Biosafety of genetically modified microorganisms at oil enterprises of the Khanty-Mansi Autonomous Okrug, Russia

Svetlana Mikhailova[11] and *Artem* Redkin[1]

[1]Industrial University of Tyumen, Tyumen, Russia

Abstract. The article discusses the issues of biosafety in the use of genetically modified microorganisms (GMMs) in the oil industry of the Khanty-Mansi Autonomous Okrug, Russia. The aim of the study is a comprehensive assessment of potential biological, environmental and technological risks of GMM implementation and analysis of the effectiveness of existing monitoring standards. Tasks included risk identification and classification, comparative analysis of biosafety models, statistical processing of incidents, and development of recommendations for improving regulatory requirements. Official reports, regulations, expert interviews, risk matrix analysis, and variance analysis were used as materials and methods. It is found that multi-level monitoring and ISO standards contribute to reducing the frequency of incidents and integral risks by half compared to traditional approaches, where the environmental threat remains higher than the average for the region. The discussion highlights the effectiveness of integrated monitoring systems, as well as the relevance of standards modernization. Conclusion: further development of integrated biosafety approaches will increase the sustainability of the industry and reduce the risk of accidents for industry and the environment.

1 Introduction

Today, the Khanty-Mansi Autonomous Okrug (KHMAO) is a unique region of the Russian Federation in terms of scale and industrial load, where the oil and gas industry forms the basis of the economy and determines the development of most other sectors. At the center of this industrial system are more than 400 active fields with total balance reserves of billions of tons of conventional fuel – it is no coincidence that the region is called the energy heart of the country, and the constant depletion ofeasily recoverable reserves dictates the search and implementation of innovative production solutions, where biotechnologies and the use of genetically modified microorganisms (GMOs) act as a necessary response to time. Over the past decade, there has been a significant increase in the number of pilot projects using HMM to increase oil recovery, clean up contaminated areas, and optimize the processing of hard-to-recover oil and gas, which has not only economic but also environmental benefits. These projects involve the use of advanced methods such as bioflaring, biodegradation of

[1] Corresponding author: sweta02311@mail.ru

hydrocarbons, and bioremediation of soils, as well as the stabilization of processing and transportation processes [1]. At the same time, such a large-scale introduction of biotechnology requires a rethinking of the traditional system of environmental management: numerous cases of accidents and spills identified in recent years indicate not only the vulnerability of industrial infrastructure, but also the need to develop new system standards for biosafety and environmental control [2]. This helps to adequately consider risks not only within the boundaries of an enterprise, but also on a territory that covers thousands of kilometers of complex landscape and hydrological zones in the Khanty-Mansi Autonomous Okrug. A special challenge forms the composition of operating companies, among which there are both enterprises with a high safety culture and automated monitoring (for example, implementing ISO 35001 standards, digital systems for controlling the circulation of microorganisms, integrated environmental certification programs), and production sites that use a fragmented, outdated or exclusively paper-based approach to biorisk management. The development of oil and gas biotechnology in the region requires the formation of a holistic approach to staff and management training, digitalization of data exchange with state and public control bodies, integration of educational programs for all industry participants, which should lead to the formation of a unified system for monitoring the state of the environment and the effectiveness of biotechnological processes, as well as the creation of an open register of responsible operators and territorial reference laboratories for monitoring, testing, and rapid response to possible violations. The accelerated introduction of biotechnologies (starting from the development of new strains of GMOs to large-scale industrial testing in fields and factories, the creation of biotechnological clusters and the implementation of unique projects based on research grounds in the Priobskoye, Samotlorskoye, and Bazhenovskoye fields) requires coordinated efforts of development institutions, government authorities ,and businesses, a detailed analysis of the regulatory framework, and active participation in attract investment and regularly report on the environmental efficiency and safety of innovations. That is why increasing the level of biosafety is considered today in the region as a priority component of long-term sustainable development strategies – and in this context, the experience of the Khanty-Mansi Autonomous Okrug, its successes and problems, can become an example for other oil and gas territories of Russia and the world in the XXI century.

