MODERN BIOLOGICAL THREATS: CHALLENGES, STRATEGIES, AND PROSPECTS

СУЧАСНІ БІОЛОГІЧНІ ЗАГРОЗИ: ВИКЛИКИ, СТРАТЕГІЇ ТА ПЕРСПЕКТИВИ

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Abstract. The fight against biological threats has been a key factor in humanity's survival throughout history. Taking into account the latest epidemiological, biotechnological, and geopolitical trends, this paper provides a comprehensive analysis of both natural and anthropogenic sources of biological hazards. Special attention is given to zoonotic infections, synthetic biology, biological weapons, bioterrorism, and global environmental factors that influence the epidemiological situation. International risk management strategies are summarized, the legal framework of biosafety is analyzed, and recommendations are proposed for improving systems for the prevention and response to biological threats.

Keywords: biological threat, biosafety, pandemic, synthetic biology, zoonoses, global health.

Анотація. Боротьба з біологічними загрозами є ключовим фактором виживання людства протягом всієї історії його існування. З урахуванням останніх епідеміологічних, біотехнологічних і геополітичних тенденцій, здійснено комплексний аналіз природних та антропогенних джерел біозагроз. Окрема увага приділена зоонозним інфекціям, синтетичній біології, біологічній зброї, біотероризму та глобальним екологічним факторам, що впливають на епідеміологічну ситуацію. Узагальнено міжнародні стратегії управління ризиками, проаналізовано нормативно-правову базу біобезпеки та запропоновано рекомендації щодо вдосконалення системи запобігання та реагування на біозагрози.

Ключові слова: біологічна загроза, біобезпека, пандемія, синтетична біологія, зоонози, глобальне здоров’я.

INTRODUCTION

In recent decades, the global community has repeatedly faced serious biological challenges, the most large-scale of which was the COVID-19 pandemic. It revealed the vulnerability of national healthcare systems and emphasized the importance of global biosafety. In addition to pandemics, biological threats include the spread of zoonoses, bioterrorism, laboratory accidents, and new risks associated with the development of synthetic biology and genetic engineering[12].

Biological threats include not only pandemics but also the transmission of diseases from animals to humans, various incidents of bioterrorism, and laboratory accidents. Particular attention should be given to new threats associated with the development of genetic technologies and synthetic biology[13]. Modern

[12] World Health Organization, *COVID-19 Strategy Update* [online], Geneva: WHO, 2020. Available at: https://www.who.int/publications/m/item/covid-19-strategy-update [Accessed 6 Jun. 2025].

[13] Koblentz, G.D., ‘The Rise of the Biotech Security Dilemma’, *Bulletin of the Atomic Scientists*, 2022, Vol. 78(4), pp. 197–205. doi: https://doi.org/10.1080/00963402.2022.2082585.

technologies allow for the creation of novel pathogens, while global oversight of such research often remains inadequate[14]. These threats — whether of natural or anthropogenic origin — require the attention of the scientific community, governmental institutions, and the international community in order to develop reliable protection systems.

The aim of this study is to analyze scientific publications from 2021 to 2024 in order to identify current trends related to biological threats, highlight the most pressing risks, and formulate proposals for improving response systems to such challenges.

RESEARCH METHODOLOGY

During the preparation of this article, an analysis was conducted of scientific papers published between 2021 and 2024, retrieved from databases such as Scopus, PubMed, and Springer Nature. In addition, official documents from international organizations, including the WHO and the UN, available through open-access internet resources, were also used.

More than 30 peer-reviewed publications were analyzed, covering various aspects of biological threats — from high-risk research (gain-of-function) and the development of synthetic biology to issues of bioterrorism and threats to global biosafety. Particular attention was paid to the analysis of recent biological threats in Ukraine.

Biological threats can be classified according to different criteria: source of origin (natural or human-induced), mode of transmission, level of contagiousness, mortality rate, availability of vaccines and treatment options, and the ability to spread beyond the borders of a single country. These criteria help to better understand the nature of the threat and to develop effective response strategies.

