

RADIONUCLIDE AND CHEMICAL CONTAMINATION OF THE ENVIRONMENT AS FACTORS OF INCREASING MUTATIONAL VARIABILITY OF ORGANISMS

Ruslan Yakymchuk^{1,2,#} and Viktoria Valiuk¹

¹ Institute of Plant Physiology and Genetics of NAS of Ukraine, 03022 Kyiv, 31/17 Vasylykivska Str., UKRAINE

² National Dendrological Park “Sofiyivka” of NAS of Ukraine, 20300 Uman, 12a Kyivska Str., UKRAINE

Corresponding author, peoplenature16@gmail.com

Communicated by Isaak Rashal

In the course of evolution, living organisms have adapted to constant contact with mutagenic factors, and the spontaneous mutations induced by them have served as the one of the most significant sources of new traits and properties. With the development of civilisation, wildlife, including humans, was exposed to contamination by mutagenic factors of man-made origin: natural and artificial radioisotopes, pollutants, and xenobiotics. The sources of their release into the environment are mineral processing, radioactive and chemical waste, nuclear weapons testing, accidents at nuclear facilities and chemical plants, and the use of xenobiotic pesticides. Increased activity of mutagenic factors in the environment leads to an increase in the frequency of mutations in plants, animals, and humans, an increase in the genetic burden, and a decrease in the adaptability of populations. Further ecological screening and genetic monitoring of hazardous areas should become a mandatory component of the preservation of natural ecosystems and scientifically sound placement of recreational areas, cultivated plants, and construction of residential, industrial, and livestock facilities to protect public health, flora, and fauna.

Keywords: *mutagenic factors, radionuclide contamination, industrial emissions, xenobiotics, genotoxicity.*

INTRODUCTION

Life, as a form of biological matter, has been constantly affected by mutagenic factors throughout its history, such as natural radiation, chemical compounds of mineral origin, chemical effects of neighbours in the ecological niche, free radical processes in the course of normal metabolism, infectious diseases, mechanical and thermal tissue damage, errors in the genetic apparatus, and ordinary stochastic processes that occur in DNA molecules at body temperature (Livnat and Love, 2024). It is believed that the spontaneous mutations induced by them, associated with molecular changes in individual genes and changes in the number or structure of chromosomes, are the only source of new traits and properties of living organisms (Lynch *et al.*, 2016).

With the emergence of humans, wildlife began to be exposed to mutagenic factors of anthropogenic origin, the intensity of which increased over time as a result of environmental pollution (Ozkara and Akyil, 2018). The level of mutational variability has been steadily increasing as a result of the accumulation of a variety of genotoxicants in the environment, including radionuclides of natural and man-made origin, chemical compounds from industrial and agricultural production, certain medicines and food additives, mutagens produced during food preparation, and infections that are accompanied by age-related reductions in the body's defence systems (Roychoudhury *et al.*, 2022; Bartoszek and Holota, 2023; Geueke *et al.*, 2025). The discovery of artificial mutagenesis was of great importance for studying the consequences of their influence, as it allowed to induce mu-

tations under experimental, controlled conditions and study their nature. The first mutagens, such as X-rays and alkylating compounds, were introduced by humans into the natural environment by using them for experimental mutagenesis (Lundqvist, 2014; Calabrese and Selby, 2024). From weapons of experimentation and originating from rare phenomena in laboratories and small-scale production, these and similar mutagenic sources are now part of the Earth's biosphere in certain areas or globally and now have a complex impact on the heredity of organisms, including humans.

The development of the mining and uranium processing industries, construction of energy facilities and nuclear reactors, nuclear weapons testing, and radiation accidents have led to massive releases of radionuclides into the environment and a global increase in the level of radiation load on the biosphere (Folkers and Pentz, 2022; Zhao *et al.*, 2023). More than 50 tons of uranium are mined annually in the world (Dudar, 2019), and about 450 nuclear reactors have been commissioned and further construction is planned in the long term (Faudon, 2022), and in addition humanity has experienced more than 440 major radiation accidents, the consequences of which will be felt for centuries (Hasegawa *et al.*, 2015). A total of 2161 nuclear explosions were carried out, including 525 in the atmosphere (Dahlman *et al.*, 2011), which, despite the Comprehensive Nuclear-Test-Ban Treaty adopted by the UN General Assembly in 1996, some countries plan to resume, exposing humanity to greater radiation hazard (Malygina *et al.*, 2024). Industrialisation and improved technologies have created the preconditions for the annual synthesis of thousands of new substances, the production of which increased from 1 million to 4 million tons in the last century alone. More than 50% of them are environmentally hazardous, and 70% have a detrimental impact on the environment (Gavrilescu *et al.*, 2015; Ozkara and Akyil, 2018). In addition, as a result of industrial production and agricultural activities, trillions of tons of chemically active substances are released into the environment as by-products, many of which are toxic and pose a danger to biological systems, even in small quantities (Cribb, 2021).

Of particular concern are the numerous accidents that have occurred at nuclear facilities, hazardous chemical production facilities, during transportation of production waste, or their uncontrolled release from storage and disposal sites. Having destroyed the balance of biodiversity and threatened the stability of genomes, they have led to environmental disasters in certain areas. Limited information about the level of mutagenic activity of xenobiotics and possible ways of their transformation during disposal has led to problems of large-scale contamination of territories not only near environmentally hazardous facilities but also far beyond them. As a result, numerous manmade contaminated sites have been formed, with more than 60,000 in the United States and Canada, and some industrialised countries in Western Europe (e.g., Germany, Denmark, Switzerland, Austria) have an equivalent or even greater number of such sites (White and Claxton, 2004). The impact on natural systems

of anthropogenic pollution in the form of pollutants and xenobiotics, in conjunction with an increased radiation background, has been demonstrated in numerous studies. The intensity of these consequences is frequently unpredictably influenced by the density of ionising radiation and the concentration of chemical mutagens. Therefore, the study of the diversity of natural and anthropogenic mutagenic environmental factors, identification of sources of their formation and distribution in nature, and establishment of the level of danger to biodiversity and genome stability of organisms can become an important component in the geographical ranking of contaminated areas, development of measures to localise them, and protection of humans from the negative effects of inducing hereditary disorders to preserve the health of future generations.

METHODOLOGY

In order to identify the sources and mechanisms of spread of natural and anthropogenic mutagenic environmental factors, which would allow to establish the consequences of their uncontrolled impact on the heredity of living organisms, including humans, on a local and global scale, a large-scale search of original peer-reviewed publications was conducted in the Wiley, Google, PubMed, Google Scholar, ScienceDirect and Scopus databases using the following keywords: mutagenic factors, radionuclide contamination, industrial emissions, xenobiotics, and genotoxicity. Based on a preliminary review of the abstracts, articles that did not correspond to the content of the review were excluded from the literature analysis. These included articles that dealt with environmental pollution by pollutants that do not have a genotoxic effect, induction of mutations by chronic exposure to stressful psychoemotional factors, physiological mechanisms of mutagenic factor metabolism, and activation of molecular repair systems. Based on the defined criteria, 121 relevant articles were selected for this study. In addition to peer-reviewed articles, also reports, conference proceedings, and book chapters were reviewed, which covered in depth the components of the problem of anthropogenic pollution and genetic consequences on the level of individual regions, countries, and the world as a whole. The collected and analysed literature is supplemented by the results of the author's own research published in professional journals.

NATURAL RADIATION BACKGROUND

Given that radiation is one of the most significant physical mutagenic factors in the environment, the question regarding the potential consequences of such a global shift in the biosphere's radiation load for all living organisms is becoming increasingly relevant. The natural radiation background consists of three components: gamma radiation from the Earth, cosmic radiation (protons, α -particles, γ -rays), and airborne radon. Earth's radiation sources are more than 60 natural radionuclides, including 32 radionuclides of the uranium-radium and thorium families, about 11 long-lived

radionuclides not included in these families (K-40, Rb-87, Te-123, Bi-209, etc.) with half-lives of more than 108 years, and cosmogenic radionuclides (Duarte *et al.*, 2023). The external radiation background is complemented by the internal one, which is formed as a result of inhalation and ingestion of K-40, C-14, U-238, Th-232, Rb-87, Rn-222 isotopes with food (Shahbazi-Gahrouei *et al.*, 2013).

Cosmic radiation consists of galactic and solar radiation, the fluctuations of which are associated with solar flares. About 90% of the cosmic rays that reach the Earth are of galactic origin and consist mainly of protons (up to 87%), as well as α -particles and a small fraction of heavy ions and electrons. Solar cosmic rays have lower energy because they are 98% protons and 2% α -particles (Duarte *et al.*, 2023). Part of the energy of cosmic rays is spent on collisions with the nuclei of atmospheric nitrogen, oxygen, and argon, resulting in secondary high-energy radiation at altitudes up to 20 km, consisting of mesons, neutrons, protons, electrons, and 14 so-called cosmogenic radionuclides, which fall to the Earth's surface with precipitation and circulate in the environment (Wilkinson, 2015). The natural radiation background is associated with some mutations, the frequency of induction of which is related to the life expectancy of the organism. For example, in drosophila, it is about 0.1% of all spontaneous mutations, and in humans, due to their accumulation, it reaches 1–6% (Huber *et al.*, 2023).

The value of the natural radiation background on the Earth's surface is not constant and is associated with both global and local anomalies. They are caused by cyclic fluctuations in cosmic radiation and geological processes that have become global catastrophes. Local anomalies are observed in some areas such as India (Kerala and Tamil Nadu) (Mohanty *et al.*, 2004; Ghosal *et al.*, 2021), Iran (Ramsar County) (Ghiassi-nejad *et al.*, 2002), Greece (Ikaria Island) (Trabidou and Florou, 2005), Egypt (Nile Delta near Rosetta Beach) (Mubarak *et al.*, 2017), France (Lodeve), Brazil (Morro do Ferro, Minas Gerais, Espirito Santo, and Rio de Janeiro), Kenya (Mombasa), Russia (Republic of Sakha (Yakutia), Bryansk, Taganrog), China (Yangjiang) (Mousseau and Moller, 2020), and Ukraine (Kropyvnytskyi), where natural radiation doses are 5–10 times higher than the world average — 0.001–0.002 Sv/year (Morgun and Yakymchuk, 2010). These are the result of geological processes during which heavy natural radionuclides, primarily U-238 and Th-232 and their decay products, moved from the subsurface to the Earth's surface through intense volcanic activity and mudflow formation. For example, in the territories of Russia and Ukraine from Taganrog to Bryansk, accumulation of “black sands” containing natural radionuclides U-238 and Th-232, which are the result of leaching of indigenous rocks, was detected. Their specific activity along the coastline of the Azov Sea can reach $6 \cdot 10^3$ Bq/kg, which causes a 200-fold increase in the level of the natural geochemical background (Abdel-Razek *et al.*, 2012). The maximum levels of ionising radiation on the ground are 20 times lower than the maximum levels that exist in the Chornobyl Nuclear Power Plant (ChNPP) exclusion zone, but

they have existed for geological periods of time, which provides ample opportunities for adaptation to ionising radiation (Mousseau and Moller, 2020). In addition to external radiation, there is internal radiation exposure, which is a consequence of radionuclides entering the body with air, water, and food. Its level is determined by radionuclide contamination of the environment and can be twice the dose from external exposure (Yakymchuk, 2019).