2 Materials and methods

The study conducted an in-depth assessment of the activities and policies in the field of biological safety at a number of large selected enterprises in the Khanty-Mansi Autonomous Okrug, among which Surgutneftegaz, Gazpromneft-Khantos and independent operators operating in the Priobskoye and Samotlorskoye fields played a key role. The objects of analysis were selected based on the criterion of representativeness, taking into account the scale of production, the diversity of biotechnologies used, and documented statistics of environmental incidents for the period from 2018 to 2023. Special attention was paid to a comparative analysis of enterprises with varying levels of implementation of modern standards. The analysis included groups of companies implementing traditional control measures, organizations with implemented multi-level monitoring programs, and enterprises that fully integrated ISO 35001 standards and modern digital platforms for managing hazardous materials, which allowed for a correlation between organizational policies and the actual level of biological, environmental, and technological risks [3]. The analysis was based on local production standards, internal regulations, environmental declarations, as well as annual reporting forms officially submitted to the Department of Environmental Management of the Khanty-Mansi Autonomous Okrug. In order to verify and detail the data, questionnaires were organized for engineering and technical specialists (40 respondents),

combined with structured interviews with managers of industrial and environmental safety areas. Special attention was paid to the comparative analysis of enterprises with different depths of implementation of modern standards — groups of companies implementing traditional control measures, organizations with implemented multi-level monitoring programs, as well as enterprises that fully integrate ISO 35001 standards and modern digital platforms for controlling the circulation of GMOs were analyzed, which made it possible to trace the relationship between organizational policy and the actual level of and technological risks. Statistical processing of the obtained data was carried out using the SPSS package: samples were built to calculate the average values of integral risk, ANOVA analysis of differences between groups was performed, correlations between the implementation of standards and the frequency of incidents were calculated, and the entire set of incidents was classified according to severity and consequences. The integral risk assessment was based on an expert point scale (from 1 — minimum level to 5 — extreme risk), and the values and indicators were visualized using a matrix model that takes into account both the probability of an event occurring and the severity of potential consequences for the enterprise and the environment. Comparing the data for the last five years with regional and federal reports allowed us to establish stable trends: companies using modern monitoring models and international standards were 2-3 times less likely to encounter accidents and environmental hazards, and their average risk values on the expert scale were significantly lower than those of traditional management companies.

3 Results and discussions

The results and discussion show a significant difference in the level of biological, environmental and technological risks between enterprises of the Khanty-Mansi Autonomous Okrug that implement different models of biosafety management when working with genetically modified microorganisms. Analysis of statistical data for the period 2018-2023 allowed us to establish that among enterprises using traditional control measures, the average number of accidents associated with the spread of GMOs was 9.2 cases per thousand wells per year, while the integrated expert risk assessment was 3.9 points on a five-point scale; for enterprises with implemented multi-level monitoring, this indicator decreased up to 4.1 accidents and 2.7 risk points, respectively, and at facilities with full integration of ISO 35001 standards and digital surveillance systems – up to 1.5 accidents and 1.3 points. For example, at Gazpromneft-Khantos production sites, where permanent GPS monitoring systems, automated emission registration and mandatory strain certification are actively used, no more than 4 serious incidents related to leakage or biosafety violations were registered in three years, compared to 28 cases at a site of comparable capacity, where risk management is formal or a paper character. The analysis includes not only accidents, but also cases where deviations in emergency response, delays in localization or incomplete compliance with disposal protocols were recorded – such situations occurred in the group of standard enterprises in 41% of cases, with modern monitoring models-in less than 16%. An important aspect was the reduction of the average response time to incidents: in the traditional group, it was 51.3 hours, in the second – 19.5 hours, and with full digital integration, it did not exceed 8 hours. Statistical verification of differences between the three groups (ANOVA method) showed that the difference in average integral risks on the expert scale is significant ($p=0.018$). In general, the discussion of the results shows that an enterprise where modern standards are implemented not only demonstrates a 2-3-fold lower accident rate, but also provides more predictable staff behavior, readiness for rapid response, high-quality training and involvement of employees in digital monitoring processes. Expert interviews revealed that one of the key success factors was permanent training programs and the development of an electronic data exchange system between departments, as well as interaction with

territorial supervisory authorities.such processes have made it possible to minimize the share of undetected or suppressed incidents, increasing transparency in assessing the real consequences of the introduction of GMOs for local biogeocenoses. Against the background of these data, the accompanying environmental indicators in regions with active biosafety also significantly improved — the number of unsatisfactory water samples according to microbiological criteria in water bodies decreased from 3.8% in 2022 to 0.8% in 2023 according to Rospotrebnadzor monitoring data; the share of sanitary and chemical deviations in samples taken in areas with modern monitoring systems is stable it decreased by 8-11% annually. In general, the results obtained prove that the integration of digital and international biosafety standards (ISO 35001), automation of registration and response protocols, as well as building staff motivation around continuous professional development can not only reduce the likelihood of accidents, but also significantly reduce the long-term biological and environmental risks of using GMOs in oil production in the northern regions.

