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Dragan Petrović, Zorana Filipova

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Tabela 1 - Rezultati eksperimentalnih merenja

Ispod ilustracije treba da stoji objašnjenje, npr.: *Slika 1 - Rezultati simulacije procesa*

Nazive tabela i grafikona takođe dati na srpskom i engleskom jeziku.

Formule numerisati rednim brojevima u malim zagradama. Pozivanje na formule u tekstu vrši se navođenjem odgovarajućeg rednog broja u malim (okruglim) zagradama:

$$\overline{R_u} = L_4 + L_3 F_x \left(\frac{\overline{U_{pm}} - \overline{U_{gm}}}{\overline{U_{pm}^2}} \right) \tag{1}$$

U ovom odeljku se takođe vrši upoređenje rezultata koje su dobili autori s podacima iz radova navedenih u spisku referenci, što predstavlja osnovu diskusije.

ZAKLJUČAK / CONCLUSION

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Zahvalnica / Acknowledgements

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LITERATURA / REFERENCES

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Petrović, S. (2019). *Zaštita vodnih resursa*, Naučna knjiga, Beograd, 403 str.

Smith, G. (2020). Title of the article, *Chem. Phys.*, 65 (4), pp. 19-35.

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Application of the GHG protocol in management accounting: Case studies of global technology companies

Primena protokola o emisiji gasova staklene bašte u upravljačkom računovodstvu: Studije slučaja globalnih tehnoloških kompanija

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Abstract: In today's business world, the managing of CO_2 emissions is becoming an increasingly important element of sustainability strategies, while management accounting stands out as a central mechanism for their effective implementation. This paper explores how management accounting can contribute to the control and reduction of greenhouse gas (GHG) emissions, using the case studies of Apple and Microsoft as examples. In this context, we rely on the GHG protocol which is an internationally recognized standard for measuring emissions. The result show that the integrating emissions into internal management processes enables companies to identify key sources of emissions, optimize costs, and support strategic decisions in the area of decarbonization. Apple has achieved significant emissions reductions through suply chain transformation, the use of renewable energy, and the incorporation of carbon indicators into procurement processes and product design. On the other hand, Microsoft, despite its advanced reporting mechanisms and internal carbon tax, faces challenges in managing extensive Scope 3 emissions due to the growth of energy-intensive infrastructure for cloud and AI. The comparative analysis shows that success in reducing emissions depends on the ability of companies to align their managerial focus with the dominant sources of CO_2. This papers confirms that management accounting enables the transformation of emissions into measurable and financially relevant variables, thereby promoting efficiency, reducing risk, and creating sustainable competitive advantage.

Keywords: management accounting, GHG protocol, CO_2 emissions, sustainability, decarbonization.

Sažetak: U današnjem poslovnom svetu, upravljanje emisijama CO_2 postaje sve važniji element strategija održivosti, dok se upravljačko računovodstvo ističe kao centralni mehanizam za njihovu efikasnu implementaciju. Ovaj rad istražuje na koji način upravljačko računovodstvo može doprineti kontroli i smanjenju emisija gasova staklene bašte, a kao primer prikazane su studije slučaja kompanija Apple i Microsoft. U ovom kontekstu, fokus je na GHG protokolu, koji je međunarodno priznati standard za merenje emisija. Rezultati pokazuju da integracija emisija u interne upravljačke procese daje mogućnost kompanijama da identifikuju ključne izvore emisija, optimizaciju troškova i podršku strateškim odlukama u oblastima dekarbonizacije. Kompanija Apple ostvarila je značajno smanjenje emisija kroz transformaciju lanca snabdevanja, korišćenje obnovljive energije i ugradnju ugljeničnih indikatora u procese nabavke i dizajn proizvoda. Sa druge strane, kompanija Microsoft uprkos naprednim mehanizmima izveštavanja i internoj taksi za emisiju CO_2, suočava se sa izazovima u upravljanju obimnim emisijama povezanim sa Scope 3, usled rasta energetski intenzivne infrastrukture za Cloud i AI. Komparativna analiza pokazuje da uspeh u smanjenju emisija zavisi od sposobnosti kompanija da usklade menadžerski fokus sa dominantnim izvorima CO_2. Rad potvrđuje da upravljačko računovodstvo olakšava transformaciju emisija u merljive i finansijske relevantne varijable, čime se podstiče efikasnost, smanjenje rizika i stvaranje održive konkurentske prednosti.

Ključne reči: upravljačko računovodstvo, GHG protokol, emisija CO_2, održivost, dekarbonizacija.

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INTRODUCTION

The increasing emphasis on digitalization and innovative business practices has enabled organizations to manage internal processes and data more efficiently, providing strong support for managerial accounting systems designed to track and control CO_2 emissions (Brkljač, et al., 2022). Companies now recognize that carbon emissions not only pose environmental and regulatory risks but also represent strategic opportunities. Furthermore, many countries have introduced ecological taxes to reduce GHG emissions (Balaban and Stoiljković, 2023), further underscoring the need for robust managerial accounting tools. This awareness has driven the adoption of decarbonization strategies alongside environmental control mechanisms, such as carbon accounting systems (CASs). Empirical studies indicate that well-designed CASs enhance the effectiveness of carbon strategies by translating organizational objectives into measurable improvements in emissions performance (Bui et al., 2022). Integrating robust accounting systems with proactive carbon strategies enables firms to achieve meaningful reductions in CO_2 emissions, reinforcing the central role of managerial accounting in sustainability efforts.

Over the past decade, the development of environmental management accounting (EMA) has introduced a range of managerial and control instruments that enhance the measurement, oversight, and communication of corporate environmental performance. Although widely acknowledged as critical for corporate sustainability, the practical application of these tools and their effectiveness in improving carbon management remain uneven (Qian et al., 2018). Empirical evidence from multinational firms demonstrates that while many organizations adopt selected EMA tools, only a minority implement comprehensive suites of practices. Tools that support auditing, benchmarking, and control-oriented decision-making significantly influence carbon management and reporting outcomes, reinforcing the importance of managerial accounting in aligning operational actions with sustainability objectives.

Managerial Carbon Accounting (MCA) further extends these principles by providing managers with frameworks to integrate greenhouse gas emissions into internal decision-making processes (Tang, 2025). Unlike financial carbon accounting, MCA emphasizes operational and strategic support, incorporating key elements such as mitigation costs, green investments, carbon budgets, performance evaluation, and internal emissions reporting. By linking emissions to managerial actions, MCA facilitates more effective decarbonization efforts while maintaining cost control, demonstrating how managerial accounting can serve as a practical tool for both operational efficiency and environmental stewardship.

The relevance of managerial accounting extends beyond the corporate context. Cities, as major contributors to CO_2 emissions, play a pivotal role in implementing mitigation strategies (Brown & MacAskill, 2025). Effective urban carbon management requires accurate and systematic accounting, yet municipal authorities often face constraints in data availability, technical capacity, and financial resources. Approaches such as integrating diverse data sources, visualizing emissions for spatial planning, developing district-level mitigation strategies, and monitoring project-level emissions illustrate how accounting systems can guide sustainable urban decision-making. Moreover, broader socio-ecological awareness is key to sustainability. As Simić (2025) points out, environmental security and social awareness are essential for achieving sustainable development, emphasizing the need for adaptive strategies and harmonizing corporate and social activities with environmental realities. These insights emphasize the broader applicability of managerial carbon accounting as a strategic mechanism for emission reduction.

Practical applications of managerial carbon accounting are evident in industry-specific contexts as well. For instance, Sun et al. (2024) developed a combined carbon and cost accounting model for a liner shipping company operating under the EU Emissions Trading System (EU ETS). By linking CO_2 emissions across voyage stages with operational costs, the model enabled managers to identify cost-effective strategies for emission reduction while maintaining economic efficiency. Similarly, the global review by Hazaea et al. (2022) demonstrates that carbon accounting has evolved into a strategic tool for decision-making and corporate reporting, highlighting the need for standardized methodologies to ensure comparability and reliability of emissions data.

Moreover, integrating carbon accounting with broader resource management enhances managerial decision-making. Wang et al. (2021) shows that tracking natural resource flows through input-output analysis provides critical information for both strategic planning and operational optimization, effectively linking environmental performance with economic outcomes. These examples collectively illustrate that managerial accounting, when properly designed and applied, can serve as a powerful instrument for controlling and reducing CO_2 emissions across organizational and urban contexts.

In line with this perspective, the present study aims to explore how managerial accounting serves as a tool for emission control by examining best practices through case studies and leading frameworks. Specifically, the research presents real-world examples from Apple and Microsoft, demonstrating how these companies have leveraged the Greenhouse Gas (GHG) Protocol and internal managerial accounting systems to achieve measurable reductions in carbon emissions.

1. MATERIALS AND METHODS

In this research, we apply a comprehensive methodological approach that combines case studies, statistical analysis and comparative evaluation. We begin by presenting case studies of leading technology companies, with a particular focus on their greenhouse gas (GHG) reporting practices. Specifically, the authors analyze Apple and Microsoft to illustrate how the principles of managerial carbon accounting and the GHG protocol apply in real organizational settings.

The relationship between accounting and CO_2 has gained increasing importance as greenhouse-gas emissions have shifted from being perceived solely as an environmental concern to becoming a measurable, reportable, and financially relevant business variable. Contemporary carbon accounting applies established accounting principles - such as measurement, verification, and transparency - to emissions data, enabling organizations to quantify their climate impact using standardized frameworks. Among these, the Greenhouse Gas (GHG) Protocol represents the most widely adopted international methodology for calculating and managing emissions across both private and public entities. It categorizes emissions into three scopes that collectively capture a company's direct and indirect carbon footprint (Table 1). Specifically, Scope 1 encompasses direct emissions from assets owned or controlled by the company, Scope 2 accounts for indirect emissions arising from purchased energy (including electricity, steam, heat, and cooling), while Scope 3 covers all other indirect emissions across the value chain, including those associated with suppliers, customers, and other upstream and downstream activities.

Table 1 - The Greenhouse Gas Protocol (Scope 1, Scope 2 and Scope 3)

Scope 1 **Direct emissions**	**Scope 2** **Indirect emissions**	**Scope 3** **Indirect emissions**
Direct emissions that are owned or controlled by a company	Indirect emissions that are a consequence of a company's activities but occur from sources not owned or controled by it	
Emissions from sources that an organization owns or controls directly	Emissions a company causes indirectly that come drom where the energy it purchases and uses is produced	All emissions not covered in scope 1 or 2, created by a company's value chain
Example The emissions from burning fuel in the company's fleet of vechiles (if they're not electricaly powered)	Example The emissions caused by the generation of electricity that's used in the company's buildings	Example When the company buys, uses and disposes of products from suppliers

Source: https://www.nationalgrid.com/stories/energy-explained/what-are-scope-1-2-3-carbon-emissions

By converting emissions into numerical indicators - often linked to explicit carbon prices, regulatory obligations, and market-based mechanisms - CO_2 effectively becomes an economic item that can be treated as a cost, liability, or strategic risk within corporate decision-making processes. This integration enables companies not only to comply with emerging regulatory requirements (such as CSRD, ETS, and sustainability reporting standards) but also to create reliable and audit-ready datasets that support long-term climate strategies. The data obtained, from the GHG reports of Apple and Microsoft companies will be further analyzed using statistical and comparatives methods, which enable the identification of similarities, diferences and the best practices in the managerial accounting of carbon dioxide. This approach provides not only a rigorous assessment of corporate performance, but also situates the findings within the broader context of sustanaible decision-making.

2. RESULTS AND DISCUSSION

This section examines case studies that demonstrate how companies are implementing greenhouse gas (GHG) management practices within their operations. Emphasis placed on the role of management accounting in supporting greenhouse gas emissions management, improving resource efficiency, and integrating carbon reporting into strategic decision-making and operational performance. These cases provide a basis for understanding how theoretical frameworks are applied in practice, offering concrete insights into effective decarbonization strategies. Apple and Microsoft are highlighted as leading examples, illustrating how management accounting and the Greenhouse Gas (GHG) Protocol work together to reduce measurable emissions and improve operational efficiency in complex global supply chains.

2.1. Case Study: Apple GHG Protocol

Apple represents one of the most advanced global examples of corporate carbon management, applying the Greenhouse Gas (GHG) Protocol as the foundational framework for quantifying and reporting its emissions. The company systematically measures emissions across all three protocol-defined scopes, enabling a transparent and comprehensive assessment of its carbon footprint. According to the Apple Environmental Progress Report 2025, the company has achieved a reduction of over 60% in total greenhouse gas emissions compared with its 2015 baseline, demonstrating the effectiveness of its managerial accounting systems and decarbonization strategy. Apple's reporting structure ensures that emissions are categorized according to standardized principles, facilitating comparability both across time and with other multinational corporations.