Based on the analysis of current research, four main categories of biological threats can be distinguished[15][16][17]:

1. Natural biological threats refer to various infectious agents that emerge in the environment without direct human intervention. Most often, these pathogens are transmitted from animals to humans and are therefore classified as zoonoses. Examples include the Nipah virus, avian influenza, and large-scale pandemics such as COVID-19 or Ebola virus disease. Key factors contributing to their spread include increased contact between humans and wildlife, the destruction of natural ecosystems (such as deforestation and dam construction), global urbanization, and the growth of international travel. Climate change plays a particularly important role by facilitating the expansion of both new and previously dormant pathogens, as rising temperatures affect the distribution of disease vectors — for example, mosquitoes, ticks, or rodents that carry dangerous viruses. It is important to note that diseases which were once geographically limited can, under certain conditions, quickly spread beyond their original regions and cause global outbreaks[18].

2. Unintentional biological threats arise from human negligence or technical failures during the handling of dangerous biological agents. This may include laboratory leaks, breaches in biosafety during the transportation of specimens, or accidents at biological research facilities. Notable examples include the 1979 anthrax incident in Sverdlovsk, which resulted in dozens of deaths, as well as more recent reports of

[14] National Academies of Sciences, Engineering, and Medicine, *Biodefense in the Age of Synthetic Biology* [online], Washington, DC: The National Academies Press, 2018. Available at: https://doi.org/10.17226/24890 [Accessed 6 Jun. 2025].
[15] Global Health Security Index, *Global Health Security Index 2021* [online]. Available at: https://www.ghsindex.org/ [Accessed 6 Jun. 2025].
[16] World Health Organization, *WHO Global Preparedness Monitoring Board Annual Report 2022* [online], Geneva: WHO, 2022. Available at: https://www.gpmb.org/annual-reports/2022 [Accessed 6 Jun. 2025].
[17] Lentzos, F., 'Synthetic Biology and the Governance of Biosafety and Biosecurity Risks', *Nature Communications*, 2023, Vol. 14(1), p. 112. doi: https://doi.org/10.1038/s41467-022-35749-y.
[18] World Health Organization, *WHO Coronavirus (COVID-19) Dashboard* [online], Geneva: WHO, 2023. Available at: https://covid19.who.int/ [Accessed 6 Jun. 2025].

biosafety violations in laboratories in the United States and China that handle highly pathogenic viruses. As the number of high-containment laboratories (BSL-3 and BSL-4) increases globally, the risk of such incidents remains significant. These risks are particularly concerning when laboratories are located near densely populated areas or operate with insufficient oversight from government authorities[19].

3. Intentional biological threats (bioterrorism) involve the deliberate creation or use of pathogens to cause harm to humans, animals, or agriculture. Such threats may be employed to spread fear among the population, destabilize economies, or be used as weapons in conflicts. The most well-known example is the mailing of anthrax spores in the United States in 2001, which occurred shortly after the September 11 terrorist attacks. In today's context, the situation is further complicated by the fact that technologies previously accessible only to governments are now, unfortunately, available to non-state actors as well — due to the development of bioinformatics, 3D printing, and open-access bio-laboratories. These advances enable the creation of new or modified pathogens with artificially enhanced transmissibility or resistance to treatment[20].

4. Dual-use threats refer to situations where peaceful scientific research may have the potential for military applications. For example, studying viruses for vaccine development or creating new treatment methods may unintentionally generate tools that can be used to engineer biological weapons. Of particular concern are so-called gain-of-function experiments — research in which pathogens are deliberately enhanced with new properties: increased infectivity, broader host range, or drug resistance. Although the primary goal of such research is usually to better understand viruses and prevent future pandemics, there is a real risk of accidental release or intentional misuse of this knowledge[21].

According to the classification by the Centers for Disease Control and Prevention (CDC), biological agents are divided into three categories based on their threat level[22]:

- **Category A** includes the most dangerous pathogens such as *Bacillus anthracis* (anthrax), *Variola major* (smallpox), botulinum toxin, and Ebola virus.
- **Category B** includes agents of moderate threat like *Brucella spp.*, ricin toxin, and *Salmonella spp*.
- **Category C** includes newly discovered or not yet fully studied pathogens that could potentially cause large-scale outbreaks in the future, such as the Nipah virus and hantaviruses.

The proposed classification of pathogens allows for more accurate risk forecasting, timely identification of threats, and the development of effective early warning systems — especially in the context of increasing globalization, migration, and climate change.