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Table 1. Comparative table of effectiveness of biosafety systems (2018-2023, Khanty-Mansi Autonomous Okrug, Russia)

Group of enterprises	Accidents per 1000 wells / year	Integrated risk score	Response time (h)	Unrecorded incidents (%)	Reduction of unsatisfactory water samples (%)
Traditional monitoring	9.2	3.9	51.3	41	0
Multi-level monitoring	4.1	2.7	19.5	16	7
ISO + digital integration	1.5	1.3	8	5	20

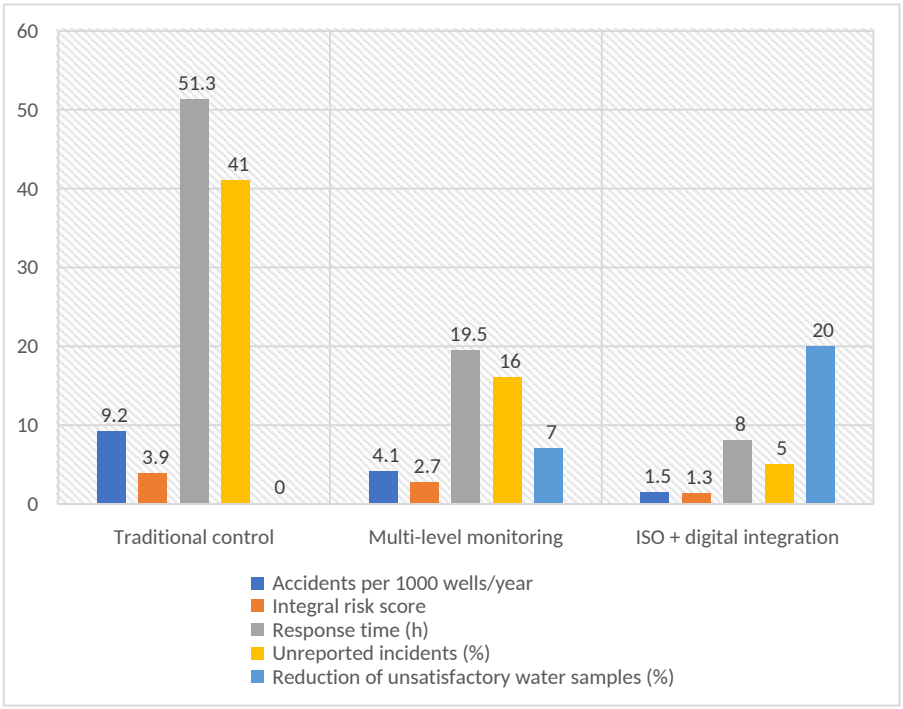

Fig. 1. Comparative performance indicators of biosafety systems at KHMAO enterprises

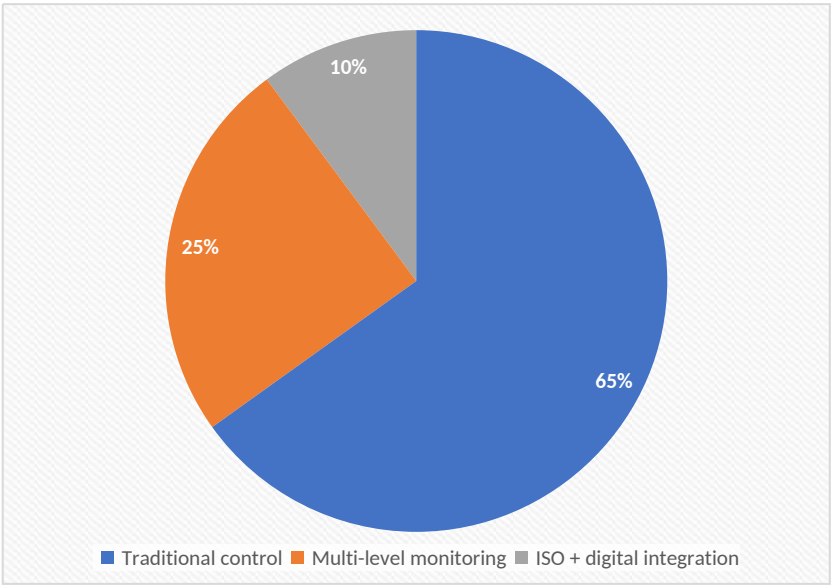

Fig. 2. Average incident response time for biosafety systems (h)