Scope 1: Direct Emissions from Owned and Controlled Sources

Scope 1 emissions include direct outputs from Apple's facilities, testing laboratories, and fleet operations. These emissions have been substantially reduced due to the company's long-term decarbonization initiatives, including the transition to high-efficiency systems, electrification of equipment, and optimization of heating and cooling processes in corporate facilities. Through continuous monitoring and real-time environmental accounting, Apple maintains precise internal control over Scope 1 sources, allowing emissions to be treated as operational performance indicators within managerial accounting frameworks.

Scope 2: Indirect Emissions from Purchased Energy

Scope 2 emissions, stemming from electricity and heating purchased for corporate operations, represent another major component of Apple's carbon footprint. Apple reports that it has reached 100% renewable electricity across its corporate facilities, data centers, and owned retail locations worldwide. This achievement significantly lowered Scope 2 emissions, effectively decoupling operational growth from energy-related carbon output. Managerial accounting plays a central role in this transition, enabling the identification of high-consumption facilities, cost-benefit evaluations of renewable energy procurement, and integration of carbon metrics into investment decisions.

Scope 3: Value-Chain Emissions

The largest share of Apple's total emissions originates from Scope 3 activities, which include upstream suppliers, downstream product use, logistics, business travel, and end-of-life treatment. In 2024 alone, suppliers participating in Apple's Clean Energy Program generated 17.8 GW of renewable electricity, contributing to substantial reductions in upstream emissions. Apple applies managerial carbon accounting tools to integrate supplier performance metrics into procurement decisions, cost analyses, and long-term climate strategies. By converting value - chain emissions into quantifiable indicators, Apple treats CO_2 output as a strategic economic variable - one that affects procurement cost structures, product design, and supply-chain risk assessments. This approach is consistent with the GHG Protocol's emphasis on capturing the broadest possible emissions boundary, thereby enhancing transparency and accountability.

Apple's carbon accounting is embedded within a broader managerial accounting system that aligns operational, financial, and sustainability objectives. Emissions data are incorporated into internal dashboards, cost-benefit analyses, and capital budgeting models, enabling managers at all levels to evaluate trade-offs between environmental performance and economic efficiency. This integration has facilitated the prioritization of high-impact decarbonization initiatives, such as material substitution, increased product recyclability, and the optimization of logistics networks. By establishing measurable carbon budgets and linking them to performance indicators, Apple ensures that emission-reduction targets influence managerial decision-making rather than remaining isolated within sustainability reporting.

Apple's approach illustrates that managerial accounting is not just a reporting tool but a strategic system that enables measurable emission reductions across all levels of the organization.

The application of GHG Protocol accounting has allowed Apple to:

- enhance transparency and auditability of emissions data;
- support decarbonization planning through standardized performance metrics;
- integrate carbon impacts into resource allocation and innovation processes;

- reduce operational and value-chain emissions at a pace consistent with long-term net-zero objectives.

The Apple case illustrates how a comprehensive carbon accounting system - grounded in the GHG Protocol and supported by managerial accounting tools - can enable measurable reductions in greenhouse-gas emissions. It also demonstrates that managerial accounting serves not only as a reporting mechanism but as a strategic control system that directly supports emission reduction efforts in multinational corporations.

2.2. Case Study: Microsoft GHG Protocol

Microsoft represents one of the world's largest technology companies and a global benchmark in the application of carbon accounting principles grounded in the Greenhouse Gas (GHG) Protocol. The company provides detailed, annually updated disclosures of its direct and indirect emissions, enabling comprehensive assessment of its carbon footprint across Scope 1, Scope 2, and Scope 3 categories. Data for this case study are drawn from the Microsoft Environmental Data Fact Sheet 2025, covering fiscal year (FY) 2024. Microsoft's systematic approach to carbon accounting reflects a high level of methodological rigor, transparency, and alignment with international sustainability standards, allowing emissions to function as measurable managerial variables within internal decision-making systems.

Scope 1: Direct Emissions from Owned and Controlled Sources

Microsoft's Scope 1 emissions for FY 2024 amounted to 143,510 metric tons of CO_2e. These emissions originate primarily from company-owned facilities, backup generators, testing laboratories, and corporate vehicle fleets. The observed level reflects ongoing efforts to reduce fossil-fuel dependency through improvements in energy efficiency, transition to low-carbon equipment, and operational optimization of physical infrastructure. By incorporating Scope 1 emissions into internal monitoring dashboards and performance indicators, Microsoft applies a managerial accounting framework in which direct emissions become quantifiable operational cost drivers.

Scope 2: Indirect Emissions from Purchased Electricity (Market-Based Method)

Microsoft reports 259,090 metric tons of CO_2e under Scope 2 (market-based) for FY 2024. These emissions reflect the environmental impact associated with the generation of purchased electricity used in Microsoft's global facilities and data centers. Although the company procures large volumes of renewable energy under power purchase agreements, its rapid expansion of energy-intensive cloud infrastructure continues to influence total Scope 2 emissions. Through managerial accounting, energy-related emissions are integrated into long-term investment decisions, enabling the company to evaluate trade-offs between cloud growth, renewable energy procurement, and decarbonization commitments. This supports Microsoft's strategic objective of achieving 100% renewable electricity across its operations.

Scope 3: Value-Chain Emissions

As with many global technology firms, Scope 3 represents Microsoft's dominant emission category. In FY 2024, Scope 3 emissions totaled 15,140,000 metric tons of CO_2e, accounting for more than 97% of the company's total carbon footprint. These emissions stem from upstream and downstream activities across the value chain, including manufacturing of devices by third-party suppliers, transportation and distribution, product use by customers, and end-of-life treatment. Microsoft employs advanced carbon accounting tools to quantify these emissions, following GHG Protocol methodologies for allocation, estimation, and boundary setting. The scale of Scope 3 emissions underscores the strategic importance of incorporating supplier performance metrics, lifecycle assessments, and product-design decisions into managerial accounting systems.

Microsoft's emissions data undergo independent third-party verification, most recently by Deloitte & Touche LLP, ensuring credibility and auditability. The company applies established recalculation policies in cases of methodological updates, acquisitions, divestitures, or expansion of reporting boundaries. This transparent methodological structure aligns with GHG Protocol's core principles - accuracy, consistency, completeness, and comparability - and strengthens the validity of Microsoft's carbon disclosures for both academic analysis and cross-company benchmarking.

Microsoft integrates GHG emissions into its internal management systems, treating CO_2 not only as an environmental metric but as a financially relevant variable that informs cost accounting, risk assessment, supply-chain strategy, capital budgeting, and long-term planning for cloud infrastructure. The company evaluates emissions intensity per revenue unit, models future carbon scenarios, and incorporates internal carbon fees into business-unit planning. This use of managerial accounting tools enables Microsoft to achieve a high degree of internal alignment between operational decisions and its long-term climate goals, including the commitment to become carbon negative by 2030. Microsoft demonstrates that integratting GHG emissions into financial and operational planning allows CO_2 to be treated as ameasurable economic variable, aligning sustainability goals with corporate strategy.

Despite reductions in Scope 1 and Scope 2 emissions, Microsoft faces persistent challenges in managing the scale and growth of Scope 3 emissions, which continue to dominate its overall carbon footprint. The company's rapid expansion in cloud computing and AI infrastructure further increases energy demand and upstream manufacturing emissions. Nevertheless, Microsoft's application of GHG Protocol accounting - combined with rigorous verification and integration into managerial accounting - provides a systematic foundation for identifying mitigation opportunities and guiding high-impact sustainability initiatives. The Microsoft case thus illustrates how carbon accounting frameworks can support managerial control mechanisms, enabling firms to balance operational growth with climate-related objectives.

2.3. Comparative Analysis: Apple vs. Microsoft GHG Protocol

A comparison of Apple and Microsoft provides insight into how different business models and managerial accounting frameworks affect the effeciency of greenhouse gas (GHG) management.

Apple and Microsoft, as two of the world's largest technology corporations, demonstrate sophisticated applications of GHG Protocol accounting principles; however, their emissions profiles and managerial responses reveal notable structural and strategic differences. These differences arise from their respective business models, supply-chain configurations, and managerial accounting systems used to monitor and reduce CO_2 emissions.

Apple and Microsoft both operate global infrastructures, yet the composition of their emissions differs substantially. Apple reports a reduction of over 60% in total emissions from its 2015 baseline, while Microsoft's emissions remain dominated by Scope 3, totaling over 15 million metric tons of CO_2e in FY 2024. Apple's emissions structure is strongly influenced by its manufacturing supply chain, but large-scale investments in supplier renewable energy programs (17.8 GW installed in 2024) have significantly mitigated upstream emissions. In contrast, Microsoft's cloud-based business model generates considerable downstream and upstream emissions related to data centers, semiconductor production, and product use.

Table 2 shows a comparative analysis of Apple and Microsoft according to the GHG protocol, including emissions by Scope category, application of management tools and startegic point focus.

Table 2 - Comparative Overview: Apple vs. Microsoft GHG Protocol

Category	Apple	Microsoft
Primary business model influencing emissions	Consumer electronics & vertically integrated supply chain	Cloud computing, AI infrastructure, hardware & software ecosystems
Scope 1 emissions	Low, declining due to electrification & facility efficiency	143,510 mt CO_2e (FY 2024) - facilities, data centers, fleets
Scope 2 emissions	Near zero; 100% renewable electricity	259,090 mt CO_2e (market-based, FY 2024); increasing energy demand
Scope 3 emissions	Largest share but mitigated through supplier renewable energy (17.8 GW in 2024)	Dominant category: 15,140,000 mt CO_2e (FY 2024)
Key managerial accounting tools	Carbon budgets, supplier scorecards, lifecycle analysis	Internal carbon fee, scenario modeling, emissions-intensity dashboards
Verification & transparency	GHG Protocol aligned, detailed reporting	Independent audit (Deloitte), recalculation policy, high transparency
Strategic focus	Supply-chain renewable energy & low-carbon materials	Cloud decarbonization, renewable procurement, carbon removal
Main challenges	High Scope 3 from manufacturing partners	Extreme Scope 3 dominance, rapid growth of cloud & AI demand

Source: Authors based on Apple (2025) and Microsoft (2025)

While both companies maintain rigorous control over Scope 1 and Scope 2 emissions, Apple's early transition to 100% renewable electricity across its corporate operations enabled near-complete elimination of Scope 2 impacts. Microsoft has made similar progress but faces larger absolute energy demand due to rapid expansion of cloud infrastructure, resulting in 259,090 mt CO_2e under Scope 2 (market-based) in FY 2024.

Both companies integrate carbon accounting into internal managerial decision-making, though the mechanisms differ in scale and scope. Apple employs carbon budgets, supplier scorecards, and lifecycle assessments as part of its managerial accounting system, enabling emissions to be treated as performance-based indicators influencing procurement and design decisions. Microsoft goes a step further by implementing an internal carbon fee, charged to business units based on their emissions. This approach operationalizes CO_2 as a financial variable, embedding emission costs directly into budgeting and planning processes.

In Apple's case, emissions accounting primarily enhances supplier management and product lifecycle optimization. For Microsoft, managerial accounting tools are more tightly connected to financial planning, scenario modeling, and cloud infrastructure investment decisions.

Apple has achieved measurable reductions in emissions through aggressive interventions in supplier renewable energy adoption, materials recycling, and product energy efficiency. Its long-term strategy centers on lowering upstream manufacturing emissions and minimizing downstream usage impacts through energy-efficient device design.

Microsoft, although committed to becoming carbon-negative by 2030, faces structural constraints due to the exponential growth of artificial intelligence and cloud computing. These sectors inherently require significant energy inputs and generate extensive supply-chain emissions. As a result, Microsoft's Scope 3 emissions - 15.14 million mt CO_2e in FY 2024 - represent its largest strategic challenge. Both firms have transparent reporting systems aligned with the GHG Protocol, but Apple demonstrates more pronounced reductions in absolute terms, while Microsoft exhibits strong methodological rigor and financial integration of carbon metrics.

The comparative analysis highlights that while both companies demonstrate strong alignment with the GHG Protocol, their managerial accounting applications diverge due to differing operational structures:

- Apple's decarbonization success is driven by supply-chain transformation, making managerial accounting a tool for operational control and sustainability performance evaluation.
- Microsoft's approach positions CO_2 as a financialized variable, internalized through carbon pricing mechanisms and embedded in budgetary control, but its emissions are more difficult to reduce due to the nature of cloud infrastructure and value-chain dependencies.

Both cases demonstrate that managerial accounting systems - when combined with standardized carbon reporting frameworks - serve as powerful tools for identifying emission hotspots, guiding investment decisions, and integrating sustainability metrics into corporate governance.

These comparisons highlight the importance of incorporating carbon metrics into management decision-making to drive both operational improvements and strategic sustainability outcomes.

Qu et al. (2022) demonstrates the application of Material Flow Cost Accounting (MFCA) within budgeting by developing an MFCA-Activity-Based Budget (ABB) model for a liqueur manufacturing company in China. The model integrates not only operational costs but also environmental flows, such as resource use, waste, and emissions, into the budgeting process. By doing so, managerial decisions incorporate both financial and ecological components, enabling managers to plan resources while considering emissions and environmental impacts. This case highlights how managerial carbon accounting can be directly applied to budget planning, linking operational and environmental management for improved sustainability performance.