MANMADE CONTAMINATION WITH NATURAL RADIOISOTOPES

As a result of human economic activity, the amount of natural radionuclides extracted from the Earth's interior with oil, coal, gas, mineral fertilisers, and construction materials has increased in the environment. In some countries, including Ukraine, contamination with radionuclides of natural and artificial origin caused by technical activities and accumulation of waste from their extraction, production, and use account for the main share (17.9%) of the uncontrollable component of the total dose to the population (Yakymchuk, 2019).

Around the world, about 250 thousand tons of used nuclear fuel and 68 million m³ of radioactive waste are stored in storage facilities, of which 45 thousand m³ are stored in European countries. For comparison, 80 radioactive waste storage facilities are located at nuclear fuel cycle facilities in the United States, while Russia has 416 radioactive waste facilities and Kyrgyzstan has 60 such storage facilities (Mousseau, 2021; National report of the Kyrgyz Republic, 2021). The total amount of solid and liquid radioactive waste in Ukraine is 2.96 million m³ and 42.3 thousand m³, respectively. The main facilities for their disposal are the Chornobyl exclusion zone, nuclear power plants, and radioactive waste storage facilities of the Ukrainian State Association Radon (Fig. 1). According to average estimates, the volume of solid radioactive waste stored at ChNPP is 246 thousand m³ and the volume of liquid radioactive waste is 3 thousand m³ (Pasyuk, 2017).

The uranium mining industry in Ukraine has created more than ten uranium tailing ponds, the largest of which, with a volume of more than 60 million tons of radioactive waste, are localised in the Dnipro region (Rozhko *et al.*, 2014). The spread of tailing pond materials caused by erosion processes and contamination of soil, atmosphere, surface, and groundwater with natural radionuclides leads to an increase in exposure of the Ukrainian population to natural radionuclides, which is 75 times higher than the total exposure from all man-made sources, including the Chornobyl accident, and almost twice the global average. As a result of the activities of uranium mining enterprises in Ukraine, zones with an elevated radiation background have been formed, which are not inferior to the ChNPP near-exclusion zone in terms of mutagenic activity (Yakymchuk, 2019). It has been established that almost half of the residents of Ukraine have accumulated lifetime doses of about 350–400 mSv (Sevalnev *et al.*, 2009), which is more than twice the world aver-

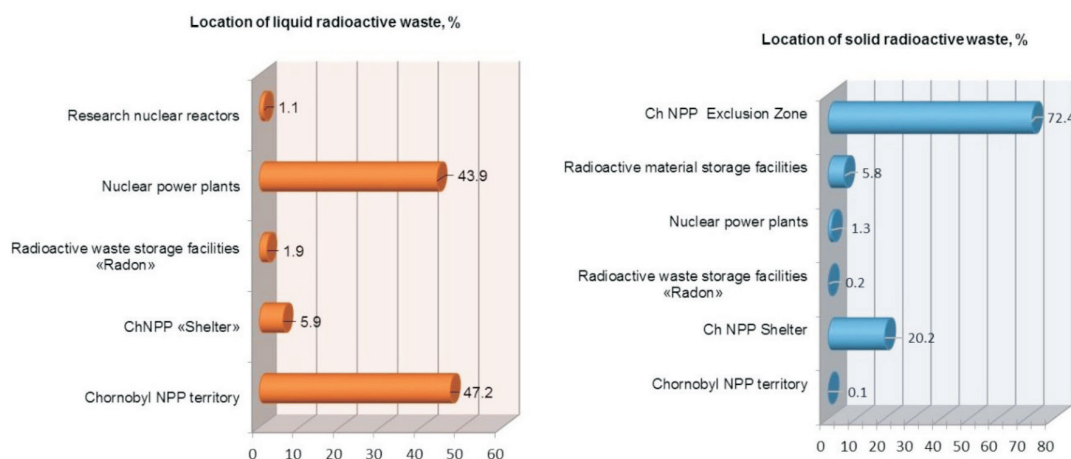


Fig. 1. Share of nuclear waste stored at different facilities in Ukraine (based on Pasyuk, 2017).

age of 170 mSv. This is reflected in genetically determined developmental defects, an increase in mortality over births, and the progressive development of diseases, among which oncological pathologies, haematopoiesis, and reproductive disorders are of particular concern (Chaturvedi and Jain, 2019).

RADIONUCLIDE CONTAMINATION CAUSED BY NUCLEAR WEAPONS TESTING AND NUCLEAR ACCIDENTS

The Semipalatinsk nuclear test sites and Novaya Zemlya Island in the former Soviet Union, Nevada in the United States, the Marshall Islands in the Pacific Ocean, the Maralinga region in Australia, Lobnor Lake in China, the islands of Indonesia, Algeria, Kerguelen Island, and others became radioecological disaster zones (Pravalie, 2014; Lawrence *et al.*, 2024). As a result of all nuclear test explosions, the content of radionuclides in nature has increased significantly. For example, before the explosions Th-232 and C-14 levels were about $4 \cdot 10^{12}$ Bq and $1 \cdot 10^{15}$ Bq, respectively, and after – $2.4 \cdot 10^{20}$ Bq and $2.2 \cdot 10^{17}$ Bq. The amount of Sr-90 in the Earth's crust under natural conditions was estimated at $5 \cdot 10^{16}$ Bq, after nuclear weapons tests; it was released into the atmosphere at $6 \cdot 10^{17}$ Bq, Cs-137 – $9.6 \cdot 10^{17}$ Bq. Due to the very long half-life of Pu-239 (24065 years), the main actinide pollutant, during the life of the current and many future generations, the amount of «bomb» Pu-239 in the biosphere will hardly change, and the total specific activity of this radionuclide will increase due to later input from other sources (Orlov and Nadtochiy, 2005).

To a large extent, the increase in radiation background is caused by the consequences of nuclear accidents, of which there have been more than 440 worldwide (Hasegawa *et al.*, 2015). According to the IAEA, 450 nuclear power units are in operation in 26 countries (Faudon, 2022). Since the 1970s, incidents have occurred at nuclear submarines, their maintenance bases, nuclear industry, and nuclear power plants. For example, on September 29, 1957, an accident occurred at the Mayak Production Association, which re-

sulted in the release of 20 MCi of radioactive substances and exposure of 270 thousand residents of the Chelyabinsk, Sverdlovsk, and Tyumen regions (Russia). A radioactive trace, later called the Eastern Ural, was formed on the ground, with an area of 23 thousand km² (Tang and Loganovsky, 2018). In the same year, a nuclear accident occurred at a reactor of one of the nuclear fuel reprocessing plants in Windscale (England). This accident was subsequently classified as category five on the IAEA INES radiation accident scale. I-137 – $8.1 \cdot 10^{14}$ Bq, Cs-137 – $2.2 \cdot 10^{13}$ Bq, Sr-89 – $3.0 \cdot 10^{12}$ Bq, Sr-90 – $3.3 \cdot 10^{11}$ Bq, as well as some H-3 and Po-210 were released into the environment (McGeoghegan *et al.*, 2010). Around the same time, radioecological studies were started at nuclear centers in the United States and Western Europe (Hanford Centre, Oak Ridge National Laboratory, Savannah River Centre, Brookhaven National Laboratory in the United States, Cadarache Nuclear Centre in France). The territories adjacent to these nuclear centres were also contaminated with radioactive waste (Gerber, 2007). In 1961, a disaster occurred at the Los Alamos National Laboratory (USA), which resulted in more than 15 thousand people being exposed to internal plutonium and external general exposure. In December 1971, the accident at the Saxton NPP, which resulted in the release of radioactive gases into the environment, amounted to 72.89-1010 Bq. On 28 March 1979, an accident occurred at the Three Mile Island NPP (Pennsylvania, USA). About $9.25 \cdot 10^{10}$ MBq of radioactive gases and $55.5 \cdot 10^{10}$ Bq of radioactive iodine were released (Yakymchuk, 2019). In 1969 and 1980, accidents occurred at the Saint-Laurent-des-Eaux NPP in the Loire River Valley, which, in terms of molten uranium emissions, were the largest in the history of nuclear power in France and the world in general (Dechy, 2020). In September 1987, another large-scale radiation incident occurred in the city of Goiânia (Brazil), which resulted in the exposure of numerous people to a wide range of doses. The dismantling of the radiotherapy facility resulted in the release of Cs-137 with activity of 50.9 GBq (IAEA, 1988).

