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Model Drivers-Pressures-State-Impact-Response as a method for analyzing hazardous waste management in the People's Republic of China: a review of international experience

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This article presents an analysis of the hazardous waste management system in the People's Republic of China using the DPSIR (Drivers-Pressures-State-Impact-Response) model. Particular attention is paid to political, technological, industrial and socio-economic factors influencing waste generation and recycling. The article considers data related to the growth of hard-to-recycle waste, including recycling dynamics. It is shown that the waste recycling rate in China has increased to 55%, but there remain significant problems with separate collection and recycling of resources. The work also considers international experience and environmental policy of China, including participation in the Basel Convention and the implementation of the principles of the circular economy. Response measures aimed at improving the efficiency of waste management are proposed, including digitalization, legislative regulation and the development of recycling infrastructure. Particular attention is paid to the impact of waste on human health and the environment, as well as the need to transition to sustainable development. The article emphasizes the importance of using the DPSIR model to analyze cause-and-effect relationships in the field of waste management and suggests ways to solve existing problems. The obtained results can be useful for the formation of public policies in the field of waste management both in China and other countries of the world.

Keywords: industrial and hazardous waste in China, circular economy, global waste management perspective, sustainable development of China, sustainable development goals and hazardous waste management.

УДК 658.477

Модель Drivers-Pressures-State-Impact-Response как метод анализа управления опасными отходами в Китайской Народной Республике (обзор международного опыта)

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В статье представлен анализ системы управления опасными отходами в Китайской Народной Республике с использованием модели DPSIR (Drivers-Pressures-State-Impact-Response). Особое внимание уделено политическим, технологическим, промышленным и социально-экономическим факторам, влияющим на образование и переработку отходов. Рассматриваются данные, связанные с ростом трудноутилизируемых отходов, включая динамику утилизации. Показано, что уровень переработки отходов в Китае вырос до 55%, однако остаются значительные проблемы с раздельным сбором и вторичным использованием ресурсов. В работе также рассмотрены международный опыт и экологическая политика Китая, включая участие в Базельской конвенции и внедрение принципов циркулярной экономики. Предложены меры реагирования, направленные на повышение эффективности управления отходами, включая цифровизацию, законодательное регулирование и развитие инфраструктуры переработки. Особое внимание уделено воздействию отходов на здоровье человека и окружающую среду, а также необходимости перехода к устойчивому развитию. Статья подчеркивает важность использования модели DPSIR для анализа причинно-следственных связей в сфере управления отходами и предлагает пути решения существующих проблем. Полученные результаты могут быть полезны для формирования государственной политики в области обращения с отходами как в Китае, так и в других странах мира.

Ключевые слова: промышленные и опасные отходы в Китае, циркулярная экономика, мировая перспектива управления отходами, устойчивое развитие Китая, цели устойчивого развития и управление опасными отходами.

Hazardous waste (HW), being one of the most problematic categories of solid waste, is a by-product of human anthropogenic activity resulting from the release of toxic substances into the environment [1]. Globally, the generation of hazardous waste is rapidly increasing due to rapid urbanization and accelerated economic growth [2, 3], which is changing the field of hazardous waste management, requiring the introduction of environmentally friendly technologies to achieve national goals and implement the Sustainable Development Goals (SDGs), developed in 2015 by the UN General Assembly as “a plan to achieve a better and more sustainable future for all” [4, 5].

It should be noted that hazardous waste causes serious problems due to its negative impact on the environment, as well as the threat of environmental disaster and depletion of resources [6]. A number of scientific studies record the volume of hazardous waste generation in various countries of the world, which indicates a high level of toxic substances and chemicals [7]. According to [8], approximately 5–7% of solid household waste should be classified as hazardous. For example, in India, about 9.3 million tons of hazardous waste are generated annually, of which 0.11 million tons are incinerated, 1.35 million tons are recycled, and 0.49 million tons are sent for safe disposal [9].

Based on the above, the problem of environmentally sound management of hazardous waste is becoming a global challenge for the whole world, especially for developing countries, as their impact on the environment and human health is becoming more radical [10, 11]. This is reflected in the fact that low- and middle-income countries are at increasing risk of diseases caused by hazardous waste recycling [12–15]. For example, according to the Waste Life Cycle Assessment (LCA), the disposal of hazardous waste by incineration has carcinogenic, toxic effects on human health, and increases global warming in the world, as persistent pollutants such as dioxins, heavy metals, and bromine-containing flame retardants are released into the atmosphere [14–16]. In [11, 12], a hypothesis was put forward about the synergistic effect of hazardous waste on various risk factors for diseases such as hepatitis B.