A Spanish winery implemented Material Flow Cost Accounting (MFCA) to monitor material flows and CO_2 emissions across the entire production process, from raw grapes to the final bottled product. This approach allowed the company to quantify the carbon footprint at each production stage, enabling precise tracking and management of emissions. The results demonstrated that integrating carbon accounting into managerial decision-making not only reduced environmental impacts but also generated significant financial benefits, including lower energy consumption, more efficient processes, and improved collaboration with suppliers. Moreover, the introduction of MFCA shifted the organizational culture, increasing employees' awareness of CO_2-related costs and fostering proactive involvement in sustainability initiatives. The winery also optimized its procurement strategy, selecting packaging with lower carbon emissions, thereby aligning operational decisions with environmental objectives. This case illustrates how managerial carbon accounting can serve as an effective tool for both environmental management and operational decision-making (Marco-Fondevila et al., 2020).

Gibassier and Schaltegger (2015) present an in-depth case study of a multinational company implementing managerial carbon accounting (MCA) to integrate both product-level and organizational-level emissions. The study highlights how MCA enables internal managers to track and control CO_2 emissions, supporting informed decision-making for mitigation strategies. By combining different accounting approaches, the company improved the accuracy of emission data and enhanced internal communication regarding carbon performance. The case illustrates that managerial carbon accounting can serve not only as a measurement tool but also as a strategic instrument for guiding operational and investment decisions. Challenges such as varying data sources, emission factors, and system integration were addressed, demonstrating practical considerations for successful implementation. Overall, the study shows that MCA can bridge the gap between theoretical carbon accounting frameworks and real-world business practices, making it highly relevant for organizations seeking to reduce their carbon footprint effectively.

Deac (2013) examines three different accounting models employed by companies participating in an Emissions Trading Scheme (ETS): the cost model, the revaluation model, and the off-balance-sheet approach. The study demonstrates how the choice of accounting method impacts the balance sheet, income statement, and key financial indicators. While the focus is primarily on financial carbon accounting, the case highlights practical implications for decision-making and illustrates how accounting choices influence both reporting and internal management of emissions. This study is particularly relevant for understanding the distinction between financial carbon accounting (FCA) and managerial carbon accounting (MCA), showing that methodology affects not only compliance and external reporting but also internal strategy and resource allocation.

These case studies from literature confirm that managerial accounting effectively bridges operational and financial decision-making with environmental impact, providing practical guidance to organizations seeking to reduce their carbon footprint.

CONCLUSION

The findings of this research demonstrate that managerial accounting plays a pivotal role in modern corporate strategies aimed at controlling and reducing CO_2 emissions. The application of the Greenhouse Gas (GHG) Protocol, as a globally recognized standard for quantifying and categorizing emissions, enables companies to establish transparent, comparable, and reliable carbon data. However, the true strategic value of the GHG Protocol emerges only when emissions information is fully integrated into internal managerial accounting systems - particularly within planning, control, budgeting, investment decision-making, and performance evaluation processes.

The case studies of Apple and Microsoft illustrate that organizations that systematically apply the GHG Protocol and embed carbon metrics into their managerial tools achieve greater accuracy in identifying emission sources and stronger effectiveness in implementing decarbonization strategies. Apple has achieved substantial progress through supply chain transformation, investments in renewable energy, and the incorporation of carbon indicators into product design and procurement processes. Microsoft, despite advanced reporting mechanisms and an internal carbon fee system, continues to face structural difficulties driven by the rapid expansion of energy-intensive cloud and AI infrastructure. These differences highlight that the success of emission-reduction initiatives depends largely on an organization's ability to align managerial focus with its dominant sources of carbon impact - whether in the supply chain, operational logistics, or downstream product use.

Overall, the analysis confirms that managerial accounting serves as a vital mechanism for operationalizing sustainability objectives. It enables CO_2 - treated as a quantified and financially relevant variable - to become an integral part of business decision-making, rather than a stand-alone environmental reporting requirement. The introduction of internal carbon budgets, carbon pricing mechanisms, emission-cost analyses, and the integration of carbon indicators into strategic planning empowers organizations to enhance efficiency, mitigate risks, and build long-term competitive advantages in an environment where decarbonization is becoming a core business imperative.

Accordingly, this study contributes to understanding how the GHG Protocol can function as a foundation for managerial accounting and demonstrates how different corporate structures and business models shape the opportunities and limitations associated with emission reduction. The empirical insights from the case studies suggest that future research should focus on developing advanced models of internal carbon cost allocation, evaluating the effectiveness of emission-reduction strategies across industries, and assessing the implications of digitalization and artificial intelligence on the evolution of corporate carbon footprints.

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Product quality and safety management in the automotive industry

Upravljanje kvalitetom i bezbednošću proizvoda u automobilskoj industriji

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Abstract: The automotive industry is one of the most complex industries, where quality and safety are key success factors. This paper analyses modern quality and safety management systems in the automotive industry, including IATF 16949, ISO 9001, ISO 45001, as well as methods and tools for process control and improvement (FMEA, SPC, APQP, PPAP, DMAIC). A special focus is placed on empirical case studies with quantitative results, which show the practical benefits of implementing these methods.

Keywords: safety, quality, management, innovation, technology.

Sažetak: Automobilska industrija je jedna od najsloženijih industrija, gde su kvalitet i bezbednost ključni faktori uspeha. Ovaj rad analizira savremene sisteme upravljanja kvalitetom i bezbednošću u automobilskoj industriji, uključujući IATF 16949, ISO 9001, ISO 45001, kao i metode i alate za kontrolu i unapređenje procesa (FMEA, SPC, APQP, PPAP, DMAIC). Poseban fokus je stavljen na empirijske studije slučaja sa kvantitativnim rezultatima, koje pokazuju praktične koristi od primene ovih metoda.

Ključne reči: bezbednost, kvalitet, upravljanje, inovacija, tehnologija..

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INTRODUCTION

The automotive industry is a complex and dynamic sector that requires constant compliance with strict quality and safety standards. The introduction and implementation of quality management systems that include ISO standards and IATF 16949, as well as quality control methods such as APQP, FMEA, SPC and PPAP, enable vehicle manufacturers to achieve high quality standards, reduce the number of errors and improve overall business efficiency. It is one of the most complex and dynamic industrial sectors, which combines engineering, high-tech production, global supply chains and extremely strict requirements for quality and safety. Product safety in this industry is not only a technical issue, but also an economic, social and ethical one. Design or manufacturing errors can lead to massive vehicle recalls, loss of reputation, serious financial consequences and, most importantly, endangering people's lives and health.

Historically speaking, the first steps in the field of safety management in the auto industry appeared in the 1950s and 1960s, in the period when production growth and mass motorization led to a sharp increase in the number of traffic accidents. It was then that the systematic introduction of seat belts, later airbags, and the first crash test procedures began. With the advent of electronics in vehicles in the 1980s and 1990s, safety challenges became even more complex, as errors in software and electronic systems could directly affect vehicle handling.

Today, in the era of digitization and autonomous vehicles, product safety includes not only mechanical reliability and passive protection measures, but also functional safety of electronic systems, as well as cyber-security. For example, systems like ADAS (Advanced Driver Assistance Systems) significantly reduce the risk of traffic accidents, but at the same time open up new questions: how to ensure the vehicle's resistance to hacker attacks and how to define liability in case of system failure in autonomous driving.

In addition to technical challenges, the introduction of increasingly stringent international standards such as ISO 26262 and IATF 16949 has led to global harmonization of design, manufacturing and quality control processes. These standards are not just administrative requirements – they are a framework for systematic risk management and ensuring that every vehicle component meets the highest safety criteria.

Quality is key to success and competitiveness in the business environment. In the automotive industry, precision, reliability and safety are extremely important, which is why quality management becomes one of the main pillars of sustainable development and customer satisfaction. Systematic quality management includes a series of activities and tools aimed at improving product and process performance, reducing costs and increasing competitive advantage.

In addition, quality management in the automotive industry aims not only to meet customer requirements, but also to achieve long-term stability and trust in the market. Product quality directly affects brand image, consumer loyalty, and a company's ability to adapt to rapid technological changes and increasing market expectations.

Today's automotive companies are increasingly integrating digital technologies, automation and artificial intelligence into their quality management systems, enabling faster data analysis, more accurate problem detection and more efficient decision-making. That is why quality becomes a strategic resource that enables long-term growth, innovation and sustainability in the globally competitive automotive industry.

1. DETERMINANTS OF QUALITY MANAGEMENT

Quality management is one of the most important parts of business. By introducing quality management systems and methods, organizations can achieve significant benefits that are reflected in increased productivity, cost reduction, customer satisfaction and loyalty, as well as maintaining high standards of product and service quality. Quality control is an indispensable part of quality management and includes activities aimed at fulfilling quality requirements through inspection, testing and statistical process control.

According to ISO (International Standardization Organization), quality represents adaptation and compliance with the requirements set by the norm itself, but also by customers (Barbosa, 2021). Quality, as applied to an object (product, service, process), is defined as "the degree to which a set of inherent characteristics (attributes) of an object satisfy a set of requirements."

Therefore, the quality of the object is determined by comparing a predefined set of characteristics with a set of requirements. If these characteristics are in accordance with the requirements, high quality is achieved; if they are not, there is a low or poor level of quality (ITRC, 2024).

Over the past decades, quality has become an important interest for both practitioners and researchers, thanks to its strong impact on organizational performance, cost reduction, customer satisfaction and loyalty, as well as profitability. Quality is difficult to define unambiguously because it depends on the context, especially in service activities, and is often subjectively evaluated based on various parameters such as industry, customer needs, organizational culture, time, etc. (Skoko, 2000).

2. QUALITY ASSURANCE

The quality assurance process helps a company to ensure that its products meet the quality standards set by the company itself or the industry. Quality assurance (QA) can also be understood as a process within a company aimed at improving product quality (ProductPlan, 2024). Quality assurance (QA) can be defined as a clear and concise framework that encompasses every part of the organization's business, not just quality management, which has a significant role in its constant and permanent improvement. The QA team participates in all stages of development – from production and testing to packaging and delivery (ISO - Quality assurance, 2024).

The primary goal of quality assurance is to reduce the risk of defects and resolve errors as early as possible in the value chain. In this way, the number of defects that are discovered in the final phase of the inspection, when correction is more difficult and expensive, is reduced. Thanks to a well-organized quality assurance system, the earlier a defective element is identified and corrected, the less time and energy is wasted, which reduces costs and preserves the brand's reputation. In practice, this implies the establishment of technical and management processes for effective monitoring and improvement of the quality of products or services. QA also ensures compliance with industry standards and regulations, which gives organizations a competitive advantage and directly contributes to greater profitability (ISO - Quality assurance, 2024). Quality assurance retains its effectiveness when implemented in accordance with a set of best practices.

Table 1. Best practices in quality assurance

Best practices	Description	Performance
Commitment and support from leadership	Quality assurance requires unwavering commitment and support from company leadership.	Creates a culture of quality within the organization.
Detailed quality planning	Integrating quality into product design and process development through careful planning.	Improves product design and process efficiency.
Training	Education of employees on the principles and procedures of quality assurance.	Ensures that all employees are aware of and able to apply quality procedures.
Documentation	Precise documentation of all processes and controls.	Maintains consistency and transparency in processes.
Cooperation and communication	Active cooperation and clear communication between teams in all segments.	It encourages teamwork and improves mutual communication.
Ongoing audits and risk assessment	Regular audits and constant assessment of potential risks.	It enables early identification and risk reduction.
Tools for statistical quality control	Application of statistical control tools to ensure quality.	Ensures consistent product quality.
Checking the effectiveness of corrective/preventive measures	It reduces the number of recurring problems and preventive measures.	It reduces the number of repetitive corrective and preventive actions.
Continuous measurement and analysis of quality data	Constant monitoring and analysis of quality data.	It enables continuous quality improvement.
Identifying and replicating best practices	Recognition of best practices and their repetition in all processes.	Ensures that best practices are continuously implemented and improved.

Source: modified in accordance with (John, 2012)

Detailed quality planning ensures the integration of quality into all phases of design and process development, thereby improving product efficiency and performance. Accurate documentation of all processes and controls helps maintain consistency and transparency, which is essential for quality monitoring and evaluation. Collaboration and communication between teams foster teamwork and improve overall coordination within the organization. Regular audits and risk assessment allow early recognition and reduction of potential problems, thereby reducing quality-related risks. The application of statistical quality control tools ensures consistency in production, while the validation of corrective and preventive measures reduces the number of recurring problems. Continuous measurement and analysis of data enables continuous quality improvement, while recognition and repetition of best practices ensures that effective methods are applied and further developed.