On 26 April 1986, the largest nuclear disaster the world has ever seen occurred — the Chornobyl accident. The total

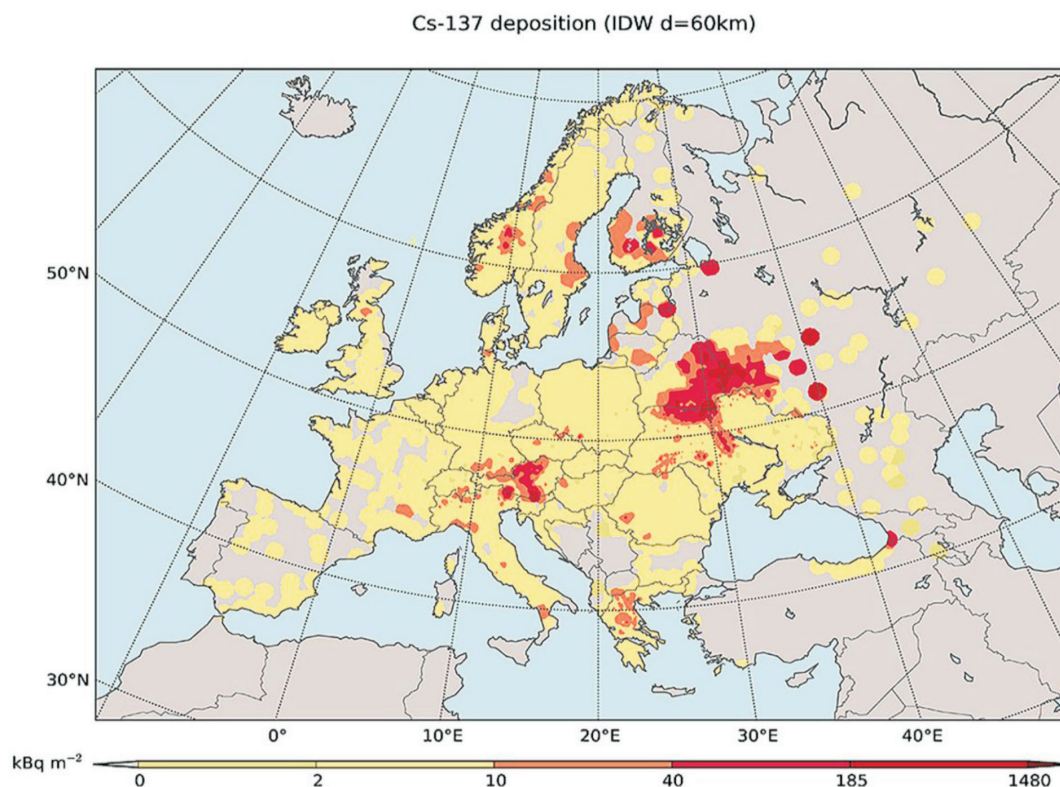


Fig. 2. Cs-137 contamination as a result of the Chernobyl accident. Resolution of 0.1° for the territory of Europe and 0.01° for the ChNPP exclusion zone (25E-40E and 47N-55N) (based on Evangelidou *et al.*, 2016).

amount of radioactive materials released was 200 times higher than the radioactivity caused by the simultaneous explosions in Hiroshima and Nagasaki (Reste *et al.*, 2016). The Chernobyl accident became a national disaster for many millions of people living in large areas of Ukraine (Tang and Loganovsky, 2018) and to some extent caused contamination of the regions of Sukhumi (Georgia), the Baltic States, Austria, Bulgaria, Hungary, Italy, Norway, Poland, Romania, England, Turkey, Greece, Germany, Finland, Sweden, Montenegro, Serbia, Croatia, Slovenia, and Macedonia. The Chernobyl disaster contaminated an area of about 150,000 km², home to 5 million people; in Northern and Eastern Europe, this area reached 45,000 km² (Evangelidou *et al.*, 2016) (Fig. 2). In Ukraine, the Chernobyl disaster resulted in the formation of a huge, potentially hazardous area of 67 thousand km², where about 2.5 million people live. Radioactive contamination has been registered in 11 regions and 74 administrative districts. To a greater or lesser extent, 37 thousand km² of land — fields, hayfields, pastures, forests — are contaminated with radionuclides; 580 km² have been withdrawn from agricultural use. The operation of hundreds of industrial and agricultural facilities has been suspended, and according to various sources, 1614–2161 settlements are in the danger zone (Yakymchuk, 2019). Experts estimate that Cs-137 and Sr-90 contamination will pose a danger for several hundred years, and Pu-239 and Am-241 for many millennia (Morgun and Yakymchuk, 2010). Am-241 poses a particular threat, the amount of which will increase 40 times by 2059 due to the relatively rapid decay of Pu-239 (half-life of 24 thousand

years). Sr-90, being an analogue of calcium; Cs-137, being an analogue of potassium, as well as radioactive phosphorus and tritium, can form complexes with chromatin. Their decay is accompanied by radiation, which leads to the breaking of chemical bonds in the DNA molecule (Gray, 2012). On March 11, 2011, as a result of a strong earthquake that triggered a tsunami, an accident occurred at the Japanese Fukushima Daiichi NPP, which caused the release of I-131 and Cs-137 into the environment, including ocean waters, with specific activity thousands of times higher than permissible standards (Kumamoto *et al.*, 2017). Nuclear accidents and nuclear weapons testing have led to an increase in the level of effective radiation doses and a global increase in the background ionising radiation. Despite the time that has passed since the nuclear accidents and the reduction of dose burdens, mutational variability in organisms of different taxonomic groups caused by radionuclide contamination continues to be high and has led to an increase in the level of genetic burden in natural ecosystems (Fuller *et al.*, 2019; Yakymchuk, 2019; Cannon and Kiang, 2022).

CHEMICAL ANTHROPOGENIC MUTAGENIC ENVIRONMENTAL FACTORS

The contribution of chemical mutagenic factors to the mutation rate in most areas of the planet exceeds the impact of the radiation background. The main categories of chemical mutagens in the environment are three groups of substances: 1) natural inorganic substances (nitrous oxides, nitrates, nitrites, heavy metals, radioactive minerals, etc.);

2) natural substances of organic origin (alkaloids, hormones, etc.); 3) processed natural substances (oil products; coal and wood combustion products; heavy metal (HM) compounds, food waste, etc.); 4) chemical products that do not occur in nature (xenobiotics): pesticides, food additives, industrial waste, synthetic compounds, including medicines, and alkylating agents (Venken and Bellen, 2014; Roychoudhury *et al.*, 2022). The Chemical Abstracts Service database accommodates over 160 million organic and inorganic compounds. Over 350,000 of them are used in many fields, such as medicine, cosmetics, agriculture, homes, and more. It is known that many of these substances are toxic in low concentrations; sometimes their effects are enhanced in combination with other pollutants or as decay products after entering the biosphere and geosphere (Naidu *et al.*, 2021). About 15 thousand new substances are added to the database every day, and there is no certainty that they have been screened for mutagenicity, as the results of studies on the biological activity of many development companies are not available (Ghani, 2020). Given the current rate of progress, it will take more than 100,000 years to assess the safety for humans and the environment of all existing synthetic chemical compounds and another 2000 years to assess the new substances synthesised annually (Cribb, 2017). Over the past decades, as a result of industrial global production, the annual volume of synthetic chemicals has doubled, exceeding 2.3 billion tons, which is 300 kg per capita. It is projected that by 2030, the use of chemicals will increase by 70%, with China and the European Union remaining as the largest consumers (Naidu *et al.*, 2021) (Table 1).

Global chemical emissions are estimated at 220 billion tons per year, which are largely cumulative (Naidu *et al.*, 2021). Chemical toxic substances alter human reproductive function, which is caused by gene mutations, DNA methylation, chromatin fragmentation, mitochondrial damage, and cell apoptosis (Messerlian *et al.*, 2017; Xue and Zhang, 2018; Selvaraju *et al.*, 2021). Penetrating into the body's cells, they can cause gene, chromosomal, and genomic mutations and, along with other mutagenic factors, significantly increase the pool of spontaneous mutations. The entire world experience of studying the carcinogenic hazards of various substances and industrial factors has been summarised in monographs of the International Agency for Research on Cancer under the WHO, which provide conclusions on 900 chemical agents, complex mixtures, and production processes. According to the ranking conducted by this organisation, 107 of these substances are classified as compounds with unequivocal evidence of involvement in human tumours (IARC, 2019). Industrial chemicals, including carcinogens and their residues, are known to be found in the blood and tissues of all populations, including infants (Soleman *et al.*, 2020; Mathiesen *et al.*, 2021), and are also found in breast milk (Hu *et al.*, 2021). The annual number of chemical-related deaths is significantly higher than during the Second World War and is now the largest form of preventable death (Naidu *et al.*, 2021). According to the WHO, in 2016, man-made air pollution caused 4.2 million premature deaths, of which about 90% occurred in the Third World (Munsif *et al.*, 2021).

Table 1. Volumes of chemical pollutants released into the environment (according to Cribb, 2021)

Aggregates of pollutants	Emissions, million tons/m ³
Total amount of waste recycled	10000–11000
household waste	2000
e-waste	50
hazardous waste	400
food waste	730
Synthesised chemicals	2500
pesticides	5
fertilisers	250
plastic	400
Food production	5000
Forestry industry	5800
Total production volume	17000
gas	4000
oil	4500
coal	7500
metals	5000
cement	4100
steel	1800
uranium oxide	0,063
Waste from the mining industry	36000–84000
Carbon	37000
Soil eroded as a result of agriculture	36000–75000
Total chemical emissions from human activities	120000–220000

GENETIC HAZARDS OF ACCIDENTAL EMISSIONS AND WASTE FROM CHEMICAL PLANTS

Often, the reason for contact with humans and the biosphere as a whole with chemical mutagenic factors can be accidents at chemical plants, the number of which has exceeded 8 thousand in the world over the past two centuries (Palaszewska-Tkacz *et al.*, 2017). For example, in the Italian city of Seveso, an explosion at a chemical plant in 1976 released 2 tons of toxic substances, including 2.5 kg of dioxin, which causes severe diseases in humans and animals. Medical experts predict that the consequences of the Seveso tragedy may manifest themselves for a long time in the form of birth defects in children (Robbe, 2016). In 1990, in Ufa (Russia), stormwater washed industrial waste containing phenols into the river. When this industrial waste reached chlorinated water, it created conditions for the formation of dioxins (Dmytrenko, 2005). The cyanide spill of 2000 in northwestern Romania, occurring in the upper reaches of the Tisza River, was described by environmentalists as the most devastating ecological disaster since Chernobyl. Cyanide levels exceeding the permissible maximum by 20 times destroyed all flora and fauna. The presence of HM in the river further complicated the situation (Gyori *et al.*, 2022). The 1990 underground crack in the Alexander-Zapad mine in Horlivka (Ukraine) led to leakage of production waste from a chemical plant and unknown chemical reactions forming toxic substances that caused deaths of miners (Dubrova, 2014). During the same period, waste from the same chemical plant from a surface storage facility entered the workings of the Vuhlehirska mine in Yenakiyev, which led to the poisoning of several dozen miners (Yakymchuk, 2019).

No lesser, but slower, damage is caused by industrial waste that is uncontrollably released into the environment. Their total weight in the world's industrial and domestic production is approximately 600 gigatons per year (Morgun and Yakymchuk, 2010). Environmental chemical pollution has been implicated in reproductive disorders, cognitive impairment, increased levels of somatic and generative mutations, premature deaths, and the decline or extinction of many plant and animal populations (Underwood, 2017; Landrigan *et al.*, 2018; Seibold *et al.*, 2019). The population declines of the bald eagle (*Haliaeetus leucocephalus*), brown pelican (*Pelecanus occidentalis*), and peregrine falcon (*Falco peregrinus*) in North America are well-known examples of the consequences of xenobiotics in the environment (Bickham *et al.*, 2000). The global loss of honey bee (*Apis mellifera*) communities due to the use of neonicotinoid pesticides has caused an international crop pollination crisis (Goulson, 2013). There are reports that xenobiotic pollutants have caused the loss of more than 40% of the total taxonomic pool of river invertebrates in some regions of Germany, France, and Australia (Beketov *et al.*, 2013). The loss of up to 78% of insect species in 290 cities in Germany has been reported (Seibold *et al.* 2019).