In the People’s Republic of China (hereinafter referred to as China), strict measures have been introduced since 2003 to control hazardous waste and its disposal, which has led to a sharp decrease in its uncontrolled release into the environment [17, 18]. However, hazardous waste pollution remains one of the most serious problems in the country. Consequently, one of the key factors of sustainable development is waste management, recycling and air quality preservation [19].

It should be noted that China’s industrial waste includes toxic, corrosive, explosive, and flammable chemicals [20] that pose a threat to human health and the environment [21–24]. China ranks second in the world after the United States in the generation and processing of toxic waste [25, 26], of which 148 are classified as extremely toxic, and it is forbidden to collect, store, use and dispose of them without special treatment [27]. For example, ash residues and fly ash, which contain heavy metals, must be subjected to special treatment before burial in order to reduce risks to ecosystems [28, 29].

The concept of efficient waste disposal is actively used in various industries in China, thereby allowing us to obtain useful products. For example, ash, artificial gypsum, metallurgical slags and mining waste are used for the production of building materials [30]; catalytic processing of polymer waste and biomass allows to obtain valuable chemical compounds that are used in the pharmaceutical industry, organic synthesis [31]; pyrolytic processing of plastic waste is used to produce hydrogen and other fuel gases [32]; sewage sludge is used to generate electricity [33, 34]; ash residues are used as alternative building materials [34].

At the global level, there is an increase in the generation of hazardous waste, while developed countries recycle more than 90% of waste, and developing countries face low rates of their collection and recycling [35]. For example, in 2010, 67% of waste was recycled in China, less than 50% in India, and only 15% in Iran [35, 36].

In the Russian Federation, namely in the Kirov region, the annual volume of waste generation is more than 700 thousand tons of production and consumption waste. Statistical data for

2022 showed that 776.7 thousand tons of waste were generated in the Kirov region, of which 42 thousand tons were processed, 669.3 thousand tons were disposed of, 26.9 thousand tons were neutralized, 89.5 thousand tons were disposed of. The share of disposed and neutralized waste in 2022 in the region was 89.6%.

According to official statistics from Kirovstat, in 2023, the volume of waste generation in the Kirov region increased slightly and amounted to 781.4 thousand tons. At the same time, the utilization rate remained at the same level – about 89.5%, which indicates the stability of the waste management system in the region. According to preliminary data, in 2024, the volume of waste generation increased to 786.2 thousand tons, while the share of recycling decreased to 88.9%, which may be due to an increase in the volume of hard-to-recycle waste such as mercury-containing lamps, electronic scrap and other types of hazardous waste. The lack of systematic separate collection and the shortage of recycling facilities continue to be key problems of the regional waste management system.

At the same time, there is practically no processing of individual components of municipal solid waste into raw materials for recycling and production in the Kirov region. A separate problem is the lack of separate collection and, in most cases, sorting of waste, which leads to significant losses of secondary resources and the disposal of toxic waste, including mercury-containing lamps, in landfills of solid household waste without prior neutralization. As world practice shows, the secondary involvement of useful fractions of solid household waste is a source of raw materials for industrial production. One of the main conditions for the use of solid household waste as secondary resources is their centralized collection and extraction of useful fractions.

It should be noted that in this paper on waste management, the People's Republic of China was not chosen by chance, it is a key research object in the field of hazardous waste management for the following reasons:

1) The scale of waste generation: China is one of the world leaders in terms of hazardous waste generation, which is associated with a high level of industrialization and urbanization. According to data for 2023, more than 69 million tons of hazardous waste were formed in the country, which requires effective management and control.

2) Global environmental impact: In the context of globalization, waste management in China directly affects the environmental situation around the world. On the one hand, the country is actively developing recycling technologies, and on the other, it remains a major producer of hard-to-recycle waste such as electronic scrap, mercury-containing materials and chemicals.

3) Environmental policy and international cooperation: China participates in international agreements such as the Basel Convention and pursues a domestic policy to implement the principles of a closed-loop economy. In 2014, an updated Environmental Protection law was adopted, which increases the responsibility of enterprises and local authorities for waste management.