2.1. Quality control

Quality control (QC) consists of that "part of quality management aimed at meeting quality requirements" (ISO 9000). While quality assurance refers to the way processes are designed and implemented, that is, to the way a product is made, quality control is more about the inspection aspect of quality management. Inspection is the process of measuring, examining or testing one or more characteristics of a product or service and comparing them to specified requirements to determine compliance. Products and processes can be reviewed to ensure that they are correct and meet requirements (ITRC, 2024).

Quality control includes a series of measures and procedures that are carried out in order to ensure the maintenance and improvement of product quality in accordance with the set standards, as well as to remove or reduce detected errors. The goal of quality control is to ensure the consistency of the product and the production process, as well as their compliance with customer requirements (Walker, 2001).

Quality control components may include (Simplilearn, 2023):

- *Inspection:* regular examination of products, materials or services in order to determine defects, non-conformities or deviations from quality standards.
- *Testing:* conducting various tests and measurements to evaluate the performance, functionality or characteristics of products or services.
- *Statistical Process Control (SPC):* the use of statistical techniques to monitor and control manufacturing processes so that they remain within acceptable quality limits.
- *Documentation and records:* keeping detailed records of inspections, testing and corrective actions to maintain traceability and accountability.
- *Corrective actions*: implementation of appropriate measures to solve observed quality problems and prevent their recurrence.
- *Training and education:* providing employees with the necessary knowledge and skills to effectively maintain quality standards.
- *Continuous improvement:* constant analysis of data and feedback to identify areas for improvement and improve the overall quality management system.

Table 2. Quality control components

Quality control components	**Description**	**Performance**
Inspection	Regular testing of products, materials or services to determine defects, non-conformities or deviations from quality standards.	Ensures products meet or exceed quality standards.
Testing	Conducting various tests and measurements to evaluate the performance, functionality or characteristics of products or services.	Identifies and corrects potential problems before they reach the customer.
Statistical Process Control (SPC)	Using statistical techniques to monitor and control manufacturing processes, ensuring they remain within acceptable quality limits.	Keeps process variations under control and reduces errors.
Documentation and records	Keeping detailed records of inspections, testing and corrective actions taken to maintain accountability.	Provides accountability for all quality-related procedures.
Corrective action	Implementation of appropriate measures to solve all recognized quality problems and prevent their recurrence.	It reduces the frequency of recurring problems and improves overall quality.
Training and education	Providing employees with the necessary skills and knowledge to effectively maintain quality standards.	Ensures that employees are competent in maintaining quality.
Continuous improvement	Constant analysis of data and feedback to identify areas for improvement and improvement of the overall quality management system.	It enables continuous improvement of products and processes.

Source: modified in accordance with Simplilearn (2023)

Quality control is closely related to quality assurance. While QC focuses on detecting and correcting defects, QA focuses on their prevention through establishing stable processes and procedures. Quality testing is usually an integral part of every stage of the manufacturing or business process. Employees often begin testing using samples from the production line, finished products, and raw materials (Simplilearn, 2023).

Testing during different stages of production can help identify the cause of problems and define corrective measures to prevent them from recurring. Customer service reviews, questionnaires, surveys, inspections and audits are just a few examples of quality testing procedures that can be applied in non-manufacturing businesses as well. A company may use various procedures or techniques to ensure that the final product or service is safe, compliant with regulations, and in line with consumer requirements (Simplilearn, 2023).

Continuous improvement involves constant analysis of data and feedback to identify areas for improvement and improvement of the entire quality management system. Although the terms quality control and quality assurance are sometimes used interchangeably, there are clear differences between the two. Quality control emphasizes quality criteria, that is, checking whether products conform to specifications, while quality assurance includes all processes and activities that prove that quality requirements are met.

3. QUALITY STANDARDS IN THE AUTOMOTIVE INDUSTRY

Quality standards in the automotive industry represent regulations and requirements related to various segments of this industry, such as safety, emissions, quality and performance, which guide the production and use of automobiles. These standards are constantly evolving to accommodate new technologies, including electric vehicles (EVs) and autonomous driving systems.

Standards organizations collaborate with industry experts, researchers, and regulatory agencies to develop guidelines and requirements that address specific safety, performance, and interoperability challenges brought about by automotive innovation (Core Automotive Standards, 2024).

4. ISO STANDARDS

Internationally recognized ISO certificates are widely used and are useful in almost every industry. Organizations operating in the automotive industry represent one of the main drivers of industrial and economic development in any country. Obtaining ISO certification is an option available to all industries, but in the automotive industry it has special significance.

ISO standards for the automotive industry define requirements for a standardized management system that ensures consistency in the delivery of quality products and services to customers. Automotive companies have a strong need to acquire internationally recognized ISO certificates in order to prove that they have an efficient and effective quality management system.

Table 3. ISO standards in the automotive industry

Quality control components	Description	Performance
ISO 9001	An internationally recognized norm that provides a framework for implementing a quality management system (QMS) in an organization	Ensures that product or service quality meets customer expectations
ISO 14001	A globally recognized norm that provides a framework for implementing an environmental management system (EMS) in an organization	It helps reduce the organization's impact on the environment
ISO 45001	A universally recognized standard that provides a framework for the implementation of an occupational health and safety management system (OHSMS)	Demonstrates commitment to the safety and well-being of employees, clients and contractors
ISO 27001	Standard for Information Security Management Systems (ISMS)	It demonstrates the ability to handle valuable data and information and helps manage cyber-attacks
ISO 50001	Standard for Energy Management Systems (EnMS)	It helps to optimize energy consumption and reduce costs, while preserving environmental resources

Source: modified in accordance with (ISO Certifications, 2024)

ISO standards for the automotive industry are extremely cost-effective because they allow the assessment and identification of all risks associated with processes, as well as finding ways to mitigate them. Also, ISO certification reduces the need for process reconstruction within the organization, which further contributes to cost reduction (ISO Certifications, 2024).

ISO certifications enable automotive companies to optimize their business operations, ensure a high level of quality and safety, and increase their competitiveness in the market (ISO Certifications, 2024). Possession of ISO certification helps the automotive sector in gaining global recognition, improves organizational income and enables the realization of maximum profit, which brings significant benefits for the organization itself (ISO Certifications, 2024).

5. IATF STANDARDS

The IATF 16949 standard provides guidance and tools for companies and organizations that want to ensure that their products consistently meet customer requirements and that quality and customer satisfaction are continuously improved. The requirements for certification according to IATF 16949 are defined in the 2016 revision of 5 rules for achieving and maintaining IATF recognition (IATF 16949 - Automotive QMS, 2024).

The IATF 16949 standard is used together with ISO standards:

- IATF 16949 – additional requirements for the automotive industry in the quality management system.
- ISO 9001 – basic requirements of the quality management system.
- ISO 9000 – basic terms and terminology.
- ISO 9004 – efficiency and effectiveness of the quality management system.
- ISO 19011 – guidelines for internal and external audits of quality management systems.
- ISO 31000 – principles and guidelines for risk management.

IATF 16949 is a quality management system standard specially developed for the automotive sector. This standard builds on ISO 9001, expanding it by integrating requirements and prerequisites for automotive manufacturers and suppliers. Compliance with IATF 16949 demonstrates a commitment to excellence and a commitment to customer satisfaction (Reis, 2024).

6. SYSTEMATIC PRODUCT QUALITY PLANNING (APQP)

Complex products and supply chains present numerous challenges, especially when launching new products. Systematic product quality planning (APQP) is a structured process aimed at ensuring customer satisfaction with new products or processes (Advanced Product Quality Planning, 2024).

APQP has a long history and various forms of application. Originally known as Advanced Quality Planning (AQP), APQP is used by advanced companies to ensure quality through planning. Ford Motor Company published the first AQP manual for suppliers in the early 1980s, helping to develop controls for the prevention and detection of new product defects. Later, North American automakers jointly developed the APQP process in 1994, and it was updated in 2008. APQP brings together the common planning activities required by all car manufacturers into a single process. Suppliers use APQP to successfully validate new products and processes and drive continuous improvement.

Within APQP, the use of a number of tools and techniques is described, and the most important core tools include:

- FMEA – Analysis of failure modes and their consequences.
- MSA – Analysis of measurement systems.
- SPC – Statistical process control.
- PPAP – Manufacturing Parts Approval Process.

Using these tools is essential for compliance with IATF 16949 (Advanced Product Quality Planning, 2024).

APQP facilitates communication between the supply chain and the organization/customer. Requirements are converted into more detailed specifications and clarified as the process progresses. Also, APQP monitors product or process changes and ensures that the risk of change is successfully managed, preventing problems caused by the changes.

6.1. Failure and Consequence Analysis (FMEA)

FMEA (Failure Mode and Effect Analysis) is a method for analysing errors that occur under certain conditions and their consequences. The main goal of the analysis is to identify and assess potential errors and their causes, and to propose solutions to reduce or completely eliminate those errors.

The goal is to achieve error-free production, thereby improving product reliability and safety and customer satisfaction. The FMEA is treated as a living document, which means that it is continuously updated with new data, especially in case of changes in the production process or design.

The implementation of the FMEA analysis is performed according to the predefined form of the FMEA report, with the calculation of the priority risk number (RPN - Risk Priority Number).

RPN is calculated by multiplying three indices:

- S – seriousness;
- O – frequency;
- D – disclosure.

Each index has values from 1 to 10, so RPN can range from 1 to 1000. Corrective measures are applied when RPN exceeds 100 or when any of the indices (S, O, D) exceeds 8.

Table 4. Error severity level

Level	Description
1, 2, 3	A slight error is very unlikely to cause any noticeable effect on the system properties. The customer probably won't notice the mistake. A low severity level causes little disturbance. The customer is likely to notice only a slight degradation of properties.
4, 5, 6	A medium level of error severity that causes some customer dissatisfaction; the customer feels uncomfortable or bothered.
7, 8, 9	A high degree of customer dissatisfaction due to the nature of the error, for example, the inability to operate the system.
10	Extremely high severity, when the error involves potential security-related consequences.

Source: modified in accordance with ASQ (2024)

7. SYSTEMATIZATION OF RISKS AND IDENTIFICATION OF CRITICAL COMPONENTS

By applying methods such as FMEA, FTA and HAZOP, combined with modern regulatory frameworks (ISO 26262 and IATF 16949), it is possible to gain in-depth insight into the ways in which the industry manages product safety. FMEA and FTA analyses show that the largest number of critical failures are concentrated in the domain of braking systems, steering and electronic control units (ECU). In practice, manufacturers such as Toyota and GM use FMECA to quantify which components require redundant mechanisms (e.g. dual brake pressure sensors). This leads to a reduction in the probability of catastrophic failures from $>10^{-3}$ to $<10^{-6}$ per vehicle-year.

Table 5. Comparative analysis of security management methods

Method	Advantages	Disadvantages	Application examples
FMEA	Systematic, prevention of failure	Subjective assessment of RPN	Brakes, batteries
HAZOP	Team approach, scenarios	Time-consuming	Fuel systems
FTA	Visualization of causes	Complexity in large systems	Management systems
Crash test	Real empirical data	Expensive, time intensive	EuroNCAP tests
ADAS	Reducing the number of accidents	Costs, cyber security	Automatic braking

Source: modified in accordance with Stamatis (2003), Kletz (1999), Vesely et al., (1981), Lund (2002), Winner et al., (2016).

8. INTEGRATION WITH ISO 26262 AND IATF 16949

With the introduction of the ISO 26262 standard, safety assessment is no longer an ad-hoc activity, but is integrated into the entire vehicle life cycle. The results show that organizations that have fully aligned their development processes with ISO 26262 record a 30-40% reduction in the number of "recalls" over a 5-year period. Similarly, IATF 16949 ensures that every step in production is tracked through continuous improvement and system traceability.

9. ADVANCED ANALYTICS AND DYNAMIC RISK MODELLING

Combining FTA with Bayesian networks enables dynamic updating of risk assessment in real time. For example, in an autonomous driving system, where the software continuously "learns" new patterns, the Bayesian FTA model allows the risk of pedestrian misidentification to be estimated with greater accuracy than in classical FTA. Results from experimental studies show that this approach can reduce the false alarm rate by 25%, while maintaining the same critical incident detection rate.

10. LIMITATIONS OF TRADITIONAL METHODS

Although FMEA and FTA are proven effective, they are not sufficient for analyzing systems using machine learning and artificial intelligence. These systems change behavior over time and thus escape classical risk analysis approaches. In this context, new methodologies such as Safety of the Intended Functionality (SOTIF - ISO/PAS 21448), which expand ISO 26262 and deal with the limitations of AI systems, are increasingly being developed.

11. PRACTICAL EFFECTS IN INDUSTRY

Companies that consistently apply risk management methodologies see significant improvements:

- reducing the number of reported incidents by customers by 20-30%,
- shortening the "name-to-market" cycle thanks to early identification of errors,

- improved cooperation with suppliers through standardized protocols.

These results confirm that safety is not only a regulatory obligation, but also a competitive advantage. In the era of autonomous vehicles and electric mobility, risk management is becoming one of the main factors of consumer trust and purchasing decisions.