A notable example of severe biological consequences is the 1956 Minamata tragedy in Japan, which caused industrial methylmercury contamination of coastal waters, resulting in widespread neurological damage among the local human population, congenital abnormalities in newborns, and profound ecological degradation (Ekino *et al.*, 2007). The discharge of wastewater containing hazardous chemicals and HMs into natural water bodies in West Bengal (India) caused the emergence of mitotic cycle abnormalities, a wide range of chromosomal aberrations, and point mutations in the fish *Channa punctatus* (Rakshit and Gangopadhyay, 2015). Toxic compounds in the wastewater of a pharmaceutical company in Ogun State, Nigeria, caused a decrease in mitotic activity in rat blood cells and increased the frequency of chromosome rearrangements (Bakare *et al.*, 2011). The high content of pollutants in the air of Brindisi (Italy) was associated with increase in the number of cases of congenital heart disease in newborns (Vecoli *et al.*, 2016). Epidemiological studies in the Toms River region (USA) (Maslia *et al.*, 2005) have shown a link between the consumption of contaminated drinking water by pregnant women and the subsequent risk of cancer in their children. Increased mortality from respiratory cancer was found in people living in areas of intense vehicle exhaust emissions (Brewer, 2023). An increased risk of mutations, malignancies, and morphoses has been observed in wildlife species near aluminum, steel, and superphosphate plants (Fedorenko *et al.*, 2012; Ali *et al.*, 2019). Industrial and transport emissions within the city limits of the south-central part of Guangdong Province (China) have caused the accumulation of moderate to high concentrations of polycyclic aromatic hydrocarbons in the soil, which have mutagenic, carcinogenic, and teratogenic properties. In places where these contaminants accumulate, the risk of overall cancer incidence increases, including among children (Ren *et al.*,

2021). Other authors have also warned in their studies about an increase in the frequency of chromosome aberrations in individuals exposed to harmful substances (Bazyka *et al.*, 2012; Demirhan *et al.*, 2019; Arbo *et al.*, 2022).

MANMADE SOURCES OF HM AND THEIR GENOTOXIC EFFECTS

HMs are considered one of the most dangerous genotoxic environmental pollutants. In terms of their toxicity, they are second only to radionuclides and pesticides (Kumar and Tripathi, 2008). The presence of polluting particles of As, Pb, Cd, Hg in the air of large cities has been documented since the times of Ancient Rome and Athens, whose inhabitants suffered from contaminated water, air, and food sources (Patterson *et al.* 1987). Over the past 100 years, 1.55 Mt of silicon, 1.5 Mt of arsenic, more than 1 Mt each of Ni and Co, and 0.6 Mt each of Zn and Sb have been released into the atmosphere. As a result of global industrial activity, annual emissions of HMs (As, Cd, Cr, Cu, Ni, Pb, Zn) are estimated at 69591 tons. Metallurgy and energy companies annually add 32% of all pollution. They cause an increase in the risk of cancer, which, according to various estimates, is 14.6–50.8% (McDuffie *et al.*, 2021). This fact is confirmed by epidemiological studies that show that one of the reasons for the increased incidence of lung cancer in urban populations compared to rural ones is more intense urban air pollution (Lee *et al.*, 2022).

In terms of environmental contamination, the ability to accumulate in food, and toxicity, the most dangerous heavy metals are Hg, Pb, Cd, As, V, Zn, Cu, Co, Mo, and Ni (Pal and Rai, 2010). Industrial HM emissions are associated with primary and secondary smelting of Cu, Al, Zn, Pb, iron ore sintering, steel production in electric arc furnaces, iron smelting, incineration of municipal solid and hazardous waste, emissions from cement kilns, coke plants, and coal-fired thermal power plants. Their maximum concentrations are recorded in areas with developed energy, metallurgical, chemical, and coke industries (Yang *et al.*, 2024). Wastewater contaminated with HM is highly toxic, with sources including metalworking, electrolysis processes, battery production, paper and pulp mills, mining, textile, and dyeing industries (Qasem *et al.*, 2021). Manmade accidents have repeatedly caused large-scale HM contamination of natural ecosystems: the 2015 environmental disaster in Brazil, which was associated with a breach of the Fundao mining company's tailings dam and the uncontrolled discharge of a huge plume (60 million m³) of waste into the Rio Docey (Frachini *et al.*, 2021), the discharge of Cu-contaminated wastewater into the Yangtze River basin (China) in 2011 and 2016 (Liu *et al.*, 2024), and the terrorist attack by Russian troops in 2023 on the critical energy facility of the Kakhovka HPP (Ukraine), which caused the spread of 83 thousand tons of toxic elements accumulated in the reservoir sediment through turbulent water flows (Shumilova *et al.*, 2025).

Exhibiting mutagenic and carcinogenic properties, HMs negatively impact numerous molecular-genetic, biochemi-

cal, and physiological processes in plants, leading directly or indirectly to the inhibition or cessation of growth and development, and in some cases, to death (Asati *et al.*, 2016). Some of them can also interact directly with DNA (Vergolyas and Goncharuk, 2016). The reason for this is the ability of HMs to actively bind to the functional sites of enzymes, change the conformation of protein molecules, nucleic acids, disrupt the integrity of cell membranes, and break down vital metabolites (Aslam *et al.*, 2014).

According to the WHO, acute metal poisoning is extremely rare nowadays, so the problem of mutagenic effects on the body of relatively low doses of their compounds and the long-term consequences of such effects is becoming particularly relevant (Yakymchuk, 2019). Given that mutagenicity is detected at much lower concentrations than toxicity, and that the population genetic consequences pose great danger, monitoring of the genotoxicity of metals accumulating in areas of environmental tension is necessary. Most such studies are related to the determination of mutagenic factors of contaminated areas and the identification of correlations between the concentrations of individual HM compounds and mutagenic effects (Ahmad *et al.*, 2011; Kumar and Pandey, 2015), but do not provide suggestions for the establishment of genetic consequences caused by their complex impact.

GENETIC CONSEQUENCES OF PESTICIDE-XENOBIOTIC CONTAMINATION

The world produces numerous xenobiotics that pose threat to the environment. The most dangerous among them are pesticides. Every year, about 1 million people suffer from contact with pesticides, and the mortality rate is 0.9–1.4%. In addition, constant contact with low concentrations of pesticides causes many diseases, including tumours and nervous system disorders (Hassaan and Nemr, 2020). The use of pesticides is also anticipated to increase, as agricultural production is projected to increase by 80% by 2050 (Khushboo *et al.*, 2024). Due to the lack of comprehensive geographical quantification of pesticide use and residues in different habitats, the global impacts of their distribution in the environment are usually unknown. The world's agricultural land is 75% at risk of contamination by active ingredients of several pesticide at concentrations exceeding maximum permissible levels, and 31% is at high risk of contamination, exceeding such levels by three orders of magnitude or more. Traces of synthetic pesticides are systematically found in 6% of organic food samples in Europe, and in Southern Germany and Switzerland, this figure reaches 28% and 9%, respectively (Schleiffer and Speiser, 2022). A high risk of pesticide contamination has been identified in Africa, China, India, Australia, and Argentina, along with sharp decline of biodiversity and chronic water shortages. According to regional analysis, 62% of European agricultural land is at high risk of pesticide contamination. This area largely covers the countries of Eastern and Southern Europe, among which the territories of the countries with the largest agricultural production have particular high risk: Ukraine

and Spain. The largest land area of all regions with a high risk of pesticide contamination (4.9 million km²) is in Asia, of which 2.9 million km² is located in China and 0.35 million km² in Kazakhstan (Tang F.H.M. *et al.*, 2021).

Every year, about 2 million tons of pesticides are produced worldwide. Organochlorine pesticides pose a particular danger, as they are stable chemicals that do not decompose in the environment for a long time and have the ability to accumulate in the fatty tissue of organisms. Organochlorines have super cumulative activity, they can change the immunological status of living organisms, and exhibit mutagenic and teratogenic properties (Hassaan and Nemr, 2020). Pesticide exposure leads to the generation of free radicals that disrupts DNA and, as a result, causes the development of serious diseases, including cancer and immunodeficiency syndrome, premature aging, and congenital pathologies.

The additional accumulation of certain groups of organochlorine xenobiotic isomers as by-products of the production of polychlorinated organic compounds continued even after the Stockholm Convention banned their use in 2001 (Mrema *et al.*, 2013). This is the reason for the intense pollution of soil, water, and air in the Kalush industrial district (Ukraine) with highly toxic compounds from the largest toxic waste landfill in Europe, Oriana Halev, and the Dombrovsky potash ore quarry, which, according to official data, contains 11087.6 tons of hexachlorocyclohexane alone (Morgun and Yakymchuk, 2018). Genotoxic xenobiotics that are common in the area have caused higher rates of genetic disorders, birth defects, tumours, and diseases of major organ systems in people who have been exposed to them for a long time. According to international UN experts, the reclamation of the landfill and the export of toxic waste for further disposal outside the country caused additional pollution of the region with highly toxic chemical compounds, which raised concerns of the international community about the possibility of a transboundary environmental and technological emergency.

The literature describes the consequences of pesticide contamination of organisms' habitats: loss of a large number and wide diversity of taxa, disturbance of the proportionality of individuals of different ages in populations, changes in trophodynamics, endocrine disorders, reduced fertility, organ abnormalities, immunosuppression, increased mortality, and phytotoxicity (Lal, 2007; Barber *et al.*, 2019; Bradley *et al.*, 2019; Covert *et al.*, 2020; Schmidt *et al.*, 2022; Oliver *et al.*, 2023). Many studies on various plants, animals, and humans have proven the cytotoxic, genotoxic, and mutagenic effects of pesticides (Ozakca and Silah, 2013; Martinez-Valenzuela *et al.*, 2017; Popova *et al.*, 2021). Some of these chemicals act as promutagens, which activate through metabolism after entering a living organism. Consumption of such substances with plant foods can cause cancer and pose a real danger to the human genome. There is evidence of the risk of congenital anomalies in children whose parents were exposed to pesticides. Their negative effects affect the reproductive system, individual development, and mental abilities (Kaur and Kaur, 2018). The pres-

ence of these pollutants in the environment in the form of chemical mixtures can lead to complex synergistic and additive effects (Schmidt *et al.*, 2022; Loken *et al.*, 2023), and their increased concentrations in areas contaminated by radionuclide as a result of the Chornobyl accident can increase the level of stochastic radiation effects (Yakymchuk, 2019).

