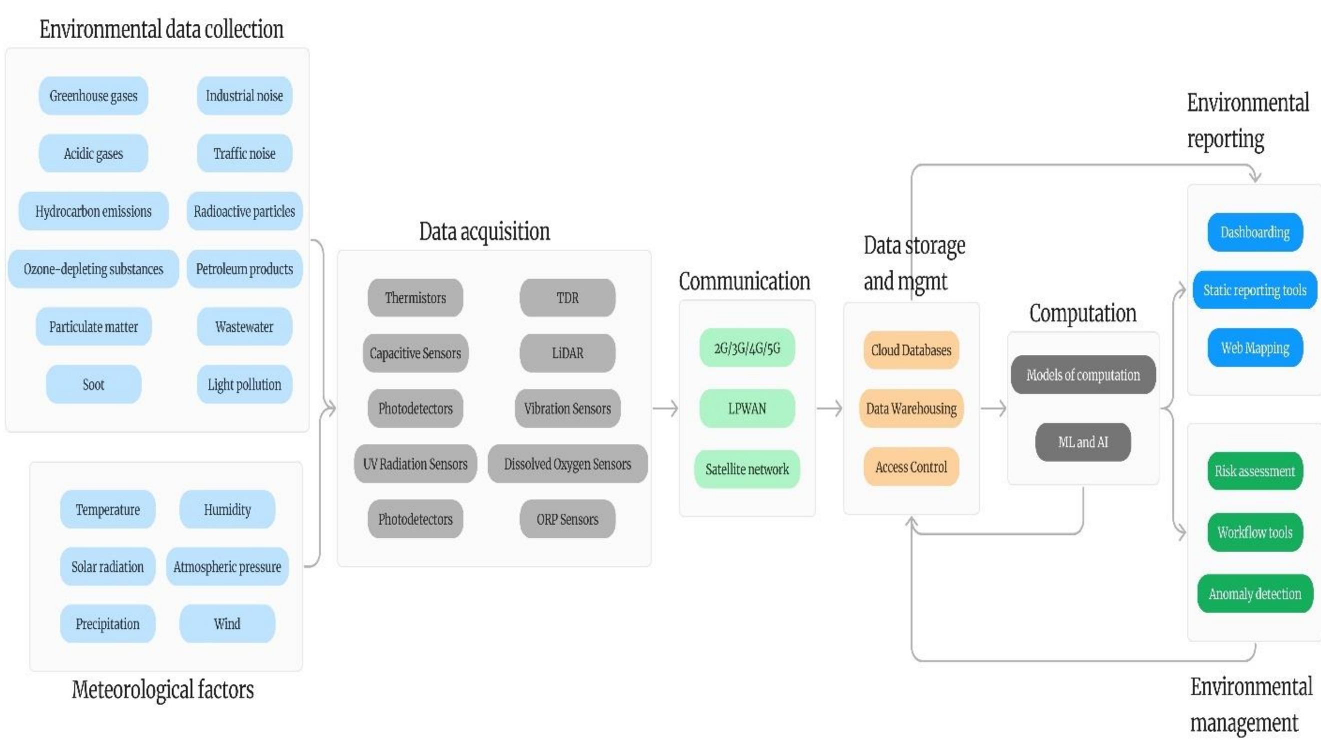

Figure 1. Elements of environmental impact monitoring software for economic activities

High-Level System Architecture (Figure 2). Environmental Management Systems (EMS) possess a complex architecture that enables efficient data collection, processing, and transmission. The illustration of the system's operation highlights the following key steps:

1. Data Collection: In the initial stage, the system gathers various environmental data, such as pollutant emissions, meteorological data, resource usage information (water, energy, etc.), and data on waste generation and management, especially hazardous wastes (Class I and II hazards). This can include automatic data collection from sensors and monitoring systems, as well as manual data entry.

2. The System Itself: At the core of the EMS is the processing and analysis of collected data. The system may include the following capabilities:

a. Environmental Impact Assessment: Analyzing data to determine the environmental impact of the organization's activities;

b. Environmental Monitoring and Forecasting: Monitoring key performance indicators (KPIs) and tracking changes over space and time;

c. Compliance Management: Ensuring the organization's activities comply with environmental regulations and standards;

d. Planning and Goal Setting: Establishing environmental objectives and developing programs to achieve them;

e. Risk Analysis: Identifying potential environmental risks and developing strategies to minimize them.