4) Technological development and digitalization. In recent years, China has been actively implementing modern information technologies such as the Internet of Things (IoT), cloud computing, and big data to improve the efficiency of waste collection, sorting, and disposal. This makes the country an interesting model for analyzing innovative approaches to waste management.

The purpose of this study is to analyze China's hazardous waste management system using the DPSIR (Drivers-Pressures-State-Impact-Response) model, which makes it possible to identify key impact factors, assess the state of the waste management system, identify environmental and social consequences, and develop proposals for improving waste management practices.

Objects and methods of research

This review of international research on hazardous waste disposal in China provides an opportunity to justify the rationality of waste management methods and assess the impact of these approaches on improving the global environmental situation. In our opinion, the DPSIR model can be effectively used to analyze socio-environmental problems in the Kirov region.

To achieve the set goal, a review and analytical method has been used. Information for the study has been selected using keywords in the Web of Science Core Collection (Clarivate Analytics) scientific citation bibliographic databases. The review includes sources published from 1994 to the present. The search for information has been conducted in international, interdisciplinary, scientific, peer-reviewed open access journals dedicated to environmental and economic issues, using the following keywords: industrial and hazardous waste in China, circular economy, global perspective on waste management, sustainable development in China, sustainable development goals, and hazardous waste management.

Our study analyzes the DPSIR (Drivers-Pressures-State-Impact-Response) model to determine the relationship between waste generation, recycling processes, the impact of economic development, the state of the environment (according to the UN Sustainable Development Goals (SDGs)), sustainable production and consumption, and efficient resource management [1, 37–42]. The DPSIR model concept was adopted by the European Environment Agency (EEA) in 1999. This method identifies cause-and-effect relationships and systematizes information in order to solve environmental problems. The main methodological approach is to identify key data (indicators) of sustainable development that combine the social, economic, and environmental aspects of these systems, which can be used for management decision-making. The DPSIR model, which is a mechanism for monitoring the state of the environment and which provides a basis for researching and analyzing processes related to environmental degradation, is one of the most important developments for summarizing data based on the concept of cause-and-effect relationships. Specifically, it assumes a cause-and-effect chain in which indicators or drivers (D) represent anthropogenic factors that can cause environmental consequences (economic, physical, or cultural changes) due to improper hazardous waste management, pressure (P) includes direct and measurable impacts of anthropogenic factors on the system, state changes (S) reflect the influence of natural and anthropogenic factors on the waste generation process, impact (I) implies monitoring changes in the state of society, the economy, and the environment [43, 44], and response (R) represents activities to eliminate negative consequences based on the following principles of environmental change, including environmental sustainability, technical feasibility, economic feasibility, social acceptability, legal admissibility, administrative feasibility, political expediency, environmental balance, ethical justification, cultural inclusiveness, and effective communication [43]. Thus, the DPSIR model, effectively used in China, is designed to identify cause-and-effect relationships and systematize information in order to solve environmental problems [1].

Driving forces of hazardous waste management

Political, technological, industrial, and socioeconomic factors should be noted as driving forces that influence sustainable hazardous waste management.

Political factors include a system of guidelines, regulatory measures, laws, a clear division of responsibilities and powers between participants in the process, and the creation of a system of incentives and penalties for participants in the industrial waste management market. As part of its “ecological civilization” concept and environmental policy, China has developed more than 100 laws and regulations to address environmental issues and achieve sustainable development goals. However, their implementation and enforcement remain insufficiently effective due to various social, economic, technical, and environmental factors, such as an outdated industrial structure, a lack of financial resources, a lack of modern technologies and information support, low environmental awareness among the public and the private sector, and the lack of effective mechanisms for monitoring and enforcing environmental standards [45, 46].

One of the most significant laws is the new version of the PRC Environmental Protection law, adopted on April 24, 2014 and entered into force on January 1, 2015, which imposes additional responsibilities on environmental users who pollute the environment and provides a clearer legal framework for improving environmental management [47]. It contains provisions on involving the public in environmental monitoring and expands the responsibilities of local authorities and law enforcement agencies [48]. In 2018, the Environmental Protection Tax Law came into force with the aim of reducing anthropogenic emissions [1]. Waste management in China uses the “4R” concept, which includes reuse, restoration, recycling, and recovery [49–54].

China is one of the first countries to introduce the concept of a circular economy as a model for industrial and economic development. The Circular Economy Promotion Law, adopted in 2009, established a legal framework for improving resource efficiency, environmental protection, and sustainable development [45, 52]. In 2013, the State Council issued an action plan for China’s circular economy development strategy, which includes measures to improve energy efficiency and promote the rational use of water and resources [18, 51, 52].