Storage facilities where banned and unusable pesticides are stored pose a danger to the environment. According to experts, they facilities contain about 500 thousand tons of outdated pesticides. The largest stockpiles are concentrated in developing countries and in Central and Eastern Europe (Mrema *et al.*, 2013). Partially or completely destroyed storage facilities in the Republic of Kazakhstan contain 6931.4 thousand tons of unusable pesticides that penetrate the soil and contaminate surface and groundwater sources. These pesticides pollute surfaces and groundwater sources when they enter soil. A positive correlation has been found between the level of somatic health of the country's population, the frequency of chromosomal aberrations, and the content of pesticides in food (Djanganlina *et al.*, 2020). In Ukraine, the largest country in Europe by area, there are more than 4000 such facilities, where 19.4 thousand tons of pesticides are stored (Yakymchuk, 2016). Soil contamination with xenobiotics within the territories of such storage facilities has a negative mutagenic effect, as evidenced by a 2–4.4-fold increase in the frequency of chromosomal aberrations and a 3.4–5.6-fold increase in visible mutations in *T. aestivum*. The high level of mutations found in winter wheat during seed germination in soil taken from the sanitary zone of the storage facility indicates the uncontrolled spread of pesticides beyond their local storage (Yakymchuk, 2019).

SUMMARY AND OUTLOOK

Throughout its evolution, the organic world has been in constant contact with environmental mutagens, such as natural radiation background and chemical compounds of abiotic and biotic origin, which are involved in inducing spontaneous mutation levels. As a result of anthropogenic impact, the number and diversity of natural and man-made mutagenic factors entering the environment have increased significantly. The development of civilisation is characterised by an unfavourable trend of growth of anthropogenic hazards: natural, manmade, and environmental disasters accompanied by prolonged releases of long-lived radionuclides and xenobiotics into the environment, their inclusion in biological migration chains, and, as a result, the formation of additional sources of mutagenic impact on all living things to the natural background. Development of mineral resources, extraction of radioactive ores, use of radioisotopes in the energy sector and the nuclear arms race, accumulation of nuclear waste, uncontrolled growth of radionuclide disposal, and unpredictable migration of radionuclides in the environment have led to an increase in the number and expansion of radionuclide-contaminated areas. The mutational variability of organisms living in these areas continues to be high and has led to an increase in the level of ge-

netic burden in natural ecosystems. The helplessness of mankind in resolving the issue of rapid remediation of radionuclide-contaminated territories by introducing measures for their artificial decontamination indicates the need to develop an international strategy for strict control over the construction of nuclear energy facilities, compliance with norms, rules, and standards for their radioactive waste management, and strict implementation of the Comprehensive Nuclear Test-Ban Treaty.

Environmental pollution with chemical genotoxic agents is associated with improper management of hazardous waste from enterprises, accidents at chemical industry facilities, intensive use of xenobiotics in agricultural production, vehicle emissions, etc. The contribution of chemical mutagenic factors to the mutation rate in most parts of the world exceeds the impact of the radiation background. The high rate of synthesis of new chemical compounds makes it impossible to conduct timely screening for mutagenicity. Many of these substances are toxic in low concentrations; sometimes their effect is enhanced in combination with other pollutants or as decay products after entering living biological systems. Some xenobiotics, such as organochlorine compounds, retain their mutagenic properties for a long time, have super cumulative activity, and pose a danger to organisms even when the environment is polluted in low concentrations. Penetrating into the cells of the body, they can cause gene, chromosomal, and genomic mutations, significantly increasing the pool of spontaneous mutations, thereby affecting the rate of the mutation process and the level of genetic burden of populations.

Identification of sources of physical and chemical mutagens in the environment and delineation of contaminated areas will minimise their impact on the heredity of organisms, and prediction of real genetic risks induced by them will help prevent the negative consequences of an increased level of mutagenic background. Literature data and our own long-term research show that the planet is increasingly polluted by physical and chemical mutagenic factors that are harmful to all living things. Further environmental screening and genetic monitoring of the respective territories should become a mandatory component of the preservation of natural ecosystems and scientifically sound placement of recreational areas, cultivated plants, construction of residential, industrial, and livestock facilities to protect public health, flora, and fauna.

ACKNOWLEDGEMENT

The author would like to thank all the researchers whose articles on radiation and chemical pollution were used in this study. Without their work, this review would not have been possible.

REFERENCES

Abdel-Razek, Y.A., Abu-Diab, A.A., Bakhit, A.F. (2013). Correlation between the concentrations of the heavy minerals and the terrestrial radioactivity at El Massaid and El Kharrouba, Sinai, Egypt. *XI Radiation Physics*

- & Protection Conference, 25–28 November 2012. *Book of Proceedings*. Nasr City, Cairo, pp. 393–404.
- Ahmad, M.A., Wahid, S.S., Ahmad, Z.A., Butt, Z.A., Tariq M. (2011). Ecophysiological responses of (*Oryza sativa* L.) to hexavalent chromium. *Pakistan J. Bot.*, **43** (6), 2853–2859.
- Ali, H., Khan, E., Ilahi, I. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. *J. Chem.*, **2019**, 1–14. <https://doi.org/10.1155/2019/6730305>.
- Arbo, M. D., Garcia, S. C., Sarpa, M., Da Silva Junior, F. M. R., Nascimento, S. N., Garcia, A. L. H., Da Silva, J. (2022). Brazilian workers occupationally exposed to different toxic agents: A systematic review on DNA damage. *Mutation Res.*, **879–880**, 503–519. <https://doi.org/10.1016/j.mrgentox.2022.503519>.
- Asati, A., Pichhoda, M., Nikhi, K. (2016). Effect of heavy metals on plants: An overview. *Int. J. Appl. Innov. Eng. Manag.*, **5** (3), 56–66. <https://doi.org/10.13140/RG.2.2.27583.87204>.
- Aslam, R., Ansari, M. Y. K., Choudhary, S., Bhat, T. M., Jahan, N. (2014). Genotoxic effects of heavy metal cadmium on growth, biochemical, cyto-physiological parameters and detection of DNA polymorphism by RAPD in *Capsicum annum* L.: An important spice crop of India. *Saudi J. Biol. Sci.*, **21** (5), 465–472. <https://doi.org/10.1016/j.sjbs.2014.07.005>.
- Bakare, A. A., Ademeso, M. M., Adetunji, O. A., Alabi, O. A. (2011). Pharmaceutical effluent induced chromosome aberration in rat bone marrow cells. *Arch. Appl. Sci. Res.*, **3** (2), 345–352.
- Barber, L. B., Rapp, J. L., Kandel, C., Keefe, S. H., Rice, J., Westerhoff, P., Bertolatus, D. W., Vajda, A. M. (2019). Integrated assessment of wastewater reuse, exposure risk, and fish endocrine disruption in the Shenandoah river waters. *Environ. Sci. Technol.*, **53** (7), 3429–3440. <https://doi.org/10.1021/acs.est.8b05655>.
- Bartoszek, A., Holota, S. (2023). Mutagenic and carcinogenic compounds in food. Staroszczyk, H., Sikorski, Z. E. (eds). *Chemical and Functional Properties of Food Components*. CRC Press, Boca Raton, pp. 469–496. <https://doi.org/10.1201/9781003265955-18>.
- Bazyka, D. A., Prysiazniuk, A. E., Romanenko, A. Iu. (2012). [Frequency of malignant neoplasms in residents of Ukrainian cities with radiation-hazardous production]. *Environ. Health*, **2**, 17–22 (in Ukrainian).
- Beketov, M. A., Kefford, B. J., Schäfer, R. B., Liess, M. (2013). Pesticides reduce regional biodiversity of stream invertebrates. *Proc. Natl. Acad. Sci.*, **110**, 11039–11043. <https://doi.org/10.1073/pnas.1305618110>.
- Bickham, J. W., Sandhu, S., Hebert, P. D. N., Chikhi, L. (2000). Effects of chemical contaminants on genetic diversity in natural populations: Implications for biomonitoring and ecotoxicology. *Mutation Res.*, **463** (1), 33–51. [https://doi.org/10.1016/S1383-5742\(00\)00004-1](https://doi.org/10.1016/S1383-5742(00)00004-1).
- Brewer, G. (2023). Air pollution promotes tumorigenesis through pre-existing oncogenic mutations. *Nature Reviews Cancer*, **23**: 350. <https://doi.org/10.1038/s41568-023-00585-3>.
- Bradley, P. M., Journey, C. A., Berninger, J. P., Button, D. T., Clark, J. M., Corsi, S. R., DeCicco, L. A., Hopkins, K. G., Huffman, B. J., Nakagaki, N., et al. (2019). Mixed-chemical exposure and predicted effects potential in wadeable southeastern USA streams. *Sci. Total Environ.*, **655**, 70–83. <https://doi.org/10.1016/j.scitotenv.2018.11.186>.
- Calabrese, E., Selby, P. B. (2024). First report of X-ray induced somatic mutation by Muller's department chair fails to support Muller's linearity hypothesis. *Arch. Toxicol.*, **98**, 2731–2737. <https://doi.org/10.1007/s00204-024-03808-0>.
- Cannon, G., Kiang, J. G. (2022). A review of the impact on the ecosystem after ionizing irradiation: Wildlife population. *Int. J. Radiat. Biol.*, **98** (6), 1054–1062. <https://doi.org/10.1080/09553002.2020.1793021>.
- Chaturvedi, A., Jain, V. (2019). Effect of ionizing radiation on human health. *Int. J. Plant Environ.*, **5** (3), 200–205. <https://doi.org/10.18811/ijpen.v5i03.8>.
- Covert, S. A., Shoda, M. E., Stackpoole, S. M., Stone, W. W. (2020). Pesticide mixtures show potential toxicity to aquatic life in U.S. streams, water years 2013–2017. *Sci. Total Environ.*, **745**, 141285. <https://doi.org/10.1016/j.scitotenv.2020.141285>.
- Cribb, J. (ed.). (2017). *Surviving the 21st Century: Humanity's Ten Great Challenges and How We Can Overcome Them*. Springer International, Switzerland. 265 šp. <https://doi.org/10.1007/978-3-319-41270-2>.
- Cribb, J. (ed.) (2021). *Earth Detox: How and Why We Must Clean up Our Planet*. Cambridge University Press, Cambridge. 317 pp. <https://doi.org/10.1080/17524032.2025.2461621>.
- Dahlman, O., Mackby, J., Mykkeltveit, S., Haak, H., 2011. Monitoring underground nuclear explosions. Dahlman, O., Mackby, J., Mykkeltveit, S., Haak, H. (eds). *Detect and deter: can countries verify the nuclear test ban?* Dordrecht: Springer, 2011, pp. 29–87. https://doi.org/10.1007/978-94-007-1676-6_2.
- Dechy, N. (2020). *The 1969 and 1980 nuclear accidents in Saint-Laurent-des-Eaux: When transition generates forgetting*. HAL (Le Centre Pour La Communication Scientifique Directe), Le Centre pour la Communication Scientifique Directe. [cit. 2025-03-20]. https://www.academia.edu/111798917/The_1969_and_1980_nuclear_accidents_in_Saint-Laurent-des-Eaux_When_transition_generates_forgetting.
- Demirhan, O., Akbaba, M., Çelik, S., Uslu, N., Çetinel, N., Tunc, E., Demirhan, O. F. (2019). Chromosomal aberrations in agricultural farmers exposed to pesticides. *Adv. Toxicol. Toxic Effects*, **3** (1), 015–022. <https://doi.org/10.17352/atte.000005>.
- Djagalina, E., Altynova, N., Bakhtiyarova, S., Kapysheva, U., Zhaksymov, B., Shadenova, E., Baizhanov, M., Sapargali, O., Garshin, A., Seisenbayeva, A., et al. (2020). Comprehensive assessment of unutilized and obsolete pesticides impact on genetic status and health of population of Almaty region. *Ecotoxicol. Environ. Safety*, **202**, 110905. <https://doi.org/10.1016/j.ecoenv.2020.110905>.
- Dmytrenko, I. P. (2005). [Sources of formation and entry of dioxins into the human body]. *Environ. Bull.*, **3**, 10–11 (in Ukrainian).
- Duarte, G. T., Volkova, P. Y., Perez, F. F., Horemans, N. (2023). Chronic ionizing radiation of plants: An evolutionary factor from direct damage to non-target effects. *Plants*, **12** (5), 1178. <https://doi.org/10.3390/plants12051178>.
- Dubrova, N. A. (2014). [Assessment of changes in filtration properties of a deformable massif as a result of repeated undermining]. Kremenchuk Mykhailo Ostrohradskyi Natl. Univ., **1**, 96–106 (in Ukrainian).
- Dudar, T. (2019). Uranium mining and milling facilities legacy sites: Ukraine case study. *Environ. Probl.*, **4** (4), 212–218. <https://doi.org/10.23939/ep2019.04.212>.
- Ekino, S., Susa, M., Ninomiya, T., Imamura, K., Kitamura, T. (2007). Minamata disease revisited: An update on the acute and chronic manifestations of methyl mercury poisoning. *J. Neurol. Sci.*, **262**, 131–144. <https://doi.org/10.1016/j.jns.2007.06.036>.
- Evangelidou, N., Hamburger, T., Talerko, N., Zibitsev, S., Bondar, Y., Stohl, A., Balkanski, Y., Mousseau, T. A., Moller, A. P. (2016). Reconstructing the Chernobyl Nuclear Power Plant (CNPP) accident 30 years after. A unique database of air concentration and deposition measurements over Europe. *Environ. Poll.*, **216**, 408–418. <https://doi.org/10.1016/j.envpol.2016.05.030>.
- Faudon, V. (2022). Power generation from nuclear energy. Hafner, M., Luciani, G. (eds.). *The Palgrave Handbook of International Energy Economics*. Palgrave Macmillan, Cham, pp. 131–144. https://doi.org/10.1007/978-3-030-86884-0_7.
- Fedorenko, Z. P., Haisenko, A. V., Hulak, L. O., Ryzhov, A. Iu., Sumkina, O. V., Kutsenko, L. B. (2012). [Cancer in Ukraine, 2010–2011. Incidence, mortality, and oncology service performance indicators]. *Bulletin of the National Cancer Registry of Ukraine*, **13**. [27.03.2018]. http://www.ncru.inf.ua/publications/BULL_13/index.htm (in Ukrainian).
- Folkers, C., Gunter, L. P. (2022). Radioactive releases from the nuclear power sector and implications for child health. *BMJ Paediatrics Open*, **6**, 1–9. <https://doi.org/10.1136/bmjpo-2021-001326>.
- Frachini, E., Ferreira, C. S. R., Kroetz, B. L., Urbano, A., Abrão, T., Santos, M. J. (2021). Modeling the kinetics of potentially toxic elements