Table 6. Comparison of risk management methods (FMEA, FTA, HAZOP)

Method	Approach	Advantages	Disadvantages	Typical usage in automotive industry
FMEA	"Bottom-up" – from components to the system	Early identification of failures. Risk Quantification (FMECA). Clear structure.	Subjective assessment of the severity of the failure. Can ignore interactions between subsystems.	Analysis of the brake system, ECU module, sensors.
FTA	"Top-down" – from the peak event to the causes	Visualization of cause and effect relationships. Logical analysis (AND/OR). Enables quantitative calculations.	Requires detailed data. Complex application in large systems.	Analysis of failure scenarios in ADAS systems.
HAZOP	Team analysis with the help of "guide words"	Multidisciplinary approach. Identification of operational deviations. Good for processes and battery chemistry.	Very time-consuming. Results depend on team experience.	Battery charging process, thermal risk management.

12. OTA UPDATES

Tesla revolutionized the automotive industry by introducing the concept of Software-Defined Vehicles and implementing Over-The-Air (OTA) updates. This technology allows software updates, enhancements and new features to be delivered directly to the vehicle via the Internet, without the need for service visits. In this way, Tesla has transformed the way safety, reliability and functionality of vehicles are maintained in real time.

OTA updates are a huge step forward in crisis management and potential bug fixes. While traditional recall processes require huge costs and logistical efforts, Tesla has shown that it is possible to introduce improvements to millions of vehicles worldwide within hours. Examples include correcting the automatic braking software and optimizing battery performance, which otherwise required physical interventions.

Apart from practical advantages, OTA systems have also created a new paradigm in user experience. Customers of Tesla vehicles see their vehicles as "living products" that are constantly being upgraded, similar to smartphones. This increases customer satisfaction, but at the same time imposes new challenges in the field of cyber security.

Namely, the more vehicles are connected to the Internet and rely on software, the greater the risk of potential hacker attacks. Experts point out that it is necessary to implement multi-layered protection systems, including communication encryption, regular vulnerability testing and isolation of critical functions such as brake control and ADAS systems. Despite these challenges, Tesla has set a new standard in the industry. Today, many manufacturers, including BMW, Mercedes and Volkswagen, follow this model and introduce their own OTA systems. This clearly shows that OTA is not a trend but the future of the automotive industry, with the potential to significantly reduce accidents, improve crisis response and increase vehicle life. Tesla thus demonstrated how software innovation can become a key component in vehicle safety management. Although cyber security challenges are increasing, OTA systems remain a powerful tool for continuous improvement in security and quality.

13. FUTURE CHALLENGES AND PERSPECTIVES

The auto industry is entering a phase of deep transformation driven by global trends of electrification, digitalization and increasingly strict regulations. Product safety management is becoming increasingly complex because it is no longer enough to ensure mechanical reliability. Modern vehicles increasingly combine software, communication networks and artificial intelligence algorithms, so safety must be viewed from a much broader perspective.

One of the biggest challenges relates to the safety of electric vehicles. A key concern centers on lithium-ion batteries, which can be susceptible to overheating and a "thermal runaway" effect that can lead to fire or explosion. Numerous reports of fires during charging or after crashes, including the Tesla Model S and Hyundai Kona, show that this risk is real. Although regulations such as UNECE R100 and ISO 6469 already exist, the improvement of standards and new technological solutions such as solid electrolytes or advanced cooling systems are needed.

Autonomous vehicles bring new perspectives in reducing human-caused accidents, but they also open up a number of unresolved issues. Classical risk analysis methods are often not sufficient to assess the functional security of machine learning algorithms. In addition to the technical challenges, there are also ethical dilemmas: how will the vehicle act in the inevitable situations where it has to choose between different forms of damage? These issues, known as the "trolley problem", are becoming the subject of regulatory debates in different countries. The question of legal responsibility in the event of an accident remains open: is the manufacturer, the developer, the owner or the vehicle itself to blame as an "autonomous agent"?

With the growing number of connected vehicles, a new dimension is emerging - cyber security. Vehicles today contain more than 100 million lines of code, making them vulnerable to hacker attacks. The Jeep Cherokee takeover demonstration in 2015 showed how serious the consequences of possible vulnerabilities are. OTA updates, while extremely useful for quick fixes, also become a potential channel for intrusion. In this context, new standards appear such as ISO/SAE 21434, which defines the principles of cyber-engineering in cars.

Table 7. Regulations by region

Region	Key standards	Notes
EU	ISO 26262, UNECE	A single European framework
USA	FMVSS standards	Strict federal regulation
Japan	MLIT	Combination of national and international rules

Source: modified in accordance with ISO (2018), IATF (2016)

The rise of artificial intelligence brings another dimension of challenge. Algorithms for recognizing pedestrians, signalling and the behaviour of other road users must be trained on millions of scenarios. At the same time, the problem of transparency and explainability of AI decisions becomes critical for gaining public trust. The European Union's Horizon 2030 research programs are already investing in the development of explainable artificial intelligence, while companies such as Tesla and Waymo are seeking to develop systems that can learn in real time. All this requires a new generation of test protocols and global standards.

Another significant challenge is the diversity of regulations by region. While the European Union insists on UNECE regulations, the United States relies on FMVSS, and Japan on a combination of national and international standards. For global manufacturers, this means increased costs and the risk of non-compliance. The future period is likely to bring attempts at harmonization, but political and economic interests make the process slow and uncertain.

Summarizing the above, the future of safety and quality management in the automotive industry will be determined by a combination of technological innovation, global regulations and ethical standards. The integration of electric mobility, autonomous driving, cyber-protection, environmental sustainability and artificial intelligence into a single system is not only a recommendation, but a prerequisite for comprehensive security. Only a multidisciplinary approach in which engineers, lawyers, ethicists and political actors collaborate can ensure that vehicles are safe, reliable and accepted by society.

14. QUALITY STANDARDS FOR CAR ELECTRONICS

The development and production of automotive electronics require high quality standards to ensure the reliability, longevity and safety of the vehicle. Today's cars contain advanced electronic systems that manage a variety of functions – from the engine and powertrain to infotainment systems, communications and safety features. All components must work flawlessly in conditions of extreme temperatures, vibrations and humidity, which places special demands on quality and reliability.

In order to ensure that the electronic components meet the high requirements, specific industry standards have been developed and applied throughout the entire manufacturing and testing process. The standards ensure compliance with quality requirements and help manufacturers meet consumer expectations for long-term and reliable vehicle performance.

Quality standards for automotive electronics are key to ensuring vehicle reliability, longevity and safety. Given the increasing complexity of automotive electronics, which includes advanced control, communication, safety and driver assistance systems, manufacturers must meet strict industry standards to meet consumer expectations and regulatory requirements.

Industry quality standards such as IATF 16949, AEC-Q100 and AEC-Q200 ensure that components undergo rigorous testing and meet the highest reliability criteria before being installed in vehicles. These standards include a series of special tests, including early failure rate and temperature cycling tests, to ensure component longevity and reliability.

Quality is not only a goal, but also a principle that guarantees long-term consumer satisfaction and the success of manufacturers in the fast-changing and demanding market of the automotive industry.

CONCLUSION

The analysis of product safety management in the auto industry shows that it is an extremely complex and multidisciplinary process that exceeds the framework of classical engineering. Modern vehicles are no longer just mechanical products, but sophisticated systems in which electronics, software, communication networks and artificial intelligence algorithms intertwine. That is why security must be seen as an integral combination of technical, organizational, regulatory and ethical factors.

Through a review of key methods such as FMEA, HAZOP and FTA, it is shown that systematic risk analysis techniques remain the basis for failure prevention and identification of critical points in vehicle design. Crash test procedures and the development of ADAS systems prove that traditional and innovative methods must work synergistically: the former as a measure of passive protection, and the latter as a means of active prevention. The ISO 26262 and IATF 16949 standards, as a global framework, ensure that these methods are integrated into all phases of the vehicle's life cycle - from design to use.

Quality is a fundamental part of business that significantly affects competitiveness, customer satisfaction and long-term sustainability of organizations. Quality management is a process that encompasses all business segments. Through quality management systems, organizations improve their products and services, optimize operations, reduce costs and increase productivity.

There are various quality management systems and standards, such as ISO 9001, IATF 16949 and AEC-Q100, that enable organizations to deliver products and services that meet or exceed customer expectations. These standards also help reduce risk, increase efficiency and ensure compliance with regulatory requirements.

Quality assurance focuses on preventive measures and process standards, while quality control deals with the inspection and correction of potential defects in products or services. In the automotive industry, the IATF 16949 and AEC-Q100 standards are particularly important, as they set high requirements for the quality and reliability of components and systems. The standards ensure that the products are tested under the strictest conditions, thus guaranteeing their longevity and safety.

The qualification of components according to these standards includes a series of tests that confirm that the components can withstand extreme conditions during use. The application of advanced tools and techniques, such as APQP, FMEA, MSA, SPC and PPAP, is essential to maintain quality in automotive manufacturing. These tools enable accurate planning, monitoring and quality improvement, reducing errors and increasing customer satisfaction. High quality standards and rigorous tests ensure that car components can withstand even the most demanding conditions.

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Rare Earth Elements Technology

Tehnologija retkih zemnih elemenata

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Abstract: Rare Earth elements (REE) present the group of lanthanides. REEs are divided into two subgroups: 1) *cerium* - lanthanum, cerium, praseodymium, neodymium, promethium, samarium, and europium (the latter is sometimes included in the yttrium subgroup); 2) *yttrium* - gadolinium, terbium, dysprosium, holmium, erbium, thulium, yttrium and lutetium. The terms "light lanthanides" (from lanthanum to gadolinium) and "heavy lanthanides" (from terbium to lutetium) are also accepted in the literature. Among the lanthanides, the most common are lanthanum, cerium, and neodymium. Cerium is more abundant in the Earth's crust than tin. Yttrium is more abundant than lead. Less common are praseodymium, samarium, gadolinium, dysprosium, erbium, and ytterbium. The rarest are europium, terbium, holmium, thulium, and lutetium. REEs are present in significant concentrations in various complex ores containing thorium, titanium, niobium, and other elements. REEs play very important role in the electronics, radio engineering, laser technology, nuclear engineering, chemical industry and non-ferrous engineering.

Keywords: rare earth elements, lanthanides, methods for separation, application of rare earth elements.

Sažetak: Retki zemni elementi (RZE) predstavljaju grupu lantanida. RZE su podeljeni u dve podgrupe: 1) *cerijum* - lantan, cerijum, prazeodimijum, neodimijum, prometijum, samarijum i evropijum (ovaj poslednji se ponekad uključuje u podgrupu itrijuma); 2) *itrijum* - gadolinijum, terbijum, disprozijum, holmijum, erbijum, tulijum, itrijum i lutecijum. Termini „laki lantanidi" (od lantana do gadolinijuma) i „teški lantanidi" (od terbijuma do lutecijuma) su takođe prihvaćeni u literaturi. Među lantanidima, najčešći su lantan, cerijum i neodimijum. Cerijum je zastupljeniji u Zemljinoj kori od kalaja. Itrijum je zastupljeniji od olova. Manje česti su prazeodimijum, samarijum, gadolinijum, disprozijum, erbijum i iterbijum. Najređi su evropijum, terbijum, holmijum, tulijum i lutecijum. RZE su prisutni u značajnim koncentracijama u različitim kompleksnim rudama koje sadrže torijum, titanijum, niobijum i druge elemente. RZE igraju veoma važnu ulogu u elektronici, radiotehnici, laserskoj tehnologiji, nuklearnoj tehnologiji, hemijskoj industriji i mašinstvu obojenih metala.

Ključne reči: retkozemni elementi, lantanidi, metode separacije, primena retkozemnih elemenata.

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INTRODUCTION

The use of rare earth elements dates back to the second half of the last century. At that time, they were used in the production of gas mantles and caps for gas lanterns. In the last decade of the 20th century, numerous studies have been conducted in various countries, highlighting the highly promising use of rare earth element compounds and the metals themselves in ferrous and non-ferrous metallurgy, the silicate industry, radio and electrical engineering, quantum electronics, nuclear engineering, and other fields. The introduction of new modern methods, such as ion exchange and extraction, into the separation of rare earth elements has made it possible to obtain relatively pure individual compounds and, in many cases, utilize their unique properties (Atwood, 2013).

Numerous articles in international literature are devoted to the use of rare earth elements and their compounds. These articles examine in detail the efficiency and feasibility of using rare earth elements. Only the most important and interesting areas of application are listed below (Czekalla et al., 1996).

1. METHODOLOGY

Due to the extreme similarity of rare earth elements' properties, their separation and the production of compounds of individual elements is one of the most challenging tasks in chemical engineering. Yttrium elements are particularly difficult to obtain, as the differences in properties are more pronounced in cerium elements. Furthermore, some cerium elements possess a pronounced variable valence, which makes it possible to exploit this and isolate them using purely chemical methods.

Currently, all rare earth elements without exception have been obtained in high purity. Such advances in the separation of rare earth elements have been achieved through the use of modern separation methods - ion exchange and extraction.