3. Data Transmission: After processing and analysis, data can be transmitted to stakeholders such as government agencies to demonstrate compliance with environmental standards and regulations. This may also include reporting to shareholders and exchanging data with other management systems.

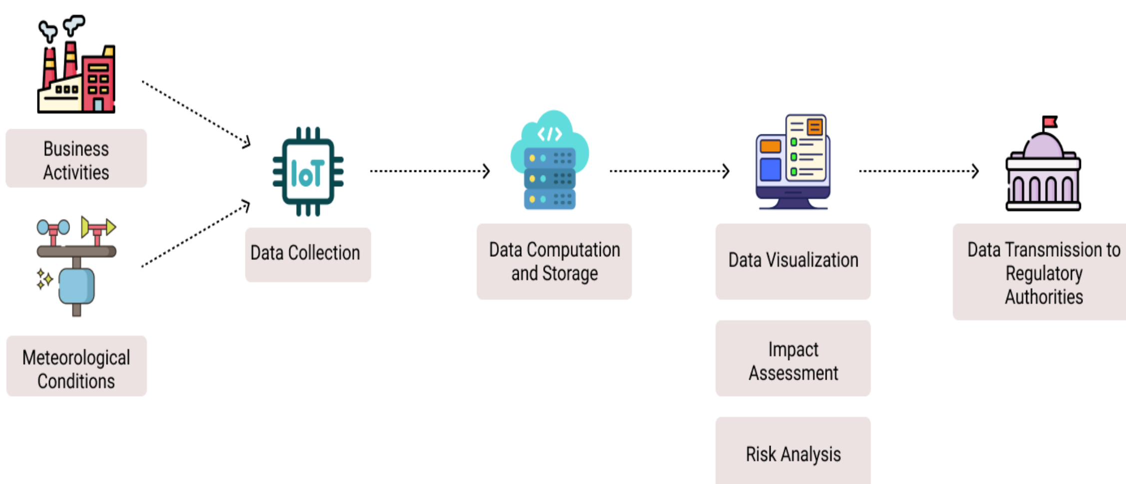

Figure 2. Schematic of environmental management system operation

Computational Models and Their Characteristics. Computational models are a key component of Environmental Management Systems (EMS), as they enable complex analysis and forecasting of impacts. Here, we examine several primary computational models and their characteristics:

Deterministic Models use fixed equations and parameters to determine the impact of environmental factors. These models provide accuracy and predictability but may not account for the uncertainty and variability of real-world conditions.

Stochastic Models, unlike deterministic models, consider randomness and uncertainty in input data. They are useful for modeling processes with high unpredictability, such as the dispersion of pollutants in the environment.

Spatial Models allow the analysis of the distribution and movement of environmental parameters in space. They are used for mapping and predicting patterns of pollutant migration, such as identifying high-risk pollution areas.

Temporal Models focus on analyzing changes in environmental parameters over time. These models are essential for tracking the dynamics of processes, for example, seasonal fluctuations.

Integrated Models combine different approaches and data types to gain a more comprehensive understanding of environmental processes. Integrated models can incorporate spatial, temporal, and stochastic elements to create a holistic analysis.

Machine Learning Models have gained popularity due to their ability to adapt and learn from data. These models can automatically detect patterns and make environmental predictions, making them useful for identifying new risks and optimizing management strategies.

Each of these models has its advantages and limitations, making them suitable for different scenarios and needs in environmental control. For example, deterministic models can be effective for determining the impact of known and stable pollution sources, whereas stochastic models are better suited for situations with significant uncertainty or variability in input data. Spatial models are indispensable for planning the territorial placement of industrial facilities or assessing the distribution of pollutants in the landscape (e.g., geochemical barriers).

When selecting and developing computational models, it is important to consider not only their technical characteristics but also their ability to integrate with other system components, ease of use, and adaptability to changing environmental conditions. Moreover, the growing focus on sustainable development goals pushes EMS developers to continually improve computational models.

Key Elements and Technical Components. EMS consist of several key elements and technical components that interact to ensure effective monitoring. Here are some of the main components:

1. Sensors and Detectors: These are fundamental components used to collect environmental data such as temperature, humidity, air pollution levels, water quality, etc. Sensors can be placed in various locations depending on monitoring needs.

2. Internet of Things (IoT): IoT plays a crucial role in collecting and transmitting data from sensors to the central processing system. IoT enables the connection of a large number of sensors and devices into a single network, providing real-time monitoring and high data accuracy (Jayashri S., 2021).