China is currently entering a new era with a plan to build an "ecological civilization," which involves creating a market system for innovation in environmentally friendly technologies, developing "green" finance as part of national efforts to achieve carbon neutrality, and strengthening the energy-saving industry and environmentally friendly production. In 2018, the State Council of the People's Republic of China issued a master plan for development for the period 2018–2035, which provides for the construction of the "City of the Future," which will become part of the Tianjin-Hebei-Beijing economic zone and the Bohai Sea coast. According to 2020 data, the total area of this urban agglomeration is 217,156 km². Thus, ecological civilization in China is developing rapidly and will continue to develop in the coming decades [55].

Technological factors. As an impact on waste management in China, technological factors should be considered, specifically the use of artificial intelligence, which makes waste management more efficient by identifying patterns of waste generation. These technologies include the Internet of Things (IoT – a multitude of physical objects connected to the internet and exchanging data), short-range wireless data transmission technologies (NFC), global positioning system (GPS) sensors, radio frequency identification (RFID), cloud computing, and big data analytics. The development of information technology is helping to transform hazardous waste management into a circular economy. IoT technology enables the collection, storage, processing, and analysis of data by connecting physical and virtual devices to the network, which optimizes waste collection and vehicle route planning. Cloud computing provides access to data, which simplifies decision-making on waste recycling and disposal. Big data analytics, geographic, and socio-economic data are combined to understand the spatial distribution of waste [25, 26].

Industrial factors also play a significant role in hazardous waste management in China, namely, industrial enterprises must take a comprehensive approach to hazardous waste management using material flow and supply chain risk assessment tools. At the same time, scientific and technological innovations must be used to develop industries related to the circular economy [26].

Socio-economic factors include the strengthening of government initiatives and the attraction of social capital, which is reflected in the allocation of grants for research and technology projects [1].

Pressure related to hazardous waste management

The next tool in the DPSIR model is organizational and regulatory pressure related to hazardous waste management. At present, China has achieved significant economic growth and improved living standards [56, 57]. Legislative regulation and established standards are the main tools for waste management, but there is a significant gap between the volume of waste generated and the capacity to process it. For example, in 2016, the volume of hazardous waste in the country amounted to 54.7 million tons, and the gap in disposal was 11.58 million tons. Comprehensive waste utilization reached 28.2 million tons, and the volume of waste disposal amounted to 16.6 million tons. The overall waste utilization rate was 79.3%, with 115.8 million tons of waste being stored without effective processing [58].

China is actively strengthening hazardous waste management institutions, improving technologies for waste disposal, recycling, and storage, and developing professional training and international cooperation to increase waste treatment and disposal capacities [57]. The Basel Convention has played a key role in shaping the legislative framework, technical standards, and policies in the field of hazardous waste management. In 2008, the list of hazardous wastes was updated, and in 2016, its second edition was released, expanding the list from 400 to 479 types of waste, grouped into 49 categories. Currently, the share of safe recycling in China is 55%, and the resource utilization of waste is 30% [58].

The process of hazardous waste generation in space-time coordinates

The next tool in the DPSIR model is to consider the spatial and temporal state of hazardous waste generation. To assess the current state of hazardous waste management in China, historical data for the period from 1998 to 2018 was analyzed, and key stages in the implementation of environmental policy under the 11th, 12th, and 13th five-year plans were taken into account. Between 1980 and 2012, the pace of urbanization in China increased from 19.4% to 52.6%, leading to a significant increase in the volume of hazardous waste [53]. China is the world's largest producer of solid waste, generating more than 10 billion tons annually [59]. The main sources of this waste are the extraction and processing of natural resources, heavy industry, and the production of consumer goods.

The volume of industrial solid waste began to grow exponentially in the 1990s, increasing by 0.6 billion tons. Since 1995, China has produced 599.4 million tons of industrial waste (78% of total solid waste) and 26.2 million tons of hazardous waste (3%), with a recycling rate of 34.2% and a disposal rate of 12%. The most common industrial wastes included coal ash, blast furnace slag, and furnace slag. In 1995, the Law on the Prevention and Control of Environmental Pollution by Solid Waste was adopted, which established legal requirements for their recycling and disposal [60, 61].