Despite the abundance of different methods for separating rare earth elements, they all share a common goal of initially isolating the most abundant elements, Ce, La, and Y, present in predominant quantities. Typically, cerium is removed after preliminary oxidation to Ce(IV); lanthanum is then removed. Yttrium is first separated from yttrium subgroup concentrates, followed by the production of concentrates and then pure individual REE compounds. The following methods are applicable for REE separation: 1) fractional crystallization and fractional precipitation; 2) selective oxidation-reduction; 3) thermal decomposition of salts; 4) ion exchange; 5) extraction (Krishnamurthy & Gupta, 2004; Powell, 1970).

Fractional crystallization method has been proposed for very different compounds. However, many of them have lost practical significance due to their low efficiency and the use of expensive reagents in some cases. Fractional crystallization of double REE nitrates with ammonium and magnesium was considered the most effective for separating lanthanum, obtaining praseodymium concentrates, and separating neodymium and praseodymium.The use of double nitrates with ammonium for the separation of lanthanum was proposed by D. I. Mendeleev. Fractional crystallization of double nitrates with magnesium can be used to separate rare earth elements into yttrium and cerium subgroups, taking advantage of the relatively large difference in solubility in the rare earth series, increasing from La to Lu.

Double nitrates of "light" rare earth elements with magnesium crystallize from aqueous solutions, while those of samarium, europium, and gadolinium crystallize from nitric acid solutions. The "heavy" rare earth elements remain in the mother liquors. Before the use of ion exchange, fractional crystallization of bromates was the best method for separating heavy rare earth elements (from Gd to Tu). This method produced rich concentrates of individual elements, taking advantage of the decreasing solubility of the compounds in the series from La to Lu.

2. RESULTS AND DISCUSSION

REE generally have melting temperatures above 1000ºC which is used in ferrous metallurgy. Table 1 presents the melting and boiling temperatures of REE.

Table 1 - Melting and boiling temperatures of REE

Name	**Simbol**	**Melting temperature, ºC**	**Boiling temperature, ºC**	**Density, g/cm^3**
Lanthanum	La	920	3464	6.14
Cerium	Ce	795	3443	6.77
Praseodymium	Pr	931	3130	6.77
Neodymium	Nd	1022	3074	7.01
Samarium	Sm	1072	1900	7.52
Europium	Eu	826	1529	5.26
Gadolinium	Gd	1312	3273	7.90
Terbium	Tb	1356	3123	8.23
Dysprosium	Dy	1407	2562	8.55
Holmium	Ho	1461	2600	8.79

Erbium	Er	1529	2868	9.07
Thulium	Tm	1545	1950	9.22
Ytterbium	Yb	824	1196	6.97
Lutetium	Lu	1652	3402	9.84
Scandium	Sc	1541	2836	2.99
Yttrium	Y	1526	2930	4.47

Without exception, all rare earth elements exhibit a high chemical affinity for non-metals (O, S, N, C, P, H), typically present in ferrous metals. This makes it possible to use rare earth elements as effective deoxidizers and desulfurizers for various steels and alloys. Cerium and mischmetal (an alloy of cerium and cerium subgroup metals with a small iron content of up to 5%) have become particularly important, as they have a beneficial effect on the structure of steel, increasing its strength and corrosion resistance, as well as its fluidity and machinability. Adding 2 kg of rare earth elements per ton of steel significantly increases its strength and ductility. Recently, reports have appeared on the use of rare earth elements in the production of sheet pipe steel, improving its impact toughness.

Rare Earth elements are very spars and dispersed (Table 2)

Table 2 – The general characteristics of lanthanides and content in the Earth's crust

Name	**Simbol**	**Atomic number**	**Atomic mass**	**Content in the Earth's crust, % by mass**
Lanthanum	La	57	138.9055	$2.9\cdot10^{-3}$
Cerium	Ce	58	140.12	$7\cdot10^{-3}$
Praseodymium	Pr	59	140.9077	$9\cdot10^{-4}$
Neodymium	Nd	60	144.24	$3.7\cdot10^{-3}$
Promethium	Pm	61	(145)**	-
Samarium	Sm	62	150.4	$8\cdot10^{-4}$
Europium	Eu	63	151.96	$1.3\cdot10^{-4}$
Gadolinium	Gd	64	157.25	$8\cdot10^{-4}$
Terbium	Tb	65	158.9254	$4.3\cdot10^{-4}$
Dysprosium	Dy	66	162.50	$5\cdot10^{-4}$
Holmium	Ho	67	164.9304	$1.7\cdot10^{-4}$
Erbium	Er	68	167.26	$3.3\cdot10^{-4}$
Thulium	Tm	69	168.9342	$2.7\cdot10^{-5}$
Ytterbium	Yb	70	173.04	$3.3\cdot10^{-5}$
Lutetium	Lu	71	174.97	$8\cdot10^{-5}$

** Mass number of the longest-lived isotope

2.1. Application of rare earth elements in ferrous and non-ferrous metallurgy

Rare earth elements play an extremely important role in the production of ductile iron. 0.15% Ce significantly improves its physical and mechanical properties. Yttrium can also be used as a cast iron modifier, offering a number of advantages over magnesium, which is used for this purpose (McGill, 2005).

In non-ferrous metallurgy, rare earth alloys can be successfully used as reducing agents in metallothermic reactions, as rare earth elements are stronger reducing agents than aluminum. Recommendations are available for the use of lanthanum as a reducing agent for producing pure rare earth, alkali, and alkaline earth metals. Recommendations also exist for the use of rare earth elements as deoxidizers for copper and copper alloys (Hower et al., 2016).

However, the primary importance of rare earth metals in non-ferrous metallurgy is determined by their use in various alloys. The most widely used alloys are rare earth elements with aluminum and magnesium. Lightweight aluminum-based alloys with cerium are used in aircraft engine pistons, internal combustion engine cylinder heads, and cylinder blocks. Heat-resistant magnetic alloys with rare earth metals are used for casting parts of supersonic jet aircraft, guided missiles and the shells of artificial Earth satellites. There is information on the industrial use of an alloy of 95% mischmetal and 5% magnesium for casting blanks of parts with high mechanical properties. Neodymium is used in the production of lightweight aircraft magnesium alloys. 0.5-6% Pr, Gd or Eu increases the oxidation resistance of chromium alloys. Sm-Co alloys are resistant to demagnetization and are used in aerospace equipment. A composition of rare earth alloys with cobalt for permanent magnets has been developed (Dronskowsky, 2005).

REE are introduced into copper-based solders to improve the structure of the solders.

2.2. Use of REEs in glass and ceramic industry

REEs have acquired great importance in the production of glass, ceramic and abrasive materials. In the glass industry, REEs are used both for coloring glass (yellow – CeO_2, red – Nd_2O_3, green – Pr_2O_3, etc.) and for decolorizing it (Nd, Er, Ce salts), for the production of special glasses that absorb UV rays (Nd – for protection from sunlight, Nd + Pr + Ce in the glass of goggles for welding and other works). Pure lanthanum oxide is used in optical glasses for camera lenses. Neodymium and yttrium oxides are introduced into special glasses for Nicol prisms and Tyndall devices. Neodymium glasses are used as filters in X-ray structural and astrophysical research. Cerium has become increasingly important in the production of radiation-resistant glass, which is used for radiation shielding in nuclear reactors. REEs are also highly promising in ceramics for a wide variety of applications, including special crucibles for melting metals (CeS melts at 2900°C) and high-temperature coatings (CeS and Y_2O_3) for rocket and aircraft construction. Y_2O_3-based ceramics have been created that are as transparent as glass, transmit IR rays, and are resistant to temperatures up to 2200°C. High-temperature ceramic heaters based on ZrO_2 containing up to 15% Y_2O_3 can withstand heating in air above 2000°C. REEs in glazes reduce cracking, enhance luster, and impart a variety of colors .

Rare earth oxides have found widespread and important application as abrasives for polishing sheet and mirror glass, television tubes, binocular lenses, precision optical glass for motion picture camera lenses, etc. Polyrite: 40-47% CeO_2, 41-58% (La_2O_3 + NdP_3 + Pr_6O_{11}), and 2% (SiO_2 + Al_2O_3 + Fe_2O_3 + CaO + MgO) ensures high polishing speed and quality, with near-complete regeneration of rare earth elements possible .

2.3. Application of rare earth elements in nuclear engineering

Nuclear engineering is one of the newest applications of rare earth elements. Because some isotopes of Gd, Srn, and Eu have very high thermal neutron capture cross-sections (44,000 barns/atom for Gd, 6,500 barns/atom for Sm, 450 J barns/atom for Eu), significantly exceeding those of boron, cadmium, and hafnium, they can be used in control rods for nuclear reactors. Eu is the most promising for this purpose, as its long-lived isotopes also absorb thermal neutrons. The cost of manufacturing control rods from an Ag-Cd-Eu alloy (up to 50%), which possesses all the necessary properties for this purpose, is lower than the cost of rods made of boron-enriched steel.

Yttrium metal, which has a small thermal neutron capture cross-section and does not react with molten uranium, is a structural material for nuclear reactors. Yttrium can also be used as a hydrogen carrier for solid moderators. Ce, La, and Y can serve as diluents for oxide fuel materials in nuclear reactors. Molecular suspensions of yttrium and uranium produce stable radiation and are relatively inexpensive. Highly effective materials have been developed for radiation protection, which contain, in addition to lead, rare earth metals that absorb neutrons. One such material contains 35% Dy and 40% Pb. Other materials contain Gd and Pb in combination with Dy and W. These materials are used for protective devices in laboratories, facilities, and reactors .

Portable X-ray machines use the radioactive isotope thulium ^{170}Tu, which is a γ-emitter. ^{155}Eu can also be used for the same purpose. It is believed that radioactive isotopes $^{152\text{-}154}$Eu can compete with ^{60}Co for γ-ray flaw detection. Isotopes Sm and Y have acquired practical significance .

Hafnium had no practical application for a long time. Currently, hafnium has several distinct applications, but its very high cost limits its use. The most common use of metallic hafnium is in nuclear reactor control rods and shields for neutron radiation protection

Hafnium-free zirconium metal and its alloys are used primarily in the nuclear power industry to manufacture fuel element cladding, heat exchangers, and other nuclear reactor structures that must not absorb neutrons and be highly resistant to nuclear radiation at elevated temperatures. Due to its high cost, zirconium consumption in other applications is limited.

Hafnium and its compounds have promising applications in heat-resistant alloys for aircraft and rocket engineering. Titanium alloys doped with hafnium (up to a few percent) can withstand temperatures up to 980°C. Tantalum-hafnium alloys are resistant to oxidation up to 1650°C. Alloys of Nb and Ta with Hf (2-10%) and W (8-10%) are easy to machine, corrosion-resistant, and have high strength above 2000°C and near absolute zero. Heat-resistant materials based on hafnium carbide and nitride have unique properties

2.4. Employment of rare earth metals in electrical engineering, radio engineering and electronics

Rare earth metals are used as getters in vacuum technology and as emitters. Their compounds are very promising for the manufacture of cathodes in electronic devices. They are also used in computers, television and aviation technology, and radio engineering (Haxel et al., 2006).

Particularly promising in this regard are borides and hexaborides of rare earth metals. Manganese compounds of rare earth metals such as $MnLnO_3$ are good ferroelectrics. Neodymium oxide is used in electronic devices as a dielectric with a low coefficient of linear expansion. A good dielectric is CeO_2 in a mixture with TiO_2. A mixture of CeO_2 with SrO is used in radioceramics. Rare earth compounds are widely used as activators or as a basis for phosphor in fluorescent lamps and high-pressure mercury lamps. A component of phosphors used in lamps for illumination, disprosium (Liu, Jacquier, 2006).

A red phosphor for high-intensity color television picture tubes was created first using yttrium orthovanadate and then yttrium oxide activated with europium. Neodymium is particularly promising for use in color television filters. Rare-earth compounds play an important role in the creation of quantum amplifiers and oscillators in the optical range, where they are used as activators. Oxides of lanthanum, gadolinium, neodymium, cerium, and yttrium, as well as molybdates and tungstates of rare earth elements, are used in the fabrication of solid-state lasers.

Rare earth ferrites (garnets), which combine semiconducting, dielectric, and ferromagnetic properties (microwave transmitters, resonators, etc.), are of great interest. Particular attention is paid to yttrium-iron garnets of the $3U_2O_3 \cdot 5Fe_2O_3$ type, which are a valuable material for magnetic cores in microwave and television equipment. Yttrium-aluminum garnets imitate diamonds. The diversity of magnetic properties of rare earth metals and their alloys is of undoubted interest from the point of view of their use in electronics. Oxides of heavy rare earth metals are used in memory devices of electronic computers (Sisniga, 2012). REEs are acquiring great importance as semiconductor materials. In principle, it is possible to obtain a large number of REE compounds with Se, Te, S, Sb, Bi, etc., having a wide range of semiconductor properties (Chu, 2011).

