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COMPARATIVE ANALYSIS OF WASTE EMISSIONS AND IOT-BASED MONITORING APPROACHES IN DIFFERENT COUNTRIES

Yuldashev Jalaliddin Faizullo ogli
Doctoral student at the Department of Mobile Communication Technologies,
Tashkent University of Information Technologies named after Muhammad Al-Khwarizmi.
Tashkent, Uzbekistan
E-mail: jalol2122@gmail.com
Phone: +998941148833

Abstract: The article discusses modern approaches to the application of Internet of Things (IoT) technologies in waste disposal systems. The relevance of monitoring emissions and pollutants arising from waste processing is highlighted. The main types of IoT sensors used for monitoring air and water quality, as well as equipment status, are analyzed. Examples of international experience in implementing 'smart' containers, sensor platforms, and waste management systems based on digital technologies are provided. The prospects for applying IoT approaches in the Republic of Uzbekistan are examined, along with key barriers and opportunities for their implementation. The conclusion emphasizes the necessity of integrating IoT solutions to enhance waste recycling efficiency and reduce environmental risks.

Keywords: Internet of Things (IoT); environmental monitoring; waste recycling; smart containers; environmental control;

Introduction

The problem of household waste disposal in the 21st century is one of the most urgent global environmental challenges. According to the World Bank, more than 2 billion tons of municipal solid waste are generated annually in the world, and this indicator is projected to grow to 3.4 billion tons by 2050 [1]. Intensive urbanization, population growth and increased consumption lead to a constant increase in waste volumes. This is accompanied by significant environmental risks: air and soil pollution, greenhouse gas emissions (co_2, methane), toxic compounds (dioxins, heavy metals), and deterioration of the sanitary and epidemiological situation [2]. In most cases, traditional methods of environmental control at waste processing plants are based on periodic measurements and laboratory tests. This approach is reactive in nature, as it allows violations to be fixed only after they occur. With the growing scale of waste and stricter international environmental standards, there is a need to switch to more modern monitoring methods that ensure continuous and automated control [3].

One of the most promising areas of digitalization of waste disposal systems is the use of Internet of Things (IoT) technologies. The IoT is a network of sensors, devices, and platforms integrated into a single system that collects, transmits, and processes large amounts of data in real time [4]. The use of such technologies in the field of waste recycling allows: 1)to carry out constant monitoring of air and water quality in the areas of influence of enterprises, 2) to control the level of emissions from incinerators, 3) to monitor the condition of filtration systems and equipment, 4) to manage waste logistics using "smart" containers and digital platforms [5].

International experience shows that the introduction of IoT solutions helps to increase the efficiency of waste treatment and reduce environmental burden. For example, projects on the use of sensor technologies for emissions monitoring are actively developing in Germany and France, and in the United States, IoT is used to optimize garbage truck routes and manage separate garbage collection [6].

For the Republic of Uzbekistan, where more than 14 million tons of waste are generated annually and the recycling rate remains at 5% [7], the use of IoT approaches is not only an urgent task, but also a strategic direction within the framework of digital transformation and environmental modernization of the industry.

IoT in environmental monitoring.

The Internet of Things (IoT) has become an important tool in the field of digitalization in recent years, finding wide application in industry, transport, agriculture and ecology. Its main feature is the integration of sensors, devices, and communication technologies into a single network that provides continuous real-time data collection and analysis. This opens up fundamentally new opportunities in environmental monitoring: air, water, and soil quality control is becoming more accurate, and recording enterprise emissions is becoming operational and transparent. Unlike traditional methods that rely on random measurements and laboratory tests, IoT allows for continuous monitoring with a high degree of detailand minimal time delays [2].