In recent years, China has shown a trend toward increasing volumes of hazardous waste. The severity of the problem is growing due to rising incomes, urbanization, and the emergence of new agglomerations in the country. For example, in 2000, 8.3 million tons of hazardous waste were produced, in 2002 – 10 million tons, and in 2004 – 11.4 million tons [62, 63]. In 2016, the total volume of hazardous waste amounted to 53.5 million tons, of which 40.4 million tons were recycled, 2.6 million tons were disposed of, and 8.9 million tons were placed in storage. In 2017, the total volume of waste increased to 69.6 million tons, with the level of recycling increasing by 38%, disposal by 37%, and storage by 43% [58, 64]. Thus, the key factor in effective waste management is the accurate determination of the volume of waste to be processed [65–67].

Impact of hazardous waste on the environment and human health

The generation of hazardous waste and its impact on the environment and human health can be described using the IPAT equation, which takes into account three factors: population, affluence, and technological progress.

The formula is as follows: $I=P \cdot A \cdot T$, where I is the impact on the environment, P is the population, A is the level of prosperity, and T is the level of technological development. This means that the impact can be calculated based on population, level of prosperity (measured by gross national income), and time. The analysis showed that from 1998 to 2025, the pace of technological development was sufficient to offset the growth in population and welfare in China [39].

According to statistics for the last 17 years, due to low recyclability and the lack of a comprehensive regulatory mechanism, various types of hazardous waste accumulate in warehouses without being disposed of or recycled, for example, various types of alkalis, acids, asbestos, non-ferrous metallurgy waste, mineral oils, chemical materials, acrylic fibers, distillation residues, waste photosensitive materials, dyes, organic solvents, organic resins, medications, medical waste, oil emulsions, spent catalysts, waste containing nickel, chromium, cadmium, zinc, mercury [68, 69].

Measures to respond to the hazardous waste management process

In China, the process of hazardous waste management began to develop relatively recently. Between 1990 and 1995, industrial waste was discharged into the environment at an uncontrolled rate (40.9%), while safe disposal accounted for only 14% (including 9.8% of hazardous waste) [61]. In 2005, there were only 177 hazardous waste disposal facilities in China, processing only 4.16 million tons of industrial waste, which accounted for 43.4% [29, 62]. By 2010, hazardous waste disposal capacity had increased to 23.25 million tons per year, and the actual volume of disposal was 8.4 million tons, which meant an increase of 226% compared to 2005 [57].

Currently, there are two main methods of hazardous waste management in China: some private companies are licensed to process and dispose of their own waste, and state-owned companies have special licenses for comprehensive hazardous waste processing. However, it should be noted that the number of industrial enterprises using centralized hazardous waste management and processing facilities is small, which makes local waste processing and disposal the main focus [1].

There are three ways to dispose of industrial waste in China. The first is to transfer waste to specialized third-party industrial companies (32%) that ensure safe and effective waste management. The second is to dispose of hazardous waste within industrial companies (68%). The third method is illegal burial and disposal of waste, which, according to the laws of the Supreme People's Procuratorate and the Supreme People's Court, is punishable by imprisonment for up to three years.

Industrial enterprises in China play a dual role: they act as producers and as enterprises that use natural resources, whose activities are associated with harmful effects on the environment, making them a key target for regulation in the field of environmental control.

Conclusion

Based on a comprehensive analysis of the DPSIR model, it should be noted that hazardous waste disposal in China is currently based on a resource-saving approach and safe treatment. China is taking measures to address the issue of waste treatment and disposal, which is linked to environmental control and the desire to create an environmentally civilized society. The hazardous waste treatment and disposal industry is becoming more organized, standardized, and modernized, and has significant potential for capacity expansion. The future development of this industry depends on finding a balance between two approaches: China's development with environmental protection in mind and environmental protection in the process of China's development. The most important areas of development that will help implement the concept of a circular economy through the management of industrial hazardous waste are: 1) strengthening state support for the hazardous waste treatment and disposal industry; 2) integrating the industrial sector of hazardous waste treatment and disposal into national plans for energy conservation, environmental protection, and sustainable development; 3) Mandatory disclosure of information on hazardous waste flows through legal mechanisms; 4) Application of big data and other digital technologies to improve the effectiveness of hazardous waste management control.

Thus, this article provides a general overview of the large-scale task of hazardous waste management. This analysis may serve as an incentive to seek new solutions to this global problem.

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