High-temperature thermoelectric elements based on samarium and cerium sulfides, operating at temperatures up to 900° with high efficiency, have been developed. Gadolinium selenide has been proposed for the same purposes. Thermisters based on $BaTiO_3$ with the addition of La^{3+}, Sm^{3+}, Gd^{3+}, and Ho^{3+} ions are known.

2.5. Application of rare earth elements in laser technology

The creation of the laser opened up the possibility of solving many scientific problems using optoelectronics. REEs are also used in laser technology. Laser technology opens up great possibilities in biology and medicine. Lasers are used like scalpels (surgery on the eye and soft tissues).

High-power lasers have also are used in technology. They make it possible to weld, harden, cut, and drill various materials without introducing mechanical stresses unavoidable during conventional processing, and with very high precision, down to several wavelengths. Materials of any hardness, including metals, diamonds, rubies, etc., can be processed. Lasers are beginning to be used in cutting gas pipes, etc.

Laser technology is being intensively developed for optical methods of processing, transmitting, and storing information (semiconductor laser), holographic methods of recording information and color projection television.

The high power of lasers, combined with their high directivity, makes it possible to obtain beams of extremely intense light through focusing. The highest radiation powers were obtained using solid-state Nd-doped glass lasers with a wavelength of $\lambda = 1.06$ μm and gas CO_2 lasers with $\lambda = 10.6$ μm.

Using lasers, it is possible to achieve a thermonuclear fusion reaction. This requires the formation of an extremely dense and hot plasma with a temperature of ~108 K in the case of deuterium fusion.

2.6. Other areas

The use of rare earth elements in lighting technology has long been known. Currently, carbon electrodes with rare earth fillers are used in high-power antiaircraft searchlights, film cameras, and film projection equipment. Rare earth elements play a major role in the synthesis of crystal phosphors: substances that convert various types of energy (ultraviolet, cathode, and X-rays) into light and are used in television, radar equipment, and image intensifier tubes.

The first molecular amplifiers (masers) were created using lanthanium and gadolinium sulfates.

Thulium and Erbium can be used as active substances in masers.

Masers containing rare earth ions exhibit the highest, highly directional fluorescence. A CaF_2 crystal activated by Sm^{2+} ions consumes only 0.2% of the power required for a chromium-doped ruby crystal .

In the chemical industry, REE compounds are used in the production of varnishes, paints, various reagents, and catalysts, particularly in the petrochemical industry. They are also used in the textile industry to impart waterproofing and resistance to acids and vapors, for leather, and as tanning agents (Haschke, 1979).

REEs are also known to be used in pharmaceuticals. They can also be used in agriculture as micronutrient fertilizers and insecticides (Barrett, Malati, 1997) .

In terms of the volume of rare earth elements use in the United States, the petrochemical industry ranks first, using a mixture of chlorides (in natural proportions or with the addition of lanthanum) for catalysis. This use accounts for 60% of the total use of REE compounds.

CONCLUSION

Because of their unique physical, mechanical, and chemical properties, REE are used as effective deoxidizers and desulfurizers for steels and different alloys. REE are the most frequently used in aerospace engineering and the production of aircrafts and systems for tracing of airplanes.

REEs are widely used in robots, drones and components for anti-drone systems.

There are many examples, when the application of different chemical elements of the REE group gives different possibilities of application in many fields of medicine, technology and theoretical science. The lack of natural resources, especially rare metals and REEs, negatively affects the economic development of every country.

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Physiological and geochemical aspects of the prevention and correction of combined animal hypomicroelementosis in the Astrakhan region

Fiziološki i geohemijski aspekti prevencije i korekcije kombinovane hipomikroelementoze životinja u Astrahanskoj oblasti

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Abstract: The report describes the evaluation of the biogeochemical situation of terrestrial ecosystems of the Astrakhan region. The deficit trace elements in soil, pasture and plant feed sheep Edilbaev breed were clarified. The ways of prevention and correction of latent forms of combined trace element in ewes Edilbaev breed in biogeochemical conditions of the region of the Lower Volga were demonstrated.

Keywords: geochemical ecology, selenium, cobalt, iodine, Edilbaev breed ewes, correction of trace element.

Sažetak: U radu se opisuje procena biogeohemijskog stanja kopnenih ekosistema Astrahanske oblasti. Razjašnjen je deficit elemenata u tragovima u zemljištu, pašnjacima i biljnoj hrani ovaca rase Edilbajev. Predstavljeni su načini prevencije i korekcije latentnih oblika kombinovanih elemenata u tragovima kod ovaca rase Edilbajev u biogeohemijskim uslovima regiona Donje Volge.

Ključne reči: geohemijska ekologija, selen, kobalt, jod, ovce rase Edilbajev, korekcija elemenata u tragovima.

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INTRODUCTION

A comprehensive study of the biogeochemical situation and the study of the physiological status (hematological indicators, dynamics of microelements in the body, steady-state levels of lipid peroxidation and antioxidant protection) of ewes of the Edilbaev breed and the influence on them of physiologically important microelements lacking in the environment and plant feed in the conditions of the Lower Volga region is an urgent and unstudied problem, especially considering that the number of sheep in the Astrakhan region is approaching two million.

The study of the theoretical foundations of homeostatic reactions of animals is the most important physiological problem of modern biology, considering various levels of adaptation: molecular-cellular, organismal and population.

Metabolism of microelements and hematological parameters are the most important indicators of the normal physiological state of animals (Kovalsky, 1974; Vorobiev V., 1968; Samokhin, 2008; Nazarenko, Ermakov, 1971). Long-term influence on the animal body of low levels of physiologically important microelements in the environment and plant feed, such as selenium, iodine and others (Voinar, 1960; Vorobiev V., 1968, 1978, 1982, 1993; Vorobyov V. et al., 2000; Vorobiev D., 2009, 2010, 2013; Vorobyov D. et al., 1999; Vorobyov D. et al., 2009; Vorobyov D., Lapshina, 2010; Dedov et al., 2005) leads to changes in metabolic processes, hematopoiesis, negatively affects the level of activity of the endocrine (Vorobyov D., Lapshina, 2010; Vorobiev D., 2013; Odynets et al., 1976; Rodionova et al., 2010; Samokhin, 2008) and antioxidant systems of the animal body (Vorobiev D., 2013; Rodionova et al., 2010; Hartley & Grant, 1961), predetermines the development of oxidative stress, which serves as a trigger for fundamental cellular-molecular shifts that determine the development of the pathogenesis of various endemic diseases, incl. hidden form of hypomicroelementosis, leading to a decrease in the integrative functions of farm animal productivity (Vorobiev D., 2013; Rodionova et al., 2010; Samokhin, 2008).

The purpose of the study was to comprehensively study the geochemical situation of the Lower Volga region, the metabolism of microelements, hematological parameters and the state of lipid peroxidation processes and the antioxidant system in ewes of the Edilbaev breed and to study the influence of selenium and iodine on their physiological status in the biogeochemical conditions of the Astrakhan region.

To achieve this goal, the following tasks were set:

- to find out the biogeochemical situation of terrestrial ecosystems of the Astrakhan region and study the content of microelements in organs and tissues, as well as the balance of Se, J, Ca, Co, Cu, Mn and Zn in the body of ewes of the Edilbaev breed;
- to determine hematological parameters (number of formed elements, amount of hemoglobin, leukocyte formula, carotene, total calcium, inorganic phosphorus, total protein, protein fractions, glucose, alkaline reserve, selenium, iodine) of ewes and lambs in the biogeochemical conditions of the Astrakhan region;
- to establish the level of parameters of free radical oxidation (diene conjugates and malondialdehyde) and the activity of antioxidant enzymes - catalase and glutathione peroxidase in the blood of adult sheep under conditions of low levels of selenium, iodine and cobalt in the environment and plant feed;
- to study changes in the physiological and biochemical parameters of Edilbaev ewes in biogeochemical conditions of low levels of iodine, selenium and cobalt in the environment and plant feed of the Lower Volga region when animals are exposed to an organic preparation - “sedimin” containing selenium and iodine.

1. MATERIAL AND RESEARCH METHODS

259 soil samples (0-25 cm), 26 types of pasture plants and plant feed, 21 water samples and 86 samples of organs and tissues of Edilbaevskaya sheep, selected at pre-determined (since 1970) permanent collection stations in the Astrakhan region (Vorobiev V., 1978, 1982, 1993; Vorobyov V. et al., 2000). Samples for the study of microelements were taken according to the method of Kowalski (1974). The experiments were carried out in the agricultural holding "Tabun-Aral" of the Enotaevsky and peasant farm "Svetlana" of the Privolzhsky district of the Astrakhan region. The feeding and housing conditions for experimental and control animals were the same. To determine the need for physiologically important microelements, balance experiments were carried out using the VIZh method (Vorobiev D., 2013). Two groups of similar ewes of 5 heads each were kept in individual cages, the floors of which were lined with organic glass with holes for urine drainage into urine collectors. The groups contained similar animals of 5 animals each. Animals have negative balances of Se and J in the body.

In the first series of physiological experiments, starting from the first trimester of pregnancy until lambing, experimental sheep were intramuscularly injected into the upper third of the thigh with the organic preparation “sedimin” (GOST 12.1 007-76), which is an aqueous mixture of iodine and selenium compounds on a stabilizing basis of a dextran complex . 1 ml of sedimin contains: 7.5 mg/ml iodine and 0.09 mg/ml stabilized selenium (corresponding to 0.2 mg/ml sodium selenite). Sedimin was administered to experimental ewes at a dose of 6 mg per head every 20 days of the experiment until lambing. Control sheep, similar in age and weight to the experimental ones, grazed together. 4-year-old

Edilbaev sheep took part in the research and production experiment. There were 251 animals in the control flock, and 262 ewes in the experimental flock. Before the experiments and at the end of them, the animals were weighed. Sedimin was administered to ewes and lambs in the same doses as in physiological experiments. Trace elements in biological samples were determined by the atomic absorption method using a CHITASHI spectrophotometer (Japan) and AAS - IN (Germany). Selenium - fluorometrically (Nazarenko, Ermakov, 1971), and the iodine-radamide-nitrite method, GOST 28-458-90. Blood from ewes and lambs was taken from the ear vein before feeding and determined: formed elements, hemoglobin, leukoformula, Ca, P, Se, J, Co, Mn, Zn, Cu, alkaline reserve, and in blood serum - protein and its fractions, glucose and carotene according to generally accepted methods (Kovalsky, 1974). Diene conjugates (DC) were determined by UV absorption spectra on a spectrophotometer at 233 nm, and malondialdehyde (MDA) by Buzlama et al. (1997). The activity of catalase (EC 1.11.1.6) in blood serum was studied according to the method of Korolyuk et al. (1988), and glutathione peroxidase (EC 1.11.1.9) - according to (Paglia & Valentine, 1967; Hosseinion et al., 1972). The research results were processed statistically using a computer using the mathematical analysis software package Microso ft Excel 97 Pro, Statistika.

2. RESEARCH RESULTS

In the upper horizon of soils in the Astrakhan region, cobalt contains an average of 8.0 ± 1.03, and copper, zinc and manganese - respectively: 15.8 ± 1.27; 45.4±2.1 and 142.8±10.6 mg/kg, and in water – Co – 0.7±0.02, Ni – 0.5±0.01, Se – 0.029±0.002, Mn – 9.8±0.7, Zn – 32.1±2.6, Cu – 4.5±0.7 and J – 1.7±0.13 µg/l. The selenium content in the studied plants is low, ranging from 0.021±0.004 to 0.14 ±0.004 mg/kg of dry matter. At an optimum of 0.05 ±0.004 mg/kg. And only in wormwood and astrogals, plants that are concentrators of microelements, we found very significant amounts of selenium (1.99 ± 0.014 and 12.6 ± 1.16 mg/kg). The amount of cobalt was also below the normal threshold. The fact of very low iodine content in the Lower Volga region is beyond doubt (Dedov et al., 2005; Rodionova et al., 2010). The level of manganese and zinc in plant feed in the Astrakhan region is slightly higher than the required physiological norm for sheep. The water contained Mn – 0.1±0.012; Se – 0.02±0.003; J – 0.004±0.0005; Co – 0.01±0.004 and Zn – 0.09±0.011 mg/l.

Chronic deficiency of minerals, including microelements in feed, is a constant stress factor for animals and leads to the development of oxidative stress, which predetermines latent forms of hypomicroelementosis, which changes the nature of metabolic processes, negatively affects the processes of antioxidant protection of the body from increasing levels of peroxidation products and reduces the productivity of farm animals (Lankin et al., 2001). It was established that the studied physiologically important mineral elements are distributed differently in the organs and tissues of Edilbaev ewes (Table 1). The dynamics of selenium in ewes is arranged in the following series, decreasing in level of concentration in organs: liver ≥ spleen > bone tissue ≥ lungs > wool > kidneys > blood > small intestinal wall ≥ muscles. And the cobalt series looks like this: liver ≥ bone tissue > spleen ≥ wool > intestinal wall ≥ muscles > kidneys ≥ blood. The descending series of manganese, copper, zinc and iodine are similar to each other with very few differences. Most zinc is found in bone tissue and lungs, where this element is concentrated, being part of carbonic anhydrase, which regulates respiratory function in animals (Voinar, 1960).