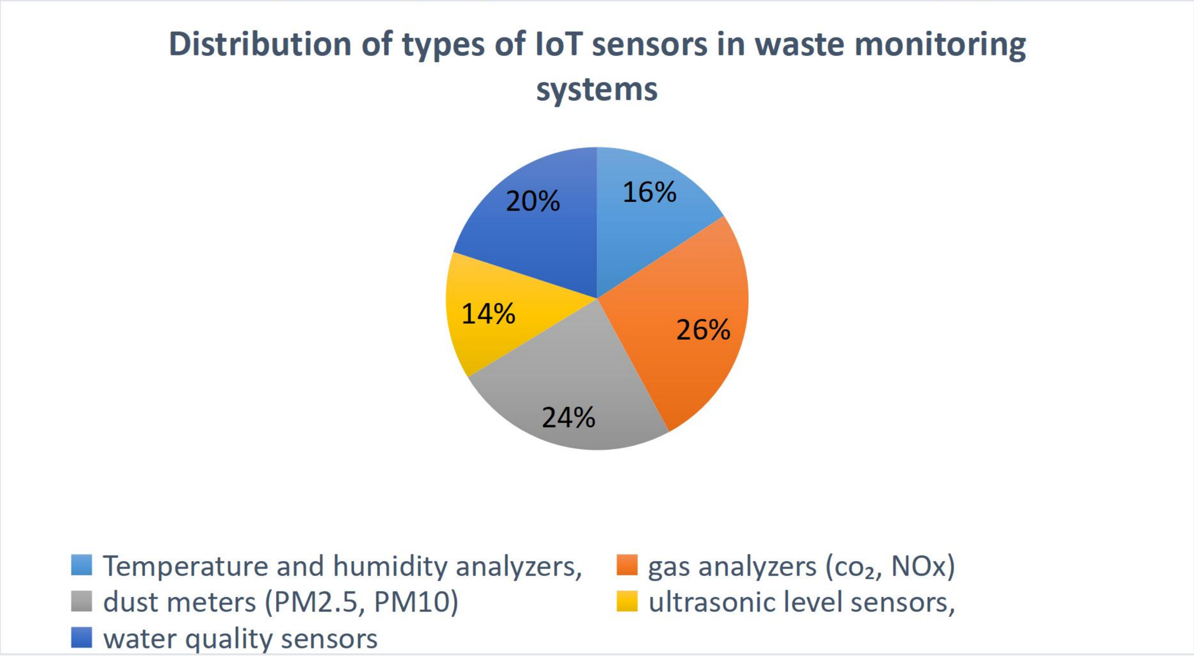

Fig1. Distribution of types of IoT sensors in waste monitoring systems.

The diagram shows the distribution of the most common types of IoT sensors used in waste monitoring systems: gas analyzers, dust meters, water sensors, ultrasonic level sensors, and temperature/humidity sensors.

The practice of using IoT in this field shows that sensors can measure a wide range of parameters: from the content of greenhouse gases and suspended particles in the atmosphere to the acidity and electrical conductivity of wastewater. The data obtained is transmitted through modern communication protocols to cloud platforms, where it is analyzed using machine learning and big data methods. This allows not only to record the current state of the environment, but also to predict possible violations, timely warn responsible services and thereby prevent emergencies. This integration of technologies makes the environmental control process more flexible and adaptive to constantly changing conditions [4].

Air quality control systems with distributed sensor networks are actively developing in a number of European countries, intelligent containers for separate garbage collection and optimization of garbage truck routes are being introduced in the USA, and projects on air quality monitoring in landfill areas are being implemented in France. All these examples demonstrate that IoT has already ceased to be an experimental technology and has become a real tool for environmental risk management. For states with a growing volume of waste, including Uzbekistan, such solutions open up prospects for a transition from reactive response to environmental threats to proactive environmental management [6].

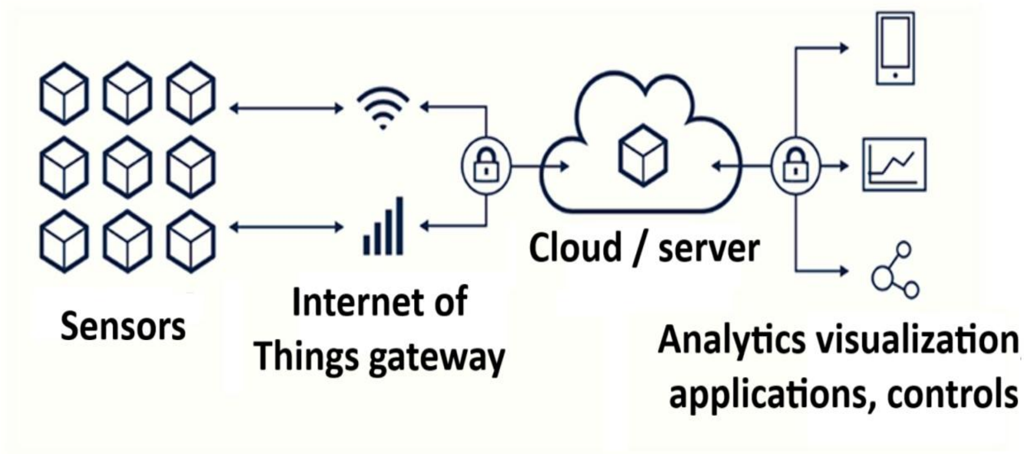

Figure 2. Diagram of the IoT waste monitoring system.