- desorption in sediment affected by a dam breakdown disaster in Doce River – Brazil. *Chemosphere*, **283**, 131157. <https://doi.org/10.1016/j.chemosphere.2021.131157>.
- Fuller, N., Ford, A. T., Lerebours, A., Gudkov, D. I., Nagorskaya, L. L., Smith, J. T. (2019). Chronic radiation exposure at Chernobyl shows no effect on genetic diversity in the freshwater crustacean, *Asellus aquaticus* thirty years on. *Ecol. Evol.*, **18** (9), 10135–10144. <https://doi.org/10.1002/ece3.5478>.
- Gasteiger, J. (2020). Chemistry in times of artificial intelligence. *Chem. Phys. Chem.*, **21**, 2233–2242. <https://doi.org/10.1002/cphc.2020005182233>.
- Gavrilescu, M., Demnerova, K., Aamand, J., Agathos, S., Fava, F. (2015). Emerging pollutants in the environment: Present and future challenges in biomonitoring, ecological risks and bioremediation. *New Biotechnol.*, **32** (1), 147–156. <https://doi.org/10.1016/j.nbt.2014.01.001>.
- Gerber, M. (ed.) (2007). *On the Home Front: The Cold War Legacy of the Hanford Nuclear Site*. Bison Books, Lincoln. 424 pp.
- Geueke, B., Parkinson, L. V., Groh, K. J., Kassotis, C. D., Maffini, M. V., Martin, O. V., Zimmermann, L., Scheringer, M., Muncke, J. (2024). Evidence for widespread human exposure to food contact chemicals. *J. Exposure Sci. Environ. Epidemiol.*, **35**, 330–341. <https://doi.org/10.1038/s41370-024-00718-2>.
- Ghani, S. S. (2020). A comprehensive review of database resources in chemistry. *Ecletica Química J.*, **45** (3), 57–68. <https://doi.org/10.26850/1678-4618eqj.v45.3.2020.p57-68>.
- Ghiassi-nejad, M., Mortazavi, S. M. J., Cameron, J. R., Niroomand-rad, A., Karam, P. A. (2002). Very high background radiation areas of Ramsar, Iran: Preliminary biological studies. *Health Phys.*, **82** (1), 87–93. <https://doi.org/10.1097/00004032-200201000-00011>.
- Ghosal, S., Agrahari, S., Banerjee, D., Sengupta, D. (2021). Assessment of a naturally occurring high background radiation area with elevated levels of thorium along coastal Odisha, India using radiometric methods. *Chemosphere*, **283**, 1312–1321. <https://doi.org/10.1016/j.chemosphere.2021.131221>.
- Goulson, D. (2013). Review: An overview of the environmental risks posed by neonicotinoid insecticides. *J. Appl. Ecol.*, **50**, 977–987. <https://doi.org/10.1111/1365-2664.12111>.
- Hasegawa, A., Tanigawa, K., Ohtsuru, A., Yabe, H., Maeda, M., Shigemura, J., Ohira, T., Tominaga, T., Akashi, M., Hirohashi, N., et al. (2015). Health effects of radiation and other health problems in the aftermath of nuclear accidents, with an emphasis on Fukushima. *The Lancet*, **386** (9992), 479–488. [https://doi.org/10.1016/S0140-6736\(15\)61106-0](https://doi.org/10.1016/S0140-6736(15)61106-0).
- Hassaan, M. A., Nemr, A. E. (2020). Pesticides pollution: Classifications, human health impact, extraction and treatment techniques. *Egyptian J. Aquatic Res.*, **4** (3), 207–220. <https://doi.org/10.1016/j.ejar.2020.08.007>.
- Hu, L., Luo, D., Wang, L., Yu, M., Zhao, S., Wang, Y., Mei, S., Zhang, G. (2021). Levels and profiles of persistent organic pollutants in breast milk in China and their potential health risks to breastfed infants: A review. *Sci. Total Environ.*, **753**, 1420–1428. <https://doi.org/10.1016/j.scitotenv.2020.142028>.
- Huber, K., Krishnan, S., Woloschak, G. E., Joiner, M. C. (2023). *Radiation and Cancer Biology Study Guide*. American Society for Radiation Oncology, Boston. 270 pp.
- IAEA (1988). *The Radiological Accident in Goiania*. International Atomic Energy, Vienna. 132 pp.
- IARC (2019). *Monographs on the Identification of Carcinogenic Hazards to Humans*. IARC. [cit. 2025-04-17]. <https://monographs.iarc.who.int/wp-content/uploads/2018/07/IARCMonographs-QA.pdf>.
- Kaur, K., Kaur, R. (2018). Occupational pesticide exposure, impaired DNA repair, and diseases. *Indian J. Occup. Environ. Med.*, **22** (2), 74–81. https://doi.org/10.4103/ijoem.IJOEM_45_18.
- Khushboo, Thakur, M., Yadav, V., Kumar, Y., Pramanik, A., Dubey, K. K. (2024). How to deal with xenobiotic compounds through environment friendly approach? *Crit. Rev. Biotechnol.*, **44** (8), 1574–1593. <https://doi.org/10.1080/07388551.2024.2336527>.
- Kumamoto, Y., Aoyama, M., Hamajima, Y., Nagai, H., Yamagata, T., Kawai, Y., Oka, E., Yamaguchi, A., Imai, K., Murata, A. (2016). Fukushima-derived radiocesium in the western North Pacific in 2014. *J. Radioanal. Nucl. Chem.*, **311**, 1209–1217. <https://doi.org/10.1007/s10967-016-5055-3>.
- Kumar, G., Pandey, A. (2015). Heavy metal induced genomic distortion in root meristems of coriander (*Coriandrum sativum* L.). *Int. J. Res. Plant Sci.*, **4** (5), 47–53.
- Kumar, G., Tripathi, R. (2008). Lead-induced cytotoxicity and mutagenicity in grass pea. *Turkish J. Biol.*, **32**, 73–78.
- Lal, B. (2007). Pesticide-induced reproductive dysfunction in Indian fishes. *Fish Physiol. and Biochemistry*, **33**, 455–462. <https://doi.org/10.1007/s10695-007-9171-4>.
- Landrigan, P. J., Fuller, R., Acosta, N. J. R., Adeyi, O., Arnold, R., Basu, N., Balde, A. B., Bertollini, R., Bose-O'Reilly, S., Boufford, J. I., et al. (2018). The Lancet Commission on pollution and health. *The Lancet*, **391** (10119), 462–512. [https://doi.org/10.1016/S0140-6736\(17\)32345-0](https://doi.org/10.1016/S0140-6736(17)32345-0).
- Lawrence, K. J., Scholze, M., Seixo, J., Daley, F., Al-Haddad, E., Craenen, K., Gillham, C., Rake, C., Peto, J., Anderson, R. (2024). M-FISH evaluation of chromosome aberrations to examine for historical exposure to ionising radiation due to participation at British nuclear test sites. *J. Radiol. Protect.*, **44**, 1–18. <https://doi.org/10.1088/1361-6498/ad1743>.
- Lee, N.-W., Wang, H.-Y., Du, C.-L., Yuan, T.-H., Chen, C.-Y., Yu, C.-J., Chan, C.-C. (2022). Air-polluted environmental heavy metal exposure increase lung cancer incidence and mortality: A population-based longitudinal cohort study. *Sci. Total Environ.*, **810**, 152186. <https://doi.org/10.1016/j.scitotenv.2021.152186>.
- Liu, Z., Sang, J., Zhu, M., Feng, R., Ding, X. (2024). Prediction and countermeasures of heavy metal copper pollution accident in the Three Gorges Reservoir Area. *J. Hazardous Mater.*, **465**, 133208. <https://doi.org/10.1016/j.jhazmat.2023.133208>.
- Livnat, A., Love, A. C. (2024). Mutation and evolution: Conceptual possibilities. *BioEssays*, **46** (2), 1–12. <https://doi.org/10.1002/bies.202300025>.
- Loken, L. C., Corsi, S. R., Alvarez, D. A., Ankley, G. T., Baldwin, A. K., Blackwell, B. R. (2023). Prioritizing pesticides of potential concern and identifying potential mixture effects in Great Lakes tributaries using passive samplers. *Environ. Toxicol. Chem.*, **42**, 340–366. <https://doi.org/10.1002/etc.5491>.
- Lundqvist, U. (2014). Scandinavian mutation research in barley: A historical review. *Hereditas*, **151**, 123–131. <https://doi.org/10.1111/hrd.12.00077>.
- Lynch, M., Ackerman, M. S., Gout, J.-F., Long, H., Sung, W., Thomas, W. K., Foster, P. L. (2016). Genetic drift, selection and the evolution of the mutation rate. *Nat. Rev. Gen.*, **17**, 704–714. <https://doi.org/10.1038/nrg.2016.104>.
- Malygina, A., Notte, H., Rusten, L. (2024). The risk of renewed nuclear testing. *Deep Cuts Working Paper*, **17**, 1–12. <https://doi.org/10.5281/zenodo.12793671>.
- Martinez-Valenzuela, C., Waliszewski, S.M., Amador-Munoz, O., Meza, E., Calderon-Segura, M. E., Zenteno, E., Huichapan-Martinez, J., Caba, M., Félix-Gastelum, R., Longoria-Espinoza, R. (2017). Aerial pesticide application causes DNA damage in pilots from Sinaloa, Mexico. *Environ. Sci. Pollut. Res. Int.*, **24** (3), 2412–2420. <https://doi.org/10.1007/s11356-016-7974-5>.
- Maslia, M. L., Reyes, J., Gillig, R. E., Sautner, J. B., Fagliano, J., Aral, M. M. (2005). Public health partnerships addressing childhood cancer investigations: Case study of Toms River, Dover Township, New Jersey, USA. *Int. J. Hygiene Environ. Health*, **208** (1–2), 45–54. <https://doi.org/10.1016/j.ijheh.2005.01.007>.
- Mathiesen, L., Buerki-Thurnherr, T., Pastuschek, J., Aengenheister, L., Knudsen, L. E. (2021). Fetal exposure to environmental chemicals; insights from placental perfusion studies. *Placenta*, **106**, 58–66. <https://doi.org/10.1016/j.placenta.2021.01.025>.

