



EUROPEAN CONFERENCE

Conference Proceedings

**XX International Science Conference
«Latest technologies and modern society:
automation of processes and improvement of
quality of life»
May 18-20, 2026
Lyon, France**

LATEST TECHNOLOGIES AND MODERN SOCIETY: AUTOMATION OF PROCESSES AND IMPROVEMENT OF QUALITY OF LIFE

Abstracts of XX International Scientific and Practical Conference

Lyon, France
(May 18-20, 2026)

UDC 01.1

ISBN – 979-8-90214-565-3

The XX International scientific and practical conference «Latest technologies and modern society: automation of processes and improvement of quality of life», May 18-20, 2026, Lyon, France, 392 p.

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The recommended citation for this publication is: Bakhishov D. Impact of mineral fertilizer application on agrochemical properties of soils under wheat cultivation in the Qobustan region. Abstracts of XX International Scientific and Practical Conference. Lyon, France. Pp. 14-18.

URL: <https://eu-conf.com/en/events/latest-technologies-and-modern-society-automation-of-processes-and-improvement-of-quality-of-life/>

THERAPEUTIC POTENTIAL AND BIOCHEMICAL MECHANISMS OF ACTION OF ORGANIC GERMANIUM COMPOUNDS IN MODERN MEDICINE: FROM IMMUNOMODULATION TO NEUROPROTECTION

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Despite the use of inorganic germanium compounds as industrial semiconductors and their toxicity to the human body upon prolonged exposure, the potential application of organic germanium compounds (in particular, propagermanium and Ge-132) as immunomodulators and antitumor agents points to the need for a deeper study of their molecular mechanisms, which have already been tested in animals, opening up new prospects for the treatment of chronic inflammatory processes, oncological, and neurodegenerative diseases.

Germanium (Ge) is a trace element characterized by moderate activity and high bioavailability in certain compounds; inorganic compounds are toxic. Organic forms of germanium (e.g., Ge-132, propagermanium, and hydrolyzed monomers based on them), however, exhibit a wide range of biological activity, including anti-inflammatory, immunomodulatory, antioxidant, and antitumor effects [1].

The immune-modulating effects of germanium (Ge) include the stimulation of interferon production, macrophage activity, and T-suppressor cells, as well as an increase in T-killer cell activity, suggesting that germanium can be used in the treatment of diseases [2]. Scientific studies in mice have shown that following the administration of Ge-132, there is an increase in interferon (IFN) activity, which stimulates NK cells and activates macrophages [3; 4], a process that is critical for the identification and destruction of cancer cells in the early stages [3; 5]. Propagermanium is used to treat chronic hepatitis B, leading to seroconversion, which indicates an effective immune response (antibody levels rise, and viral load decreases) [6].

The radioactive isotope Ge-68 (which emits minimal radiation from the ⁶⁸Ge source to the patient), a precursor to Ga-68 (gallium-68), has also been used in PET (positron emission tomography). Although GeTM (Germanium Transmission Measurement) has

poorer image quality and a high noise level, it involves a lower radiation dose than PET or CT [7].

Today, GeTM has been almost entirely replaced by CT attenuation; however, germanium sources may still be encountered in scientific research or when using specialized PET systems (such as those for animals or certain PET/MRI systems).

The biological role of organic germanium as a powerful antihypoxant is one of its most interesting properties. Organic germanium has the ability to bind oxygen molecules and deliver them to cells that are oxygen-deprived. This is particularly important in pathological conditions where the blood's transport function is impaired. The antihypoxic function of germanium lies in stimulating hematopoiesis; germanium compounds (in particular, spirogermanium and Ge-132) directly affect the bone marrow, increase oxygen uptake in the blood, which can bind to blood cells, stimulating the formation of red blood cells and participating in the regulation of the differentiation and proliferation of blood stem cells [8; 9; 10].

The antioxidant effect of germanium lies in its ability to prevent the Maillard reaction, specifically the formation of AGEs (Advanced Glycation End-products), which are the primary drivers of reactive oxygen species (ROS) formation. Currently, this effect has not been sufficiently studied, but recent scientific research suggests that germanium compounds catalyze the breakdown of hydrogen peroxide, thereby preventing oxidative stress in cells. Germanium can also be used as an antioxidant supplement, but so far it has not demonstrated stronger properties than currently available standard antioxidants, such as ascorbic acid and polyphenols [11].

The organic form of germanium, monocarbonylgermanium sesquioxide (CGS/Ge-132), is considered the safest and most biologically active form for neuroprotection. CGS/Ge-132 has a protective effect in cerebral ischemia and Parkinson's disease, as well as against lipid peroxidation in hippocampal tissues following cerebral ischemia. CGS/Ge-132 also has an inhibitory effect on the formation of oxygen radicals and enhances the function of the endogenous oxygen radical scavenging system. This protective effect was observed in rats with ischemic-reperfusion brain injury. In these studies, ischemia-reperfusion injury mimics stroke conditions: first, a cessation of blood supply (ischemia), followed by its sudden restoration (reperfusion), which causes a powerful "oxidative burst" [10].

Conclusions. An analysis of the biological role of germanium suggests that this trace element is a unique multifunctional agent whose efficacy depends critically on its chemical form. While inorganic germanium compounds remain toxic to the body due to the risk of nephrotoxicity, organic forms, such as Ge-132 (monocarbonethylgermanium sesquioxide) and propagermanium, demonstrate a high safety profile and a broad spectrum of therapeutic activity. Despite the significant success of animal studies, further development requires the expansion of clinical trials in humans and a more detailed study of the molecular cascades underlying germanium's antioxidant action. Organic germanium may become a key component in the comprehensive treatment of chronic inflammatory, oncological, and age-related pathologies.

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