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CHEMICAL TECHNOLOGY: SCIENCE, ECONOMY AND PRODUCTION

ЗБІРНИК НАУКОВИХ ПРАЦЬ

IX Міжнародної науково-практичної конференції

ХІМІЧНА ТЕХНОЛОГІЯ: НАУКА, ЕКОНОМІКА ТА ВИРОБНИЦТВО

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Збірник містить наукові праці учасників IX Міжнародної науково-практичної конференції «Хімічна технологія: наука, економіка та виробництво», що складаються з узагальнених матеріалів науково-дослідних робіт науковців різних галузей виробництв та наукових закладів України.

У збірнику висвітлюються актуальні питання спеціальної хімічної технології і виробництва боєприпасів, утилізації відходів виробництв різних галузей, енергозбереження, моделювання технологічних процесів, соціально-економічні аспекти виробництва та природокористування в умовах війни.

Збірник корисний робітникам хімічної промисловості, науковим співробітникам, аспірантам і студентам спеціальностей хіміко-технологічного та соціально-економічного профілів, фахівцям інформаційних технологій виробництва.

Наукові праці учасників конференції подаються в авторській редакції.

PROBLEMS OF CHEMICAL INDUSTRY RECOVERY AFTER WAR

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Armed conflicts have a devastating impact on industrial infrastructure, including the chemical industry, which is among the most environmentally sensitive sectors. The destruction of factories, accidents at chemical storage tanks, and uncontrolled releases of toxic waste result in long-term contamination of soil, water, and the atmosphere. International experience in restoring chemical production after military conflicts highlights key principles, technological approaches, and environmental safety measures that can be applied in countries affected by war, including Ukraine [1].

In the past, military conflicts have also caused significant destruction in the chemical industry. For example, in Germany, after World War II, the destruction of chemical plants in the Ruhr region led to widespread soil contamination with heavy metals and organic toxins, posing a threat to public health. In South Korea, following the Korean War of 1950–1953, the destruction of chemical and pharmaceutical enterprises resulted in contamination of water resources and soils. In Lebanon, after the civil war from 1975 to 1990, chemical plants in the vicinity of Beirut were similarly affected by fires and structural damage, leading to the pollution of coastal areas of the Mediterranean Sea with toxic substances and petroleum products. In Iraq, after the 2003 war, destroyed petrochemical plants in Basra and Baghdad became sources of toxic substance leaks, including petroleum products and chemical reagents, resulting in the contamination of the Tigris River and the Shatt al-Arab waterway.

The destruction of industrial infrastructure is accompanied not only by the direct release of toxic substances but also by long-term changes in ecosystems, making the restoration of the chemical industry after war complex and requiring a comprehensive environmental approach.

The restoration of Ukraine’s chemical industry after the war represents a complex, multi-level process requiring a strategic approach, substantial investments, and institutional coordination. Prior to 2022, Ukraine’s chemical sector held a significant position within the national economy, providing exports of mineral fertilizers, ammonia, polymers, and other products, contributing a considerable share of foreign exchange earnings, and supporting related sectors such as agriculture, metallurgy, and mechanical engineering. However, military actions caused the destruction of production capacities, degradation of infrastructure, loss of skilled personnel, and contraction of markets, threatening the integrity of the entire industry.

One of the key challenges is the physical destruction of production facilities, especially in the eastern and southern regions of the country, where the largest chemical complexes were located. The loss of enterprises such as «Stirol» in Horlivka or the Azov fertilizer plants entails not only the reduction of production capacities but also the destruction of logistics hubs connected to exports. Systemic damage to energy and transport infrastructure further limits recovery opportunities, as the chemical industry is energy-intensive and depends on stable supplies of raw materials, water, gas, and electricity.

The restoration of Ukraine’s chemical industry cannot be limited to the reconstruction of factories but must be accompanied by large-scale environmental rehabilitation of areas affected by decades of industrial impact. The experience of Germany between 1945 and 1955 demonstrated that systematic monitoring of soil, water,

and air conditions makes it possible to identify territories with the highest concentrations of toxic substances and to plan measures for their safe reclamation. At that time, soil and water chemical analyses were used, along with environmental assessments that included biological toxicity tests and evaluations of risks to the population. This approach ensured the consistent restoration of production while minimizing environmental consequences.

In Iraq, international organizations, including UNEP, developed methodologies for mapping contaminated areas and assessing chemical risks to restore industrial zones after military actions. These methodologies included the analysis of the chemical composition of soil, water bodies, and air, as well as modeling the spread of toxic substances. Particular attention was given to identifying zones with a high likelihood of negative impacts on public health, which made it possible to plan comprehensive measures for reclamation, wastewater treatment, and the prevention of further pollution. In addition, mobile laboratories and remote monitoring methods were employed to obtain real-time data on contamination in the affected areas.