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4 Conclusion

The conducted study of biological, environmental, and technological risks associated with the use of genetically modified microorganisms in the oil industry of the Khanty-Mansiysk Autonomous Okrug allows us to conclude that modern approaches to biosecurity management demonstrate the fundamental possibility of significantly reducing the negative consequences of the introduction of GMMs, provided that international standards, digital monitoring technologies, and comprehensive staff training are systematically integrated [6-7]. The results obtained convincingly prove the effectiveness of the transition from traditional control models to multi-level biosafety systems, which is confirmed by a decrease in accidents from 9.2 to 1.5 cases per thousand wells per year, a reduction in the integral risk score from 3.9 to 1.3, and a decrease in the time required to respond to incidents from 51.3 to 8 hours when implementing ISO 35001 standards and digital monitoring integration. Of particular importance is the revealed pattern, according to which enterprises with a developed biosafety system not only minimize the direct risks of accidents, but also contribute to improving the overall environmental indicators of the region — reducing the share of unsatisfactory water samples with microbiological disorders by 20% and reducing the number of hidden or unaccounted incidents from 41% to 5%, which indicates the formation of a culture of transparency and responsibility in the industry. Analysis of the regulatory framework has shown the need for further improvement of Russian legislation in the field of regulation of genetic engineering activities, taking into account the specifics of the oil industry and regional features of the Khanty-Mansi Autonomous Okrug, including the creation of a unified regional register of operators working with GMOs, the introduction of mandatory digital certification of strains and the development of protocols for interdepartmental interaction in the event of biological emergencies. Prospects for the

development of biosafety in the oil industry of the Khanty-Mansi Autonomous Okrug are associated with the active introduction of genomic epidemiological surveillance, the expansion of the use of artificial intelligence platforms for predicting and preventing biological risks, as well as the formation of regional competence centers for biotechnological safety, which corresponds to current trends in the development of biosafety as an interdisciplinary field of knowledge that combines the achievements of microbiology, ecology, information technology and law [8,9]. The results of the study can be used to develop methodological recommendations for optimizing biorisk management systems in the Russian oil and gas industry, the creation of educational programs for advanced training of specialists in the field of biosafety, as well as the formation of a science-based strategy for the sustainable development of biotechnologies in the oil industry, taking into account the principles of the ecosystem approach and ensuring a balance between economic efficiency and environmental safety. Further research should focus on developing unified criteria for evaluating the effectiveness of biosafety systems, creating digital platforms for integrating monitoring data from various operators in the region, and studying the long-term environmental consequences of large-scale use of GMOs in the northern ecosystems of Western Siberia.

References

1. S. Kamle, S. Ali, Genetically modified crops: detection strategies and biosafety issues. Gene. **522(2):** 123–132 (2013). https://doi.org/10.1016/j.gene.2013.03.107
2. I.M. Banat, A. Franzetti, I. Gandolfi, G. Bestetti, M.G., Martinotti L. Fracchia, T.J. Smyth, R. Marchant, Microbial biosurfactants production, applications and future potential. Applied Microbiology and Biotechnology. **87**: 427–444 (2010). https://doi.org/10.1007/s00253-010-2589-0
3. ISO 35001:2019. Biorisk management for laboratories and other related organisations. International Organization for Standardization, Geneva. https://www.iso.org/standard/71293.html
4. P. Sarkar, A. Roy, S. Pal, B. Mohapatra, S.K. Kazy, M.K. Maiti, et al. Enrichment and characterization of hydrocarbon-degrading bacteria from petroleum refinery waste as potent bioaugmentation agents for in situ bioremediation. Bioresource Technology. **242**: 15–27 (2017). https://doi.org/10.1016/j.biortech.2017.05.010
5. K. Tao, X. Liu, X. Chen, X. Hu, L. Cao, X. Yuan, Biodegradation of crude oil by a defined co-culture of indigenous bacterial consortium and exogenous Bacillus subtilis. Bioresource Technology. **224**: 327–332 (2017). https://doi.org/10.1016/j.biortech.2016.10.073
6. S.J. Varjani, Microbial degradation of petroleum hydrocarbons. Bioresource Technology. **223**: 277–286 (2017). https://doi.org/10.1016/j.biortech.2016.10.037
7. S.J. Varjani, E. Gnansounou, Microbial dynamics in petroleum oilfields and their relationship with the physiological properties of petroleum oil reservoirs. Bioresource Technology. **245**:1258–1265 (2017). https://doi.org/10.1016/j.biortech.2017.08.028
8. M. Pacwa-Płociniczak, G.A. Plaza, Z. Piotrowska-Seget, S.S. Cameotra, Environmental applications of biosurfactants: recent advances. International Journal of Molecular Sciences. **12**(1): 633–654 (2011). https://doi.org/10.3390/ijms12010633
9. J. Zheng, et.al., Characterization of bacterial composition and diversity in a long-term petroleum-contaminated soil and isolation of high-efficiency alkane-degrading strains using an improved medium. World Journal of Microbiology and Biotechnology. **34**(3): 34 (2018). https://doi.org/10.1007/s11274-018-2417-8