- McDuffie, E. E., Martin, R. V., Spadaro, J. V., Burnett, R., Smith, S. J., O'Rourke, P., Hammer, M. S., Donkelaar, A., Bindle, L., Shah, V., *et al.* (2021). Source sector and fuel contributions to ambient PM_{2.5} and attributable mortality across multiple spatial scales. *Nature Commun.*, **12**, 1–12. <https://doi.org/10.1038/s41467-021-23853-y>.
- McGeoghegan, D., Whaley, S., Binks, K., Gillies, M., Thompson, K., McElvenny, D. M. (2010). Mortality and cancer registration experience of the Sellafield workers known to have been involved in the 1957 Windscale accident: 50-year follow-up. *J. Radiol. Protect.*, **30** (3), 407–431. <https://doi.org/10.1088/0952-4746/30/3/001>.
- Messerlian, C., Martinez, R. M., Hauser, R., Baccarelli, A. A. (2017). Omics and endocrine-disrupting chemicals — new paths forward. *Nature Rev. Endocrinol.*, **13**, 740–748. <https://doi.org/10.1038/nrendo.2017.81>.
- Mohanty, A. K., Sengupta, D., Das, S. K., Saha, S. K., Van, K. V. (2004). Natural radioactivity and radiation exposure in the high background area at Chhatrapur beach placer deposit of Orissa, India. *J. Environ. Radioact.*, **75** (1), 15–33. <https://doi.org/10.1016/j.jenvrad.2003.09.004>.
- Morgun, V. V., Yakymchuk, R. A. (2018). Cytogenetic anomalies of winter wheat cells, induced by chemical contamination of the territory of Kalush industrial district. *Regul. Mech. Biosyst.*, **9** (3), 446–452. <https://doi.org/10.15421/021867>.
- Morgun, V. V., Yakymchuk, R. A. (eds.) (2010). [Genetic consequences of the Chernobyl NPP accident]. Lohos, Kyiv. 400 pp. (in Ukrainian).
- Mousseau, T. A. (2021). The biology of Chernobyl. *Annu. Rev. Ecol. Evol. System.*, **52**, 87–109. <https://doi.org/10.1146/annurev-ecolsys-110218-024827>.
- Mousseau, T. A., Moller, A. P. (2020). Plants in the light of ionizing radiation: What have we learned from Chernobyl, Fukushima, and other “hot” places? *Frontiers Plant Sci.*, **11**, 1–9. <https://doi.org/10.3389/fpls.2020.00552>.
- Mrema, E. J., Rubino, F. M., Brambilla, G., Moretto, A., Tsatsakis, A. M., Colosio, C. (2013). Persistent organochlorinated pesticides and mechanisms of their toxicity. *Toxicology*, **307**, 74–88.
- Mrema, E. J., Rubino, F. M., Colosio, C. (2013). Obsolete pesticides — a threat to environment, biodiversity and human health. Simeonov, L., Macaev, F., Simeonova, B. (eds.). *Environmental Security Assessment and Management of Obsolete Pesticides in Southeast Europe. NATO Science for Peace and Security, Series C: Environmental Security*. Springer, Dordrecht, pp. 1–21. https://doi.org/10.1007/978-94-007-6461-3_1.
- Mubarak, F., Fayez-Hassan, M., Mansour, N. A., Ahmed, T. S., Ali, A. (2017). Radiological investigation of high background radiation areas. *Sci. Rep.*, **7**, 1–12. <https://doi.org/10.1038/s41598-017-15201-2>.
- Munsif, R., Zubair, M., Aziz, A., Zafar, M. N. (2021). Industrial air emission pollution: Potential sources and sustainable mitigation. Viskup, R. (ed.). *Environmental Emissions*. IntechOpen Limited, London, pp. 1–13. <https://doi.org/10.5772/intechopen.93104>.
- Naidu, R., Biswas, B., Willett, I. R., Cribb, J., Singh, B. K., Nathanail, C. P., Coulon, F., Semple, K. T., Jones, K. C., Barclay, A., Aitken, R. J. (2021). Chemical pollution: A growing peril and potential catastrophic risk to humanity. *Environ. Int.*, **156**, 1–12. <https://doi.org/10.1016/j.envint.2021.106616>.
- National report of the Kyrgyz Republic (2021). *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*. Bishkek. 34 pp.
- Oliver, S. K., Corsi, S. R., Baldwin, A. K., Nott, M. A., Ankley, G. T., Blackwell, B. R., Villeneuve, D. L., Hladik, M. L., Kolpin, D. W., Loken, L., *et al.* (2023). Pesticide prioritization by potential biological effects in tributaries of the Laurentian Great Lakes. *Environ. Toxicol. Chem.*, **42** (2), 367–384. <https://doi.org/10.1002/etc.5522>.
- Orlov, O. O., Nadtochiy, P. P. (2005). [Plutonium and americium: sources and dynamics of biosphere contamination, migration in soil and vegetation cover]. *Agroecol. J.*, **2**, 3–14 (in Ukrainian).
- Ozakca, D. U., Silah, H. (2013). Genotoxicity effects of flusilazole on the somatic cells of *Allium cepa*. *Pesticide Biochem. Physiol.*, **107** (1), 38–43. <https://doi.org/10.1016/j.pestbp.2013.05.001>.
- Ozkara, A., Akyil, D. (2018). Environmental pollution and pollutants on the ecosystem: A review. *Turkish J. Sci. Rev.*, **11** (2), 11–17.
- Pal, R., Rai, J. P. N. (2010). Phytochelatin: Peptides involved in heavy metal detoxification. *Appl. Biochem. Biotechnol.*, **160**, 945–963.
- Palaszewska-Tkacz, A., Czerczak, S., Konieczko, K. (2017). Chemical incidents resulted in hazardous substances releases in the context of human health hazards. *Int. J. Med. Environ. Health*, **30** (1), 95–110. <https://doi.org/10.13075/ijmeh.1896.00734>.
- Pasyuk, O. (ed.) (2017). [Impossible to cope. Management of radioactive waste in Ukraine after the Chernobyl accident]. Print Quick FOP “Popov Dmytro Viktorovych”, Kyiv. 34 pp. (in Ukrainian).
- Patterson, C. C., Shirahata, H., Ericson, J. E. (1987). Lead in ancient human bones and its relevance to historical developments of social problems with lead. *Sci. Total Environ.*, **61**, 167–200. [https://doi.org/10.1016/0048-9697\(87\)90366-4](https://doi.org/10.1016/0048-9697(87)90366-4).
- Popova, T., Vasileva, P., Stoyanov, I., Ilieva, I., Staykova, T., Ivanova, E. (2021). Cytotoxic and mutagenic effects of pesticides Verita WG and Actara 25 WG on sweet pepper (*Capsicum annuum* L.) and onion (*Allium cepa* L.). *Bulgarian J. Agric. Sci.*, **27** (3), 569–574.
- Pravalić, R. (2014). Nuclear weapons tests and environmental consequences: A global perspective. *Ambio*, **43** (6), 729–744. <https://doi.org/10.1007/s13280-014-0491-1>.
- Qasem, N. A. A., Mohammed, R. H., Lawal, D. U. (2021). Removal of heavy metal ions from wastewater: A comprehensive and critical review. *npj Clean Water*, **4** (1), 1–15. <https://doi.org/10.1038/s41545-021-00127-0>.
- Rakshit, A., Gangopadhyay, K. (2015). Study on genotoxic effect of agricultural and industrial effluents on chromosomes of *Channa punctatus* of polluted water bodies in West Bengal, India. *Int. J. Fish. Aquat. Stud.*, **3** (1), 233–238.
- Ren, K., Wei, Y., Li, J., Han, C., Deng, Y., Su, G. (2021). Polycyclic aromatic hydrocarbons (PAHs) and their derivatives (oxygenated PAHs, azaarenes, and sulfur / oxygen-containing heterocyclic PAHs) in surface soils from a typical city, south China. *Chemosphere*, **283**, 131190. <https://doi.org/10.1016/j.chemosphere.2021.131190>.
- Reste, J., Zvagule, T., Kurjane, N., Diesters, A., Silova, A., Eglite, M., Cirule, J., Gabruseva, N., Ziverts, A., Eurbakova, E. (2016). Investigations on health conditions of Chernobyl Nuclear Power Plant accident recovery workers from Latvia in late period after disaster. *Proc. Latvian Acad. Sci., Section B*, **70** (5), 257–265. <https://doi.org/10.1515/prolas-2016-0040>.
- Robbe, F. (ed.) (2016). *Seveso 1976. Oltre la diossina* [Seveso 1976. Beyond dioxin]. Castel Bolognese, Itaca. 160 pp.
- Roychoudhury, S., Jha, N. K., Ruokolainen, J., Kesari, K. K. (2022). Mutagenic factors in the environment impacting human and animal health. *Environ. Sci. Pollut. Res.*, **29**, 61967–61971. <https://doi.org/10.1007/s11356-022-22247-x>.
- Rozhko, M. M., Biletska, E. M., Shmatkov, H. H., Ersteniuk, H. M., Kryzhanivska, A. Y., Onyshchenko, S. V., Rudko, H. I., Samoiluk, M. S., Semchuk, Y. M., Soloviov, V. V. (2014). [Development and implementation of a system for reducing technogenic load on the territory and population of ecologically critical areas]. *Ecol. Nature Manag.*, **18**, 97–110 (in Ukrainian).
- Schleiffer, M., Speiser, B. (2022). Presence of pesticides in the environment, transition into organic food, and implications for quality assurance along the European organic food chain; A review. *Environ. Pollut.*, **313**, 120116. <https://doi.org/10.1016/j.envpol.2022.120116>.
- Schmidt, T. S., Miller, J. L., Mahler, B. J., Van Metre, P. C., Nowell, L. H., Sandstrom, M. W., Carlisle, D. M., Moran, P. W., Bradley, P. M. (2022). Ecological consequences of neonicotinoid mixtures in streams. *Sci. Adv.*, **8** (15), 1–12. <https://doi.org/10.1126/sciadv.abj8182>.
- Seibold, S., Gossner, M. M., Simons, N. K., Bluthgen, N., Muller, J., Ambarli, D., Ammer, C., Bauhus, J., Fischer, M., Habel, J. C., *et al.* (2019).