In the Balkan region countries, such as Croatia and Bosnia and Herzegovina, after the conflicts of the 1990s, audits of residual chemical substances at industrial sites were carried out, including chemical and biological analyses of soil, water, and wastewater. Such audits made it possible to identify priority sites for remediation and to minimize environmental risks during the restoration of production and the introduction of new technological lines. To assess the state of the environment, modern geographic information systems and remote sensing methods were used, which allowed contaminated areas to be identified with high accuracy and enabled the development of individualized reclamation plans for each site.

Additionally, international practice includes the use of digital technologies and predictive modeling to forecast the further spread of toxic substances. The use of GIS, drones, and robotic sensor platforms makes it possible not only to map contamination but also to conduct rapid measurements of the chemical and biological parameters of soil and water. Such a comprehensive approach enables the planning of environmentally safe recovery, taking into account both current and potential risks.

The Ukrainian experience during the war demonstrates that international practices of chemical industry recovery can be directly adapted to national conditions. The destruction of industrial complexes in the Donetsk and Luhansk regions, the damage to chemical plants in Sievierodonetsk, and the frontline areas of the Zaporizhzhia region led to large-scale emissions of ammonia, nitrogen compounds, and heavy metals, resulting in the pollution of the Siverskyi Donets and Inhulets rivers as well as local groundwater reservoirs. As early as 2022–2023, the State Environmental Inspectorate of Ukraine, together with international partners, began conducting rapid assessments of contaminated areas using mobile laboratories and field tests for detecting toxins in soil and water. In addition, remote sensing projects supported by the EU and the United Nations Development Programme were launched, which made it possible to detect chemical leaks and assess the scale of destruction in real time. Particular attention was given to the development of regional environmental risk maps that included data on the condition of industrial facilities, the likelihood of chemical contamination, and the dynamics of water quality changes. This approach essentially replicated the UNEP methodology applied in Iraq but relied on more advanced digital solutions, including high-resolution satellite imagery and analysis using neural network algorithms.

In parallel, Ukrainian universities have initiated projects to implement biotesting of water bodies, based on analyzing the responses of aquatic organisms to the toxicity of

wastewater. These developments laid the foundation for comprehensive monitoring, similar to that applied in Germany during the post-war period but adapted to modern technological standards. Ukraine is also actively drawing on the experience of Balkan countries, since in conditions of destroyed infrastructure and limited access to certain areas, auditing residual chemical substances at industrial sites and storage facilities plays a key role. For example, during the elimination of emergency chemical storage sites in Donbas in 2023–2024, methods of combined analysis of soil and water samples were tested, followed by the implementation of programs for the individualized reclamation of contaminated territories. The use of GIS and drones made it possible to detect leaks and contamination hotspots in hard-to-reach areas, which accelerated decision-making and minimized risks to the population.

Taking into account accumulated experience and modern technological capabilities, Ukraine, in the process of restoring its chemical industry, should focus on modernizing wastewater treatment systems and implementing closed-loop water use cycles. This will significantly reduce the pressure on water resources and enhance their sustainability. Promising directions in this regard include membrane filtration technologies, biological treatment methods using microorganisms, and water recirculation systems, which have already proven effective in European chemical enterprises. It is essential that such solutions are integrated into national water security programs, as the preservation of freshwater resources is a critical factor for sustainable development.

Equally important is the establishment of effective mechanisms for the disposal and recycling of industrial waste, with an emphasis on technologies for secondary raw material use. Ukraine can adapt European practices such as chemical recycling of plastics and the development of industrial symbiosis, where the waste of one enterprise becomes a resource for another. Such initiatives have already demonstrated their effectiveness in Scandinavian countries, where «closed-loop» industrial parks simultaneously reduce the volume of waste disposal and increase the resource efficiency of the economy.

The transition to «clean» production technologies in Ukraine should be based on the use of energy-efficient equipment, renewable energy sources, and innovative catalysts that reduce atmospheric emissions. Examples of such solutions include solar and biogas installations to supply energy to chemical enterprises, as well as next-generation catalysts that significantly reduce nitrogen oxide emissions. Additionally, a promising direction is the implementation of carbon capture and storage (CCUS) technologies, which are actively used in several European countries and can be adapted to Ukrainian conditions with the support of international partners.

A comprehensive approach that combines digital monitoring methods, modernization of treatment technologies, the development of “green” production cycles, and integration into the European environmental standards system forms the foundation for the environmentally safe restoration of the chemical industry and its long-term sustainability.