According to the order of the Ministry of Health of Ukraine, biological agents are divided into four hazard groups based on their level of infectious threat:

Group 1 – biological agents that are not capable of causing disease in humans.

Group 2 – biological agents that can cause human disease and may pose a hazard to workers, but are unlikely to spread to the community, and for which effective preventive or therapeutic measures are available.

Group 3 – biological agents that can cause serious disease in humans, pose a significant risk to laboratory personnel, and may spread to the community, but for which preventive or therapeutic measures are usually available.

[19] Koblentz, G.D., 'Laboratory Escapes and "Self-fulfilling Prophecies"', *Frontiers in Bioengineering and Biotechnology*, 2022, Vol. 10, article 815572. doi: https://doi.org/10.3389/fbioe.2022.815572.
[20] National Research Council, *Globalization, Biosecurity, and the Future of the Life Sciences*, Washington, DC: National Academies Press, 2022.
[21] National Science Advisory Board for Biosecurity (NSABB), *Recommendations on Gain-of-Function Research*, USA: NSABB, 2023.
[22] Centers for Disease Control and Prevention, *Bioterrorism Agents/Diseases [Категорії A, B, C]* [online], CDC, 2023. Available at: https://emergency.cdc.gov/agent/agentlist-category.asp [Accessed 6 Jun. 2025].

Group 4 – biological agents that can cause severe human disease, present a high risk to workers and the public due to their potential for rapid spread, and for which effective preventive or therapeutic measures are generally not available.

Over the past few decades, there have been several documented cases of dangerous pathogen leaks from laboratories worldwide. One of the most well-known incidents occurred in 1979 in the city of Sverdlovsk (then in the USSR), where a release of *Bacillus anthracis* spores resulted in the deaths of dozens of people[23].

In the 2000s, similar incidents were reported in the United States, China, and the United Kingdom. For example, in 2004, two laboratory employees in Beijing were infected with the SARS-CoV virus during research activities[24]. Although modern laboratories are equipped with advanced biosafety systems, there is always a risk associated with human error, technical malfunction, or failure to follow safety protocols.

Following the COVID-19 pandemic, the origin of the virus has been actively debated, particularly the possibility that SARS-CoV-2 may have entered the human population through a laboratory leak. While various media outlets have reported different theories, there is currently no definitive evidence to confirm this, and the topic remains highly controversial within the scientific community[25].

Bioterrorism — the deliberate use of pathogenic microorganisms or toxins to harm humans, animals, or plants — is considered especially dangerous. Such actions may aim to incite panic, inflict economic damage, or destabilize a government or society.

A striking example of bioterrorism is the 2001 anthrax letter attacks in the United States, in which an unidentified perpetrator mailed envelopes containing anthrax spores. As a result, five people died and more than twenty others were infected[26]. This case demonstrated that even highly developed countries are vulnerable to biological attacks.

According to reports from international organizations such as the United Nations, there is growing concern that terrorist groups may gain access to pathogens — either through the black market or through cyberattacks targeting biological laboratories[27].

Modern science has reached a point where researchers can synthetically construct viral genomes and develop entirely new microorganisms. While this offers great promise for medicine — including vaccine development, new therapies, and diagnostic tools — it also introduces the serious risk that such technologies could be used for military purposes[28].

These developments are referred to as dual-use technologies. Of particular concern are gain-of-function studies, in which scientists deliberately alter pathogens to study how they might become more transmissible or lethal.

Experts in biosafety have called for the creation of strict international regulations to control research in synthetic biology. This includes limiting access to synthetic DNA services, restrictions on the dissemination of sensitive information, and the implementation of ethical standards in scientific practice[29].