It is based on sensors that are installed at a waste recycling plant or landfill (Fig. 2). Each sensor performs its own task: some measure air quality (co_2, NOx, PM2.5), others monitor the state of wastewater (pH, BOD), and others determine the level of container filling or temperature. These devices continuously record changes in the environment.

The collected data is sent to the IoT gateway, a device that combines information from different sensors and transmits it via modern communication channels (LoRaWAN, NB-IoT, 4G/5G). The gateway is needed so that even from remote or hard-to-reach objects, data can stably reach the system. Then the information gets to a cloud platform or server, where it is stored and analyzed. Big data and artificial intelligence algorithms are used here. For example, if the concentration of harmful substances increases, the system can predict in advance the risk of exceeding the norms and generate a warning. The results of the analysis are displayed on the dashboards in the form of graphs, tables and maps. These panels are available to environmental services and management of enterprises. Specialists see the situation in real time and can make quick decisions.

The last stage is process management. If excess emissions are detected, the system automatically reports this to the operator or directly transmits a signal to the equipment: turn on the filters, reduce the load on the installation, change the operating mode. Thus, the company not only fixes the problem, but also gets the opportunity to eliminate it promptly.

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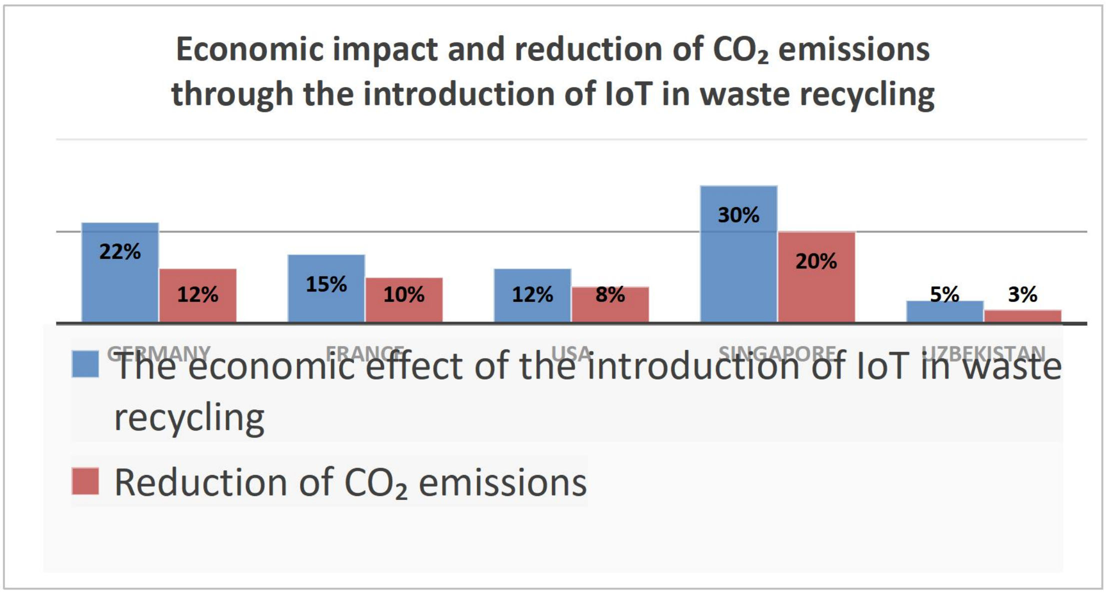

Figure 3.Economic impact and reduction of CO_2 emissions through the introduction of IoT in waste recycling

Figure 3 shows a comparison of the economic impact of the introduction of Internet of Things (IoT) technologies in the field of waste recycling in a number of countries. The data shows that Singapore has demonstrated the highest level of efficiency, where the integration of smart containers and centralized management platforms has reduced operating costs by about 30%. This is due to the complex nature of the implementation and the high level of digitalization of the infrastructure.