3. Data Collection Systems: These include software and hardware for aggregating and storing data generated by sensors. They can be implemented as databases, cloud storage, or local servers.

4. Computational Models and Analytical Tools: These are used to process, analyze, and interpret collected data. They may include statistical methods, machine learning, geographic information systems (GIS), and other analytical platforms.

5. User Interfaces: These allow users to interact with EMS, view data, generate reports, and manage the system. Interfaces can be implemented as web portals and mobile applications.

6. Reporting and Notification Mechanisms: These are used to inform responsible parties about environmental events, regulatory exceedances, or potential environmental and production risks. Systems can automatically generate reports and send notifications via email, messages, or other communication channels (Li T., 2019).

7. Integration Mechanisms: These enable EMS to interact with other management systems such as quality, occupational safety, and energy management systems. Integration promotes synergy between different management aspects and improves the overall efficiency of the system.

8. Security and Privacy Measures: These ensure the protection of collected data from unauthorized access, malicious use, or loss. They include encryption, access control, backups, and other technologies.

Each of these elements and components plays an important role in the functioning of EMS, with the Internet of Things (IoT) being a key technology that enables the collection of a large amount of real-time data and its integration into EMS.

Functionality of Environmental Monitoring Systems: Detailed Overview of System Functions.

EMS offer a variety of functions for effective monitoring and management of an organization's environmental aspects. By analyzing systems such as *Envira DS, EHS Software by EnviroDataSolutions, EHS Insight, ERA Environmental Management System, Envirosuite Omnis, and Rotronic RMS*, several key functional groups can be identified.

Each of these groups of functions plays a crucial role in ensuring effective environmental management. For example, data collection and monitoring allow organizations to obtain accurate and up-to-date information about the state of the environment, which forms the basis for further analysis and decision-making (Chan, 2016).