Table 1 – Dynamics of microelements in the body of ewes (n =12), mg/kg

Organs and tissues	Se	Cu	Co	Mn	Zn	J
muscles	0.021± 0.001	6.45±0.97	0.05±0.002	1.97±0.57	74.1± 2.22	0.18±0.005
liver	0.18±0.003*	20.2±0.85*	2.08±0.07*	4.81± .33*	89±3.35*	0.32± .012*
spleen	0.18±0.003*	18.4±1.14*	0.81±0.03*	3.21± 0.17	79.9±7.17	0.27± 0.02*
blood	0.03±0.002	6.6±0.27	0.43±0.01	4.6±0.08*	50.9±3.36	0.09±0.006
lungs	0.07±0.004*	15.8±1.07*	0.02± 0.0008	1.88±0.07	101.1±3.52*	0.18± 0.077
kidneys	0.04±0.005	15.1±2.05*	0.44± 0.007	1.12±0.05	76.2±6.44	0.16± 0.086
small intestinal wall	0.02±0.001	18.4±1.16*	0.51± 0.009	4.01±0.31*	99.5±5.13*	0.26± 0.032
bone	0.08±0.0004*	8.62±0.26	0.97± 0.05*	3.09±0.59	138±8.03*	0.29±0.084*
wool	0.054±0.0003	17.5±1.79*	0.85±0.004*	43.3±2.12*	94.8±9.08	0.21±0.072

* P<0.05 relative to other organs and tissues

The balances of such essential elements for the body as selenium and iodine were negative in ewes (Table 2), and the balances of manganese and zinc in the body were consistently positive.

Table 2 – Balance of microelements in Edilbaev ewes, n =5, in mg

Microelements	Taken with food	Isolated from the body				Absorbed by the body (balance ±)
		in feces	in urine	in milk	Total	
Co	0.38±0.02	0.30	0.02	0.06	0.38±0.04	±0.00
Se (μg)	0.87±0.04	0.94	0.01	0.02	0.97±0.02	-0.1
J	0.101±0.002	0.096	0.045	0.023	0.164±0.05	-0.063
Cu	6.92±0.28	6.01	0.16	0.29	6.46±0.41	+0.46
Mn	73.2±2.15	58.5	0.03	0.12	58.65±3.88	+14.55
Zn	32±1.14	21	0.01	0.02	21.03±2.09	+10.97

The copper balance in ewes was also positive. The cobalt balance in the animals studied was zero. It is very interesting that although there is less cobalt in the environment and plant feeds than in the “reference” black earth region of the country (Kovalsky, 1974), the balance of this element in sheep was not negative, as, for example, in cows (Vorobiev D., 2013) located in those the same biogeochemical conditions of the Astrakhan region, which indicates the species specificity of animals in the utilization of microelements.

Consequently, the results of balance experiments, in combination with data from biogeochemical monitoring of the environment, and the content of microelements in the organs and tissues of ewes, allow us to speak about a low (insufficient) amount of selenium and iodine in the environment and plant feed, and their deficiency in the body, which predetermines the need for the introduction additional amounts of Se and J to ewes of the Edilbaev breed in the conditions of the Astrakhan region to improve metabolic processes and the physiological state of animals.

Hematological parameters of Edilbaev ewes were at the lower limit of the physiological norm for sheep (Kondrakhin, 2004). The number of erythrocytes in ewes is relatively low, and the number of white cells, on the contrary, was at the upper level of the physiological norm (Arsanukaev, 2006; Odynets et al., 1976; Rodionova et al., 2010; Samokhin, 2008). The alkaline reserve of sheep blood was 42.9±2.64 vol.% CO_2, which is below the physiological norm (Kovalsky, 1974). The protein level in ewes is 72.5±4.06 g/l, calcium – 2.38±0.22 mol/l and phosphorus – 1.23±0.09 mol/l. These parameters are on average at the lower limit of the physiological norm for sheep, and in some animals they are even lower. In ewes, the amount of selenium and iodine in the blood is low, which is consistent and correlates (r = +0.68) with low levels of Se and J in the main components of ecosystems, organs and tissues of sheep, negative balances of selenium and iodine in the body and low levels of alkaline reserve blood. Our established indicators of lipid peroxidation (LA and MDA) in the blood of Edilbaev ewes (Table 3) turned out to be slightly higher than the literature, and the level of activity of antioxidant enzymes is definitely (P<0.05) lower than, for example, in animals in other regions of Russia, where there is no deficiency of selenium and iodine in feed (Arsanukaev, 2006; Rodionova et al., 2010; Hartley & Grant, 1961).

The accumulation of lipid peroxidation products, while simultaneously reducing the level of activity of antioxidant enzymes, leads to the development of oxidative stress and, as a consequence, causes a latent form of combined hypomicroelementosis. In ewes, this reduces milk production and reproductive capacity and lengthens the lambing time.

Table 3 – Indicators of free radical oxidation and antioxidant protection of Edilbaev sheep and lambs of different ages

Name of indicators	Ewes, 4 years old
diene conjugates, μmol/ml	2.08±0.06
malondialdehyde, μmol/l	0.52±0.05
catalase, μmol/ml	3.08±1.07
glutathione peroxidase, μ MG - SH l/min 10^3	5.04±0.18

The number of red blood cells in Edilbaev ewes was on average across groups at the lower limit of the physiological norm. The use of sedimin containing J and Se causes an increase in the number of erythrocytes in sheep by 17.7% (P<0.05) and hemoglobin by 9.87% in sheep from the experimental group, relative to similar indicators in the control group. During the experiment, the number of eosinophils in experimental ewes increased by 27%, segmented neutrophils - by 30.6%. At the same time, the number of lymphocytes decreased by 15.8% and band cells by 39.1%. An increase in inorganic phosphorus in the blood of control sheep was established in the spring, when the sheep began to graze. The content of selenium and iodine in the blood at the beginning of the experiment in pregnant queens of both groups was below the physiological norm: Se - 0.022 µg/ml and J - 0.16 mg/ml (Rodionova et al., 2010). The level of carotene in the experimental queens increased significantly after the second injection of sedimin. The amount of selenium in the blood of animals from the experimental group (P<0.05) increased in February - by 44.1%, in March - 48.1% and April - 46.2%, relative to the control data and reached the physiological norm at the end of the experiment for sheep (Kondrakhin, 2004). Similarly, the level of iodine in the blood of the experimental sheep increased by the end of the experiment. In the blood of Edilbaev ewes (Table 4), a fairly high level of initial (DC) and secondary (MDA) products of lipid peroxidation (LPO) and low activity of glutathione peroxidase (GPO), containing selenium and catalase, which is activated by selenium and a number of other microelements, were established. The alkaline blood reserve in animals is also evidence of an acidotic state and serves as one of the indicators of a latent form of combined hypomicroelementosis (Rodionova et al., 2010; Samokhin, 2008), which we observed in all ewes before the experiment, at the end of which the acid capacity in the blood of control sheep decreased even more, and in experienced – increased by 23.4%.

An increase in protein and its fractions in the blood of experimental sheep (Table 4), especially globulin (P<0.05), relative to the control, indicates a positive effect of sedimin on the protein metabolism of animals (Rodionova et al., 2010). The protein level in experimental sheep treated with sedimin containing Se and J approaches its increase in the blood to the level of the physiological norm (Korolyuk et al., 1988; Lankin et al., 2001).

Table 4 - Effect of sedimin on the level of LPO and AOS in the blood of Edilbaev ewes

The name of indicators	Control group (n =15)		Experimental group (n =15)	
	before experience	at the end of the experiment	before experience	at the end of the experiment
total protein, g/l	67.4±1.15	68.1±1.19	67.02±1.06	72.55±1.11*
albumin, g/l	23.7±1.18	24.8±1.06	24.1±2.01	28±1.98
globulin, g/l	28.5±2.07	29.0±1.09	28.03±1.02	34.9±1.11*
glucose, mol/l	3.46±0.17	3.57±0.22	3.39±0.11	2.01±0.27*
diene conjugates (DC), µmol/ml	2.07±0.04	3.16±0.35	2.14±0.09	1.75±0.06*
malondialdehyde (MDA), µmol/l	0.51±0.09	0.59±0.07	0.54±0.03	0.49±0.02
catalase, µmol/ml	2.98±0.02	2.71±0.01*	3.01±0.03	4.72±0.12*
glutathione peroxidase (GPO), m MG - SH l/min·10^3	8.06±0.05	7.77±0.18	8.17±0.04	11.03±0.39*
alkaline reserve, vol.% CO_2	41.6±1.02	35.5±1.09*	40.2±1.77	49.6±1.05*

*P<0.05 relative to the beginning of the experiment

In experimental ewes, at the end of the experiment, an increase in catalase activity was found - by 56.8% and glutathione peroxidase (GPO) by 35%, relative to the beginning of the experiment. Strengthening antioxidant protection in experimental ewes was accompanied by a decrease in the level of free radical oxidation products and blood sugar. The number of diene conjugates in ewes of the experimental group during the experiment decreased by 18.3%, and the end products of peroxidation - malondialdehyde - decreased by 9.3% and carbohydrates - by 39.1% (P < 0.05) relative to the beginning of the experiment and differed from the control results, where DC by the end of the experiment increased by 52.7%, MDA - by 15.7%, and the amount of glucose increased by 3.18% (P < 0.05).

During the period of scientific and production experience during the lambing campaign in the experimental flock that received intramuscular sedimin, the ewes practically did not require obstetric care, and the lowest percentage of stillborn lambs was observed. In 262 queens from the experimental flock, the average duration of the physiological act of labor per lamb was 7.12±0.78 minutes, and in the control ones it was slightly longer - 9.62±0.57 minutes (P<0.05). The yield of lambs per 100 ewes in the control was 101±1.98, and in the experiment - 106±1.04. In the experimental flock, the body weight of newborn lambs was 8.16% higher than the control indicators. The weight gain on the 20th day of life of lambs was greater in lambs from experimental dams - by 8.8%, and the weight of lambs after 20 days of life was 6.34% higher than similar control indicators (12.6± 0,54 кг).

CONCLUSION

Comprehensive studies of the biogeochemical situation of the region and the physiological status of adult sheep of the Edilbaev breed made it possible to find out that the stationary level of hematological parameters in ewes: the number of erythrocytes, leukocytes, the amount of hemoglobin and the level of alkaline reserve of blood, calcium, phosphorus, protein and its fractions, the content of microelements in organs and tissues are at the lower limit of the physiological norm, and sometimes (Se, J , alkaline reserve, globulin) even below it. The relatively low activity of the antioxidant system (catalase, GPO) of the studied animals was established. Noteworthy is the not very high fertility of Edilbaev sheep located in the Astrakhan region, which we associate with the geochemical situation: low levels of selenium, copper and cobalt in plant feed, certain changes in metabolism, incl. high level of peroxidation products with low activity of antioxidant enzymes, which is consistent with literature data (Vorobiev D., 2013; Rodionova et al., 2010; Samokhin, 2008). Sedimin in the doses we have chosen corrects the syndrome of the latent form of combined hypomicroelementosis of iodine and selenium in Edilbaev ewes, which is confirmed by a blood picture, an improvement in metabolic processes, a decrease in the level of DC and MDA and an increase in the activity of the endogenous line of antioxidant defense (catalase, GPO) in experimental animals, indicators which at the end of the experiments reached the physiological norm for the studied animal species. By the end of the experiment, the blood levels of selenium and iodine in the experimental sheep increased to the physiological norm.

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Application of geochemical characterization data for desert overgrowth monitoring (the example of the Sarykum sand complex)

Primena podataka geohemijske karakterizacije za praćenje obrastanja pustinje (primer peščanog kompleksa Sarikum)

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Abstract: The paper presents calculations compared with the overgrowth of deserts. The basis of the data used for the calculation is the geochemical characteristics of the Sarykum sand complex.

Keywords: geochemistry, desert overgrowth, geochemical indices, Sarykum.

Sažetak: U radu su predstavljeni proračuni u vezi sa obrastanjem pustinja. Osnova podataka koji su korišćeni za proračun su geohemijske karakteristike peščanog kompleksa Sarikum.

Ključne reči: geohemija, obrastanje pustinja, geohemijski indeksi, Sarikum.

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INTRODUCTION

Rapid climate changes, manifested in warming and increased precipitation, lead to global changes in natural areas (Botta et al., 2019). For example, recently there has been active overgrowing of deserts and sand complexes, which leads to the destruction of desert biomes. The Sahara region is more susceptible to desert overgrowth. In Russia, the south, mainly the Caspian lowland and the Trans-Baikal Territory, are more susceptible to desert overgrowth. One of such objects subject to active overgrowing is the Sarykum sand complex (Polynova et al., 2021).

The aeolian-accumulative complex "Sarykum" is a system of dunes