International cooperation plays a key role in ensuring the environmentally safe recovery of chemical enterprises in post-conflict zones. Experience shows that without coordination with international experts and organizations, restoration efforts risk being incomplete, and the environmental consequences can be long-lasting. In Iraq and Syria, the restoration of destroyed chemical plants was carried out with the participation of the United Nations Environment Programme (UNEP), international non-governmental organizations, and specialists from the European Union, who provided not only expertise in technological processes but also oversight to ensure compliance with environmental

standards. International teams were involved in assessing chemical contamination of soil and water bodies, developing reclamation plans, and implementing technologies for the safe handling of toxic substances, including chemical reagents and petroleum products.

The implementation of international standards such as ISO 14001 and protocols for the safe handling of chemical substances ensured systematic control over production processes and restoration activities. Specifically, these standards enabled the establishment of structures for managing environmental risks, regulating emissions monitoring and wastewater quality, as well as overseeing the storage and disposal of hazardous waste. Such approaches significantly reduced the likelihood of recontamination and minimized long-term impacts on ecosystems and public health.

In the Balkan countries, following the military conflicts of the 1990s, international organizations provided support in implementing waste management standards, emissions monitoring, and chemical safety controls at restored enterprises. Within the framework of joint projects, local specialists were trained, methodological guidelines were developed, and comprehensive pollution control systems were implemented, allowing production to be restored while simultaneously preventing further environmental contamination.

Similar methods were applied in Germany and France during the restoration of the chemical industry after World War II and numerous local conflicts. International expert missions monitored compliance with environmental requirements and assisted in implementing modern techniques for soil reclamation, water treatment, and industrial waste disposal. In particular, experts ensured the integration of “green” technologies and pollution monitoring systems, which allowed production to be restored while maintaining high environmental standards and minimizing the risk of long-term damage to ecosystems.

The Ukrainian context underscores the critical importance of international cooperation in ensuring environmental safety amid a devastated industrial infrastructure. Between 2022 and 2024, projects supported by the EU, UNEP, and the UN Development Programme were implemented in Ukraine, aimed at assessing the damage to chemical enterprises in Donetsk, Luhansk, and Zaporizhzhia regions. In collaboration with international experts, environmental risk maps were developed, identifying areas of destruction, potential sources of toxic substance leaks, and forecasts of their spread. These data were used to plan soil reclamation and the purification of contaminated water bodies, replicating successful practices previously tested in Iraq and the Balkans.

Particular attention was given to the implementation of international ISO 14001 standards, as well as the adaptation of European norms to the Ukrainian environmental management system. This included the development of national methodological guidelines for handling hazardous waste and the improvement of air and water quality monitoring systems. With the support of international partners, training programs were conducted for Ukrainian specialists, enhancing their competencies in risk assessment, the application of treatment technologies, and the implementation of “green” standards.

An essential condition for the sustainable development of the sector is the integration of environmental management with international standards of sustainable production, which will increase the competitiveness of Ukrainian chemical products in European and global markets. The European Green Deal and the experience of implementing EMAS environmental management systems can serve as a reference point. Harmonizing Ukrainian legislation with EU directives on environmental protection and industrial

safety will promote foreign investment, the development of green financing, and the creation of new value-added chains.

The human resources issue also has a strategic dimension. Mass population migration and the disruption of educational networks have weakened the industry's capacity to train qualified engineers, chemical technologists, and production operators. Addressing this requires systemic measures, ranging from the creation of state programs for the repatriation of specialists to the expansion of international academic cooperation and the introduction of dual education programs in partnership with European universities and corporations. Engaging the Ukrainian diaspora could be particularly important, as it is capable of integrating modern managerial and technological practices into the country [2].

Financial challenges further increase the sector's vulnerability. High military and post-conflict risks limit private investors' interest, making international support a decisive factor. The European Bank for Reconstruction and Development, the World Bank, and the European Investment Bank are already considering the provision of credit lines for modernization projects. However, it is important not only to attract resources but also to ensure their effective allocation through transparent public-private partnership mechanisms.

A particular strategic challenge is the need to restructure the production model. In the context of the global transition to a "green" economy and the decarbonization of the chemical industry, Ukraine's chemical sector should focus not merely on restoring old technologies but on implementing energy-efficient and low-carbon solutions. This involves the development of biochemical production, the manufacture of "green" fertilizers and biopolymers, and the use of renewable energy sources in technological processes. Ukraine has an opportunity to integrate into European value chains, especially within the framework of the European Green Deal, where there is a growing demand for sustainable chemical products.

Thus, the restoration of Ukraine's chemical industry after the war should be based on a concept of deep transformation rather than a reproduction of the pre-war structure. Addressing infrastructure, environmental, human resources, and investment challenges must be integrated into a long-term sustainable development strategy grounded in European integration, innovation, and the principles of a circular economy. Such an approach will allow the sector not only to recover but also to secure a competitive position in the global system, ensuring economic resilience and technological modernization for Ukraine.

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