In Germany and France, the figures were 22% and 15%, respectively, due to the development of air quality monitoring systems and the optimization of garbage truck routes. In these countries, savings are achieved primarily by reducing fuel costs, vehicle maintenance, and reducing manual controls. In the United States, this figure is 12%, reflecting the effectiveness of IoT-based logistics solutions in waste disposal.

In Uzbekistan, the introduction of IoT technologies is still a pilot, and the level of economic efficiency is about 5%. The main limiting factors remain the high cost of sensors, the lack of specialists and poor integration with the existing infrastructure. Nevertheless, even at this stage, there is a reduction in costs due to automation of waste accounting and improved control over their movement.

Prospects of using IoT for environmental control in waste disposal systems in Uzbekistan. Over 14 million tons of solid household waste are generated annually in the Republic of Uzbekistan, while the recycling rate remains at 5%, which is significantly lower than in developed countries [8]. Most of the waste is disposed of at landfills, which are often not equipped with modern emission control and environmental monitoring systems. As a result, the burden on ecosystems is increasing: there is an increase in air and water pollution, and a deterioration in the sanitary and hygienic situation in populated areas [9].

The introduction of Internet of Things technologies opens up new opportunities for improving the effectiveness of environmental control. The use of IoT sensors will make it possible to organize round-the-clock monitoring of air quality at landfills and incinerators, ensure control of wastewater composition, and create a real-time waste volume accounting system [10]. The use of smart containers and route tracking systems for garbage trucks can reduce logistics costs by up to 15-20% and at the same time reduce CO_2 emissions from transport [11]. Additionally, the integration of IoT with big data systems and analytical platforms will make it possible to predict environmental risks and formulate strategies to prevent them [12].

Indicator	Meaning	Notes / source
Annual formation of solid waste	10.2 million tons	plastic waste is about 1.05 million tons (10.3%) [13]
Alternative estimates of the total volume of MSW	13-15 million tons per year	up to 15 million tons [14]
Solid waste disposal / recycling	less than 8 %	8% of the waste is recycled, the rest are buried in landfills or stored without treatment [14]

Despite the significant potential, there are objective barriers that limit the large-scale implementation of IoT in the field of waste management. These include the high cost of sensor devices and IoT gateways, limited capabilities of local manufacturers, and a shortage of specialists capable of servicing such systems. In addition, the country lacks uniform standards for digital monitoring and legal mechanisms for integrating IoT technologies into government environmental control programs [8, 9].

Taking into account current trends, several promising areas can be identified for Uzbekistan: firstly, the introduction of pilot IoT projects at large landfills in the Tashkent and Samarkand regions, which can serve as a model for other regions; secondly, the creation of a national environmental monitoring platform combining data from different facilities; thirdly, the development of educational programs for training specialists in the field of IoT and environmental engineering [10]. In the long term, the introduction of such technologies will increase the level of waste recycling to 15-20%, reduce unauthorized emissions and improve the environmental situation in the country [11, 12].

Conclusion

An analysis of modern approaches to environmental control in waste disposal systems shows that the introduction of Internet of Things (IoT) technologies is an effective tool to reduce the negative impact on the environment. The international practice of Germany, France, the USA and Singapore confirms that the use of sensor systems and digital platforms allows not only to reduce emissions of pollutants, but also to achieve tangible economic benefits by optimizing logistics and reducing operating costs.

In Uzbekistan, from 10 to 15 million tons of solid household waste are generated annually, while the share of recycling does not exceed 5-8% [8, 9]. This situation increases the burden on the environment and requires the introduction of modern digital solutions. The use of IoT sensors for monitoring air and water quality, smart containers and logistics platforms can ensure the transition from reactive to preventive environmental control. This will reduce the volume of waste disposal, increase the transparency of processes and improve the sanitary and hygienic environment.

The prospects for the use of IoT in Uzbekistan are directly related to the digital transformation of the waste management system. The development of national pilot projects, the creation of a unified environmental monitoring platform and the training of qualified personnel can ensure an increase in the level of waste recycling to 15-20% in the medium term and significantly reduce environmental risks.

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