layered approach using advanced anomaly monitoring technologies and artificial intelligence to detect threats. It is necessary to improve the legislative framework and cybersecurity standards, taking into account the specifics of Ukraine's energy sector.

Government policy should promote investments in the digital transformation of the energy sector through tax incentives and targeted funding programs. It is necessary to develop a national roadmap for implementing Industry 4.0 technologies in the energy sector with clear efficiency indicators. International cooperation and exchange of experience should become catalysts for innovative development of Ukrainian energy in the context of European integration.

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COMPARATIVE ANALYSIS OF NATURAL SORBENTS IN THE PROCESSES OF BIOREMEDIATION OF OIL-CONTAMINATED SOILS

The problem of oil contamination of soil is one of the leading anthropogenic impacts on the environment. Spills of oil and oil products during their extraction, transportation, processing and storage lead to disruption of natural ecosystems, loss of land fertility and pose a threat to human health. In this context, the development and implementation of effective, economically feasible and environmentally friendly technologies for cleaning up contaminated areas is an urgent scientific and practical task [1, 4].

The aim of the study is to investigate the effectiveness of using sorbents based on natural materials for soil cleanup from oil contamination, taking into account

their sorption properties, economic feasibility and environmental safety. Experimental studies were conducted in the laboratory of the Department of Environmental Protection Technology and Occupational Safety of Ivano-Frankivsk National Technical University of Oil and Gas. The objects of study were oil-contaminated soils and natural sorbents: peat, sawdust, straw, and activated carbon. To conduct the study, soil samples weighing 100 g each were prepared and artificially contaminated with oil products at a concentration of 5% by weight of soil (5 g per 100 g of soil). All sorbents were pre-dried at 105°C for 2 hours and crushed to a particle size of 1-2 mm to ensure homogeneity of the experiment [1, 3].

The study was conducted in triplicate for each type of sorbent. The prepared sorbents were applied to the contaminated soil samples in the amount of 10 g per sample. After sorbent application, the samples were thoroughly mixed and kept for 24 hours at room temperature (22±2°C) [3, 5].

The effectiveness of soil cleanup was assessed by reducing the concentration of oil products. Additionally, the phytotoxicity of the cleaned soils was assessed using test crops: flax, mustard, corn, oats, barley, and watercress.

The results of the study showed that all the natural sorbents studied have significant efficiency in cleaning soils from oil contamination. The highest purification rate was observed when using activated carbon (75.4%), which is explained by its developed porous structure and high specific surface area. Peat showed the second most efficient result (68.8%), which makes it a promising material for cleaning up contaminated areas, given its availability and low cost. Sawdust and straw demonstrated slightly lower cleaning rates (63.2% and 57.0%, respectively).

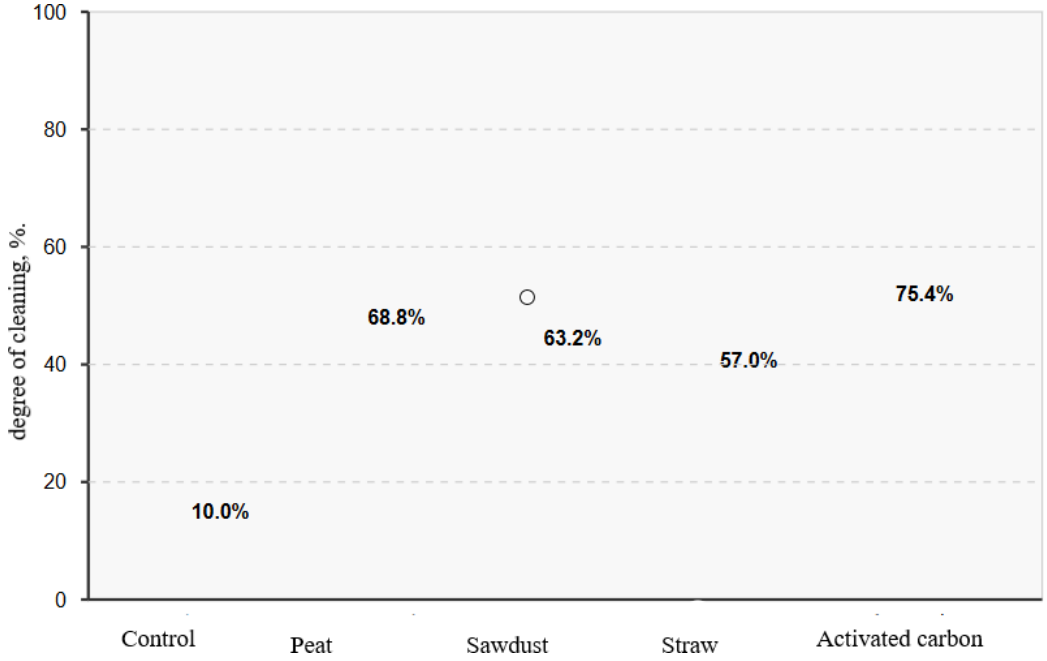

Fig. 1 – Efficiency of soil cleaning from oil products with different sorbents

Statistical processing of the results confirmed the reliability of the data obtained. The coefficients of variation for all sorbents did not exceed 2%, which indicates the stability of their sorption properties. The correlation coefficient

between the sorption efficiency and the specific surface area of the sorbents was 0.97, indicating a strong positive correlation [2, 3].

The analysis of the dynamics of the purification process showed that the highest intensity of oil absorption is observed in the first 12 hours after the introduction of sorbents. Compared to the control variant (natural cleaning without sorbents, 10.0% efficiency), the use of natural sorbents increases the cleaning efficiency by 5.7-7.5 times. The results of phytotesting confirmed the effectiveness of soil treatment and the possibility of their further use. Seed germination of test crops in soils treated with activated carbon was 87.4-92.8% of the control, for peat - 84.5-89.2%, for sawdust - 81.8-86.4%, for straw - 77.2-83.5%. The phytotoxic effect in the soils after treatment was significantly reduced compared to the contaminated samples: for activated carbon - up to 7.2%, for peat - up to 9.8%, for sawdust - up to 15.4%, for straw - up to 21.2% (compared to 63.8% in the contaminated soil) [1, 5].

All the natural sorbents studied showed significant efficiency in cleaning the soil from oil contamination, which confirms the feasibility of their use in the technologies of remediation of contaminated areas. The highest efficiency was demonstrated by activated carbon (75.4%) and peat (68.8%), which makes them the most promising materials for practical use. A strong positive correlation between sorption efficiency and physical properties of sorbents (specific surface area and porosity) was found, which allows predicting the sorption capacity of materials based on their physical characteristics. The results of phytotesting confirmed the effectiveness of soil purification and reduction of their phytotoxicity after the use of natural sorbents, which opens up opportunities for further use of the restored areas.

The practical significance of the results is the possibility of using available natural materials for effective soil cleanup from oil pollution, which helps to reduce the technogenic load on the environment and restore disturbed ecosystems.

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