[23] Meselson, M., 'A Cloud over Sverdlovsk: Anthrax Outbreak of 1979', *Science*, 1994, Vol. 266(5188), pp. 1202–1208.
[24] World Health Organization, *Severe Acute Respiratory Syndrome (SARS): Status of the Outbreak and Lessons for the Immediate Future* [online], Geneva: WHO, 2004. Available at: https://apps.who.int/iris/handle/10665/70863 [Accessed 6 Jun. 2025].
[25] Lancet COVID-19 Commission, 'Task Force on the Origins of SARS-CoV-2: Interim Report', *The Lancet*, 2022, Vol. 400(10349), pp. 792–803. doi: https://doi.org/10.1016/S0140-6736(22)01598-8.
[26] Inglesby, T.V., O'Toole, T., Henderson, D.A., et al., 'Anthrax as a Biological Weapon, 2002: Updated Recommendations for Management', *JAMA*, 2002, Vol. 287(17), pp. 2236–2252.
[27] United Nations Office of Counter-Terrorism, *Countering the Threat Posed by Bioterrorism* [online], UN Briefing Paper, 2022. Available at: https://www.un.org/counterterrorism [Accessed 6 Jun. 2025].
[28] National Academies of Sciences, Engineering, and Medicine, *Biodefense in the Age of Synthetic Biology*, Washington, DC: The National Academies Press, 2018. doi: https://doi.org/10.17226/24890.
[29] Lentzos, F. and Koblentz, G.D., 'The Biosecurity Benefits of Restricting DNA Synthesis Orders', *Nature Biotechnology*, 2023, Vol. 41, pp. 33–36. doi: https://doi.org/10.1038/s41587-022-01567-1.

Over the past five years, there has been an intensification of international efforts in the field of biosafety, primarily in response to the COVID-19 pandemic. These efforts encompass both the creation of new global mechanisms and the reform of existing emergency response systems in public health. One of the most significant developments is the WHO Pandemic Accord. In 2025, WHO Member States approved the final text of a new pandemic agreement. This document provides for enhanced coordination during outbreaks, improvements in early warning systems, equitable access to medical tools, and the creation of a global preparedness fund[30]. Although the accord was supported by most countries, some major powers — notably the United States — did not join, reflecting geopolitical divisions in global health governance.

Another key international initiative is the U.S. Global Health Security Strategy. In 2023, the U.S. administration presented a program aimed at improving the capacity of 50 countries to detect and respond to biological threats. The strategy includes support from the Centers for Disease Control and Prevention (CDC) and other institutions, with a focus on infrastructure development, workforce training, and cross-sectoral cooperation[31].

In response to the challenges posed by the pandemic, the European Union established HERA (Health Emergency Preparedness and Response Authority), which has been operational since 2022. HERA is responsible for forecasting, preparedness, and response to health threats. It coordinates strategic stockpiles, invests in manufacturing capacities, and supports vaccine development.

The Global Health Security Index (GHS Index), which evaluates countries' preparedness for biological threats, was revised after the pandemic. Despite high scores for some countries — including the United States — their response to COVID-19 was widely considered insufficient, raising doubts about the reliability of existing assessment methodologies.

The One Health approach is promoted by international organizations such as WHO, FAO, and WOAH. It acknowledges the interconnectedness of human, animal, and environmental health. A joint action plan is in place for the years 2022–2026 to implement an integrated response to zoonotic and other biological threats.

Although modern international strategies for responding to biological threats reflect a growing commitment to improved coordination, rapid response, and enhanced global preparedness, several issues remain unresolved. These include geopolitical fragmentation, inequalities in access to resources, and the persistent need for stronger multisectoral collaboration.

THE WAR IN UKRAINE AND BIOTHREATS

russia's attack on Ukraine in 2014 caused profound transformations in many areas of life - from the economy to healthcare from the economy to healthcare. The issue of biological security has become particularly acute. Military actions using various means of destruction, massive forced population displacement, significant infrastructure destruction and environmental disasters have created unique conditions for the spread of infectious diseases and increased risks associated with biological agents. These threats include both natural factors (epidemics) and anthropogenic factors (unintentional leaks from laboratories or the potential use of biological weapons.

[30] The Guardian, 'World Agrees Pandemic Accord for Tackling Outbreaks of Disease', *The Guardian*, 20 May 2025. Available at: https://www.theguardian.com/global-development/2025/may/20/world-agrees-pandemic-accord-for-tackling-outbreaks-of-disease-who-covid [Accessed 6 Jun. 2025].

[31] Associated Press, 'Biden Administration Announces New Partnership with 50 Countries to Stifle Future Pandemics', *AP News*, 2024. Available at: https://apnews.com/article/11571e564eda19f091bdad50d367cbcd [Accessed 6 Jun. 2025].

The growth of biological risks in wartime necessitates a systematic analysis of the situation in Ukraine, as well as an assessment of the current state of the biosecurity system and the state's ability to to effectively counter new challenges.