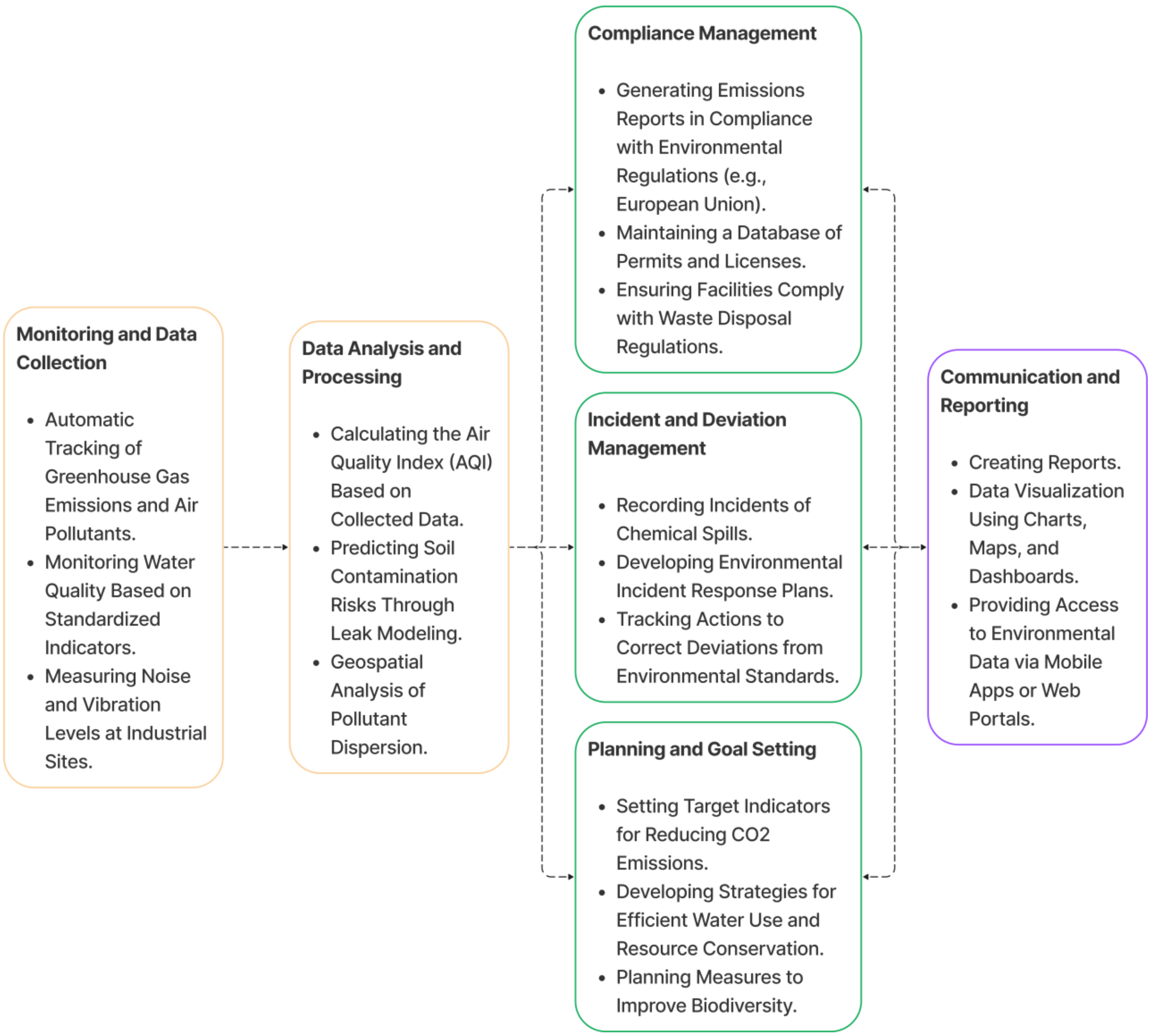

Figure 3. Diagram of Key Functions of the Systems

Analysis and data processing help identify trends and issues, assess environmental risks, and develop strategies to minimize them. Compliance management ensures adherence to environmental standards and regulations, preventing potential fines and sanctions (Zucki, 2015).

Incident and deviation management is vital for responding promptly to unforeseen situations and preventing their recurrence. Planning and goal setting enable organizations to establish specific environmental objectives and develop plans to achieve them, enhancing environmental performance.

Communication and reporting ensure transparency and openness regarding the environmental aspects of an organization's activities, increasing stakeholder trust and improving corporate reputation (Campos, 2015; Su, 2022).

Overall, the functionality of environmental monitoring systems encompasses a wide range of tasks, from environmental monitoring to risk management and reporting, allowing organizations to manage their activities effectively.

Tasks that can be solved using such systems include: Environmental monitoring of pollutant emissions, assessment and management of environmental risks, water resource management, waste disposal control, biodiversity conservation planning, environmental auditing and reporting, and raising environmental awareness among employees and engaging the public in addressing urgent environmental issues.

Let's consider two tasks in detail. Environmental Audit and Reporting require organizations to ensure compliance with environmental standards and regulations, as well as to submit accurate and timely reports to governmental authorities and oversight agencies (Hartman D., 2018). EMS automates data collection and report generation processes, ensuring the accuracy and timeliness of information. The system can automatically track indicators subject to reporting and generate standardized reports ready for submission to regulators. EMS can also provide analytical tools to identify trends and deviations, aiding in the improvement of environmental policies and practices.

Environmental Risk Management involves identifying and managing environmental risks, requiring a comprehensive approach to data analysis and response strategy development. EMS allows for systematic risk analysis based on collected data. The system can use computational models to assess the likelihood and potential consequences of various environmental risks, such as water or soil contamination, chemical spills, or industrial accidents. Based on this assessment, EMS can help develop action plans to minimize risks, including preventive measures and incident response plans (Zhang, 2020). These tasks illustrate the broad applicability of EMS in enhancing environmental performance and compliance within organizations, ultimately contributing to more sustainable and responsible industrial practices.

Current Challenges. One of the primary challenges is the difficulty in integrating these systems with an organization's existing technologies and infrastructure, which can lead to technical difficulties and increased implementation costs (Xi, 2016). Additionally, many systems have limited flexibility in terms of customization and adaptation to the specific needs of an organization, complicating their use in various industries or unique environmental contexts (Li, 2017).

Cost is another significant barrier. The high cost of licenses, maintenance, and updates for some systems limits their accessibility for small and medium-sized enterprises. The effectiveness of EMS also heavily relies on the quality and accuracy of input data. Poor data quality can lead to erroneous analyses and incorrect decisions. Some systems also have limited analytical capabilities, making it challenging to conduct deep data analysis and identify complex patterns.

Data Security and Privacy: Storing large amounts of environmental data requires robust solutions to ensure their security and confidentiality, which can be challenging for some existing systems. The complexity of these systems necessitates specialized user training, increasing the time and cost of implementation.

Resistance to Change: Resistance among management also slows the integration of these systems within organizations. Low environmental awareness, lack of commitment to innovations among operational managers, and reluctance to adopt standards such as ISO 14001:2015 are significant factors delaying the implementation of EMS (Voli, 2021).