- Arthropod decline in grasslands and forests is associated with landscape-level drivers. *Nature*, **574**, 671–674. <https://doi.org/10.1038/s41586-019-1684-3>.
- Selvaraju, V., Baskaran, S., Agarwal, A., Henkel, R. (2021). Environmental contaminants and male infertility: Effects and mechanisms. *Andrologia*, **53** (1), 13646. <https://doi.org/10.1111/and.13646>.
- Sevalnev, A. I., Kostenetskiy, M. I., Torgun, V. P., Kutsak, A. V. (eds.) (2009). [Radon: radiation safety and protection methods]. ZSMU, Zaporizhzhia. 91 pp. (in Ukrainian).
- Shahbazi-Gahrouei, D., Gholami, M., Setayandeh, S. (2013). A review on natural background radiation. *Adv. Biomed. Res.*, **2** (1), 65–70. <https://doi.org/10.4103/2277-9175.115821>.
- Shumilova, O., Sukhodolov, A., Osadcha, N., Oreshchenko, A., Constantinescu, G., Afanasyev, S., Koken, M., Osadchyi, V., Rhoads, B., Tockner, K., et al. (2025). Environmental effects of the Kakhovka Dam destruction by warfare in Ukraine. *Science*, **387** (6739), 1181–1186. <https://doi.org/10.1126/science.adn865>.
- Soleman, S. R., Fujitani, T., Fujii, Y., Harada, K. H. (2020). Levels of octachlorostyrene in mothers' milk and potential exposure among infants in Sendai city, Japan 2012. *Int. J. Environ. Res. Publ. Health*, **17** (9), 3064. <https://doi.org/10.3390/ijerph17093064>.
- Sreeju, S. N., Michael Babu, M., Mariappan, C., Selvamohan, T. (2011). Effect of physical and chemical mutagens on biopolymer producing strains and RAPD analysis of mutated strains. *Arch. Appl. Sci. Res.*, **3**, 233–246.
- Tang, F. H. M., Lenzen, M., McBratney, A., Maggi, F. (2021). Risk of pesticide pollution at the global scale. *Nature Geosci.*, **14**, 206–210. <https://doi.org/10.1038/s41561-021-00712-5>.
- Tang, F. R., Loganovsky, K. (2018). Low dose or low dose rate ionizing radiation-induced health effect in the human. *J. Environ. Radioact.*, **192**, 32–47. <https://doi.org/10.1016/j.jenvrad.2018.05.018>.
- Trabidou, G., Florou, H. (2005). Radiological impact in an area of elevated natural radioactivity background: The case of the island of Ikaria–Aegean Sea, Greece. *International Congress Series*, 1276, 390–391. <https://doi.org/10.1016/j.ics.2004.11.122>.
- Underwood, E. (2017). The polluted brain. *Science*, **355**, 342–345. <https://doi.org/10.1126/science.355.6323.342>.
- Vecoli, C., Pulignani, S., Andreassi, M. G. (2016). Genetic and epigenetic mechanisms linking air pollution and congenital heart disease. *J. Cardiovasc. Devel. Dis.*, **3** (4), 32. <https://doi.org/10.3390/jcdd3040032>.
- Venken, K. J. T., Bellen, H. J. (2014). Chemical mutagens, transposons, and transgenes to interrogate gene function in *Drosophila melanogaster*. *Methods*, **68** (1), 15–28. <https://doi.org/10.1016/j.ymeth.2014.02.025>.
- Vergolyas, M. R., Goncharuk, V. V. (2016). Toxic effects of heavy metals on the hydrobionts' organism. *J. Educ. Health Sport*, **6**, 436–444. <http://dx.doi.org/10.5281/zenodo.56065>.
- White, P. A., Claxton, L. D. (2004). Mutagens in contaminated soil: A review. *Rev. Mutat. Res.*, **567** (2–3), 227–345. <https://doi.org/10.1016/j.mrrev.2004.09.003>.
- Wilkinson, P. (2015). Book review: Cosmogenic radionuclides: Theory and applications in the terrestrial and space environments. *Hist. Geo- Space Sci.*, **6**, 1–2. <https://doi.org/10.5194/hgss-6-1-2015>.
- Xue, T., Zhang, Q. (2018). Associating ambient exposure to fine particles and human fertility rates in China. *Environ. Pollut.*, **235**, 497–504. <https://doi.org/10.1016/j.envpol.2018.01.009>.
- Yakymchuk, R. A. (2016). [Mutagenic activity of soil contamination in areas where prohibited and unsuitable pesticides are stored]. *Plant Physiol. Gen.*, **48** (2), 146–157 (in Ukrainian).
- Yakymchuk, R. A. (ed.) (2019). [Genetic consequences of environmental pollution by natural and man-made mutagenic factors]. Lohos, Kyiv. 379 pp.
- Yang, Q., Liu, G., Falandysz, J., Yang, L., Zhao, C., Chen, C., Sun, Y., Zheng, M., Jiang, G. (2024). Atmospheric emissions of particulate matter-bound heavy metals from industrial sources. *Sci. Total Environ.*, **947**, 1744–1767. <https://doi.org/10.1016/j.scitotenv.2024.174467>.
- Zahm, S., Bonde, J., Chiu, W., Hoppin, J., Kanno, J., Abdallah, M., Blystone, C., Calkins, M., Dong, G., Dorman, D., et al. (2024). Carcinogenicity of perfluorooctanoic acid and perfluorooctanesulfonic acid. *The Lancet. Oncology*, **25** (1), 16–17. [https://doi.org/10.1016/S1470-2045\(23\)00622-8](https://doi.org/10.1016/S1470-2045(23)00622-8).
- Zhao, X., Ye, Q., Candel, S., Vignon, D., Guillaumont, R. (2023). A Chinese–French study on nuclear energy and the environment. *Engineering*, **26**, 159–172. <https://doi.org/10.1016/j.eng.2023.04.011>.

Received 22 June 2025

Accepted in the final form 12 February 2026

RADIONUKLEOTĪDU UN ĶĪMISKAIS APKĀRTĒJĀS VIDES PIESĀRŅOJUMS KĀ FAKTORS, KAS PALIELINA ORGANISMU MUTAGĒNO MAINĪBU

Paaugstinātu mutagēno faktoru klātbūtni dabā var izraisīt minerālu dabisko atradņu izstrādāšana, radioaktīvie un ķīmiskie atkritumi, atomieroču izmēģināšana, avārijas atomelektrostacijas un ķīmiskās ražotnēs, plaša un nekontrolēta ķīmisko preparātu izmantošana lauksaimniecībā un tml. Tas noved pie mutāciju frekvences pieauguma augiem, dzīvniekiem un arī cilvēkam un līdz ar to — pie dabisko populāciju adaptācijas spējas samazināšanās.