Despite some progress in regulatory progress in biosafety regulation, Ukraine still lacks a clear comprehensive and effective system of biological risk management. This is is confirmed by numerous studies, including reports by the Center for of Public Health and expert opinions of Ukrainian and international experts. The reports indicate that the existing system has a structure in which Responsibility is divided between the Ministry of Health, State Service of Ukraine on Food Safety and Consumer Protection, Ministry of Internal Affairs, Ministry of Defense, the National Police, the Security Service of Ukraine, and local administrations. Unfortunately, the lack of a single coordinating body complicates the interaction between the agencies, slows down the exchange of information and the appropriate response to biological incidents.

Recent studies, including those by V.I. Velychko (2021), emphasize the importance of integrating efforts within the framework of the "One Health" concept, which entails coordinated actions across medical, veterinary, and environmental sectors to prevent the spread of infectious agents at the interface of different environments[32].

Military actions have significantly exacerbated the environmental crisis in Ukraine. Bombings and destruction of industrial enterprises, chemical facilities, and oil depots have led to massive releases of hazardous substances into soil, air, and water. According to the Ministry of Environmental Protection and Natural Resources, more than 1,200 environmental incidents related to military operations in Ukraine were recorded during 2022–2023[33].

The destruction of wastewater treatment plants, water supply, and sewage systems has had a substantial impact on the state of the environment. This, in turn, contributes to contamination of drinking water sources and increases the risk of outbreaks of intestinal infections, including cholera, dysentery, and salmonellosis. The spread of these diseases typically accompanies humanitarian crises in war-affected regions[34].

The presence of BSL-3 biological laboratories in Ukraine, engaged in research on highly pathogenic microorganisms, creates a risk of incidents in the event of breaches in safety protocols. Under conditions of shelling or occupation, there is a threat of damage to facilities, theft of samples, and loss of control over pathogens[35].

Taking into account historical precedents (Beijing, 2004), the international community calls for maximum strengthening of biosafety measures. UN and G7 reports note that war creates unique conditions for increased risks of accidental or deliberate release of dangerous agents[36].

In addition to biological factors, the war has caused active use of toxic chemical substances. According to the Ukrainian Institute for the Future, more than 4,500 cases of use or suspected use of chemical agents, including phosgene, chlorine, and ammonia, have been recorded since the beginning of the conflict[37]. Such attacks pose a serious threat to the civilian population and can lead to respiratory diseases, immune suppression, and secondary infections.

[32] Величко, В.І., 'Біобезпека в Україні: нормативно-правове забезпечення та перспективи реформування', *Медична безпека*, 2021, №1, pp. 17–25.
[33] Міністерство захисту довкілля та природних ресурсів України, *Аналітичний звіт про екологічні наслідки війни*, Київ, 2023.
[34] World Health Organization, *Ukraine: Environmental Health Risks in Conflict Zones. Situation Report*, Geneva: WHO, 2023.
[35] Гуменюк, С., 'Лабораторна біобезпека: виклики під час війни', *Журнал громадського здоров'я*, 2023, №2, pp. 45–51.
[36] United Nations Office for Disarmament Affairs (UNODA), *Biological Risks in Conflict Regions*, Geneva, 2022.
[37] Український інститут майбутнього, *Аналітична записка про хімічні загрози в умовах війни*, Київ, 2024.

Due to mass population displacement, significant deterioration of sanitary and hygienic conditions, and limited access to drinking water and medical services, Ukraine has experienced increased incidence of tuberculosis, intestinal infections, hepatitis, measles, and diphtheria[38]. In frontline areas, the number of acute intestinal infection cases reportedly rose by 35.0–40.0%. Lack of adequate vaccination and shortages of medicines threaten to increase previously controlled infections and the formation of new epidemiological hotspots[39].

Although there are currently no officially confirmed cases of biological weapons use in Ukraine, international discussions continue regarding their possible future use. In particular, there is concern about the use of genetically modified pathogens or artificially created viruses with enhanced infectivity and rapid spread potential[40]. Experts believe that modern technologies (synthetic biology, nanomedicine) enable the creation of new biological agents that could be used as weapons. In this context, international agreements, monitoring of dual-use laboratories, and transparency in biological research are becoming increasingly important[41].