Potential Paths for Functionality Improvement. Key improvements include integrating these systems with the existing technologies and infrastructure of organizations. Developing more flexible interfaces and application programming interfaces (APIs) can facilitate integration and promote more efficient data exchange between different systems.

Reducing implementation and operational costs is crucial to ensuring their accessibility for a wide range of organizations and enterprises. Developing flexible pricing plans and utilizing cloud solutions can help lower overall costs and make the systems more affordable for small and medium-sized businesses.

Ensuring data security and privacy is critical in the context of increasing cyber threats. Implementing advanced encryption technologies, user authentication, and access control can help protect environmental information from unauthorized access and malicious use.

Finally, simplifying the user training process is important for ensuring the rapid and effective implementation of the system. Developing intuitive interfaces, providing detailed documentation, and offering access to online courses can facilitate the system's adoption and reduce the time required for its implementation.

Collectively, these improvement directions can help make environmental monitoring systems more effective, flexible, and accessible.

The Market for Environmental Management Systems (Table 1). The market for environmental control software development includes several key companies, each offering unique solutions that differ in functional capabilities, target market segments, and approaches to integration and implementation.

Envira Global offers the Envira DS product, which focuses on air quality monitoring and management. The software includes tools for automatic data collection from sensors, analysis, and report generation, making it useful for organizations aiming to control pollutant emissions and comply with environmental standards.

EnviroDataSolutions offers EHS Software, which is oriented towards a wide range of tasks in the field of environmental protection, health, and safety. The software includes modules for managing data on emissions, waste, risks, and incidents, as well as ensuring compliance with environmental regulations and standards.

EHS Insight offers a solution for environmental management that enables enterprises to monitor their environmental impact. The software includes features for emissions monitoring, resource and energy management, as well as environmental auditing and reporting.

ERA Environmental Management System offers a comprehensive approach to environmental management, covering aspects from pollutant monitoring to waste and water resource management. The system supports integration with other corporate systems and provides tools for data analysis and decision-making.

Envirosuite Omnis is an industrial monitoring platform that allows users to track various environmental parameters, such as air quality, noise, vibrations, and odors. The system provides real-time monitoring and data analysis, as well as supports the development of strategies to minimize negative environmental impacts.

1. Comparative Analysis of Environmental Monitoring Software Solutions

Company	Main Functions	Target Segment	Module Availability
ENVIRA DS	● Data collection from stations (integrated with all types of instruments, emission data, meteorological data) ● Data verification and automation ● Detection of anomalous situations ● Trend determination, seasonally adjusted, and visualization on a single platform	Air transport, heavy industry, oil refining industry	Yes
EnviroData EDMS	● Monitoring and analysis of water quality data ● Management of bioanalysis and soil quality data ● Monitoring of meteorological conditions	Water management, laboratories, regulatory authorities	Yes
EHSInsight	● Conducting audits and generating reports ● Tracking environmental parameters ● Data visualization	Oil refining industry, automotive industry	Yes
ERA environmental	● Management of the water sampling process and analysis of their quality ● Management of wastewater treatment processes ● Monitoring of greenhouse gases ● Tracking and management of hazardous chemical waste	Aerospace industry, chemical industry, automotive industry	No
EnviroSuite Omnis	● Hyperlocal tracking of meteorological data ● Noise and dust control ● Air emissions modeling ● Detection and analysis of noise and vibration data	Mining industry, extraction industry	No

Rotronic RMS offers a solution for environmental condition monitoring that focuses on the accuracy and reliability of data collection. The system is suitable for use in analytical laboratories and production facilities.

Trends in the Development of Environmental Management Systems. Currently, several key trends are shaping the future of the EMS market.

First and foremost, integration with other management systems is becoming increasingly common. Organizations are striving to create a unified platform that provides a comprehensive view of all management aspects, including quality, occupational safety, energy management, and environmental management. This promotes better coordination of actions and resource optimization.

The second important trend is the use of cloud technologies. Cloud-based EMS offers greater flexibility and accessibility, allowing users to easily access data and tools from anywhere in the world. This also facilitates collaboration between different departments and organizations.

The third trend is the use of artificial intelligence. Modern EMS incorporates AI tools that enable deeper analysis of large volumes of environmental data, identify trends, and make predictions.

The fourth trend is the growing focus on mobility. Mobile applications and interfaces are becoming more widespread, allowing employees to monitor and manage environmental risks directly from their smartphones or tablets. This enhances the efficiency of environmental control and reporting, and enables the rapid provision of environmental information and notifications to the public when necessary.

Users of Environmental Management Systems and Control of Anthropogenic Impact on Environmental Components. EMS are applied across various industries as organizations strive to reduce their environmental impact and comply with increasingly stringent environmental regulations.

One of the primary industries where EMS are actively used is heavy industry, including chemical plants, metallurgical complexes, and other enterprises that generate significant volumes of emissions and waste (Magjun, 2020).

The energy sector also widely employs EMS to manage greenhouse gas emissions. This is particularly relevant for thermal and nuclear power plants, as well as companies involved in the extraction and processing of coal, oil, and gas (Razit, 2022).

Water management and wastewater treatment is another area of EMS application. These systems help monitor water quality, track pollutant levels in wastewater, and optimize treatment processes.

Additionally, EMS are used in the construction and real estate sectors to manage the environmental impact of large construction projects and monitor emissions from construction machinery (Zucki, 2015).

These industries rely on EMS to ensure compliance with environmental regulations, minimize their ecological footprint, and enhance sustainability practices.

Examples of Successful Use of Systems (Corporations BASF and

Valspar). BASF is one of the largest chemical companies in the world, producing a wide range of products, from growth regulators to plastics. By using EMS, BASF has improved its data management processes for emissions and waste. The application of the system has allowed the company to save over 2000 working hours per year, which, at an average specialist wage of $75 per hour, translates to savings of approximately $150,000 annually (ERA Environmental Management Solutions, 2016).

Valspar, a renowned manufacturer of paints and coatings, also uses EMS to manage its environmental commitments. The system has enabled the company to automate processes for data collection on emissions, waste management, and reporting. As a result, Valspar has noted a reduction in the time spent on data entry and number processing by over 75%, leading to significant time and cost savings. These examples demonstrate how EMS can be used by large corporations to effectively manage environmental risks and ensure compliance with regulatory requirements.

Conclusions and Recommendations. Currently, EMS are not merely tools for environmental monitoring, control, and reporting, nor just for reducing environmental taxes and fines, but they are also powerful means for optimizing rational natural resource use. The progress in EMS development is a clear indication of how technologies can serve the achievement of sustainable development goals and the ecological safety of industrial activities. The successful implementation of such systems by large companies like BASF and Valspar demonstrates that with the right approach and tools, businesses can not only thrive but also contribute to environmental protection and the rational consumption of natural resources. It is also important to remember that EMS require continuous updates, adaptation to new challenges, and interaction with other management systems. The implementation of such environmental control, monitoring, and risk prevention systems in the industrial activities of enterprises will simplify the procedure for environmental reporting and compliance with environmental requirements and legislation at enterprises in Ukraine.

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КОМПЛЕКСНИЙ ОГЛЯД СУЧАСНОГО ПРОГРАМНОГО ЗАБЕЗПЕЧЕННЯ З УПРАВЛІННЯ ВПЛИВУ НА НАВКОЛИШНЄ СЕРЕДОВИЩЕ

О. Заверталюк, О. І. Наумовська

Анотація. *У сучасному світі ефективний екологічний контроль набуває нового значення через антропогенний вплив на екосистеми та їх компоненти. Системи екологічного контролю та управління (EMS) стають необхідністю для промисловості, допомагаючи зменшити антропогенний вплив на навколишнє середовище та оптимізувати використання природних ресурсів. Стаття розглядає різні типи EMS, їхні особливості, архітектуру та моделі обчислень. Основні функції систем включають моніторинг та збір даних, аналіз та обробку даних, управління відповідністю, управління інцидентами та відхиленнями, планування та встановлення цілей, а також комунікацію та звітність. EMS вирішують завдання, пов'язані з екологічним аудитом, звітністю та управлінням екологічними ризиками виробничих процесів. На ринку існують різні системи, кожна з яких пропонує унікальні рішення для різних індустрій. Приклади успішного використання систем включають компанії BASF та Valspar, які заощадили значні ресурси завдяки впровадженню EMS у виробництво. У висновках наголошується на важливості EMS для сталого розвитку та екологічної безпеки, а також на необхідності їх постійного оновлення та адаптації до нових викликів.*

Ключові слова: *Environmental monitoring, Environmental control, Environmental pollution, Environmental risk management, Sustainable natural resource management, Environmental Management Systems, Compliance Management, Sustainability, Industrial Impact Reduction*

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