Despite difficult conditions, Ukraine is taking measures to strengthen biological security. In 2021, a biosecurity and biosafety strategy was adopted, which envisages raising the professional level of personnel, developing a national biological monitoring system, legislative updates, and integrating the "One Health" approach[42]. Thanks to the support of international partners (USA, EU, WHO), various equipment for detecting and controlling the spread of infections is being supplied, training for medical workers and laboratory staff is conducted, and mobile laboratories for rapid response are being created[43]. At the initiative and with the support of the State Emergency Service and the Ministry of Health of Ukraine, joint training exercises have been held in recent years involving medical workers, police, rescuers, and students to simulate the elimination of consequences of emergencies related to medical-biological and chemical threats.

The war in Ukraine has created unique and simultaneously extremely complex challenges for the biosecurity system, including environmental contamination by various chemical, industrial, and biological agents, the spread of diverse infectious diseases, destruction of residential and business infrastructure with increased risks of leaks, and the potential threat of the use of biological weapons.

To overcome these challenges, comprehensive reform of the national biosecurity system is required, with particular emphasis on interaction among various units, agencies, and services; legislative improvements based on the experience of leading European and global countries; development of the laboratory network with the capacity for rapid pathogen detection; and international coordination. The "One Health" approach should become the foundation for an integrated response to new biological threats. Strengthening biosecurity in Ukraine also requires integration into European early warning mechanisms and the development of bioethical education for scientists. The strategic goal is to create a system capable not only of timely responding to biological or chemical threats but also of predicting them.

One of the key factors in reducing biological threats is the active role of the scientific community and the education system at all levels, starting from preschool institutions, as well as effective scientific-medical communication for experience exchange. These elements form the foundation for sustainable biosecurity at national and global levels.

[38] Міністерство охорони здоров'я України, *Офіційна статистика інфекційних захворювань, 2022–2024 рр.*, Київ: МОЗ, 2024.
[39] Центр громадського здоров'я, *Аналітичний звіт про санітарно-епідеміологічну ситуацію в Україні*, Київ, 2023.
[40] National Academy of Sciences, *Biodefense in the Age of Synthetic Biology*, Washington, DC: NAS, 2022.
[41] World Health Organization, *Enhancing Preparedness for Emerging Biological Threats*, Geneva: WHO, 2023.
[42] Кабінет Міністрів України, *Стратегія біобезпеки та біозахисту України на період до 2025 року*, Постанова №894-р від 21 липня 2021 року.
[43] WHO Ukraine, *Joint Activities in Biosafety Enhancement, 2022–2024. Official Update*, May 2024.

Modern achievements in genomics, epidemiology, bioinformatics, and molecular diagnostics allow much faster identification of new pathogens, modeling their spread, and assessing risks. Scientific research plays a key role in developing vaccines, antiviral agents, and diagnostic test systems.

However, the scientific community faces challenges such as uneven resource distribution, "scientific nationalism," limited access to biobanks and pathogen samples. Strengthening international cooperation, open data exchange, and support for multidisciplinary research are necessary. Biosecurity and biosafety require highly qualified specialists: microbiologists, virologists, bioethics experts, and risk analysts. Therefore, it is important that university programs include modules on biosecurity, bioethics, biological risk assessment, and emergency response.

Continuous education for medical workers, laboratory personnel, and crisis response specialists is also necessary. Developing professional networks, trainings, and simulations is an effective tool to increase system readiness for emergencies.

In the 21st century, biological threats have become a global challenge encompassing natural infectious processes and anthropogenic factors, including bioterrorism and potential laboratory leaks. The COVID-19 pandemic was an unprecedented test for the global health system, increasing awareness of the vulnerability of even developed countries to biological threats.

An analysis of the past four years shows significant progress in vaccine development, early pathogen detection, and coordination of international response. At the same time, structural problems remain: uneven resource access, insufficient high-security laboratories in many world regions, and the threat of misuse of biotechnology.

Ukraine, as a country at war, demonstrates an example of adaptation to difficult conditions and strives for integration into the international biosafety system. Further steps should include systemic modernization of laboratory infrastructure, development of human capital, and involvement of scientific potential in forming state security policy. Overall, only a multisectoral and globally coordinated approach will reduce risks associated with biological threats and prepare the world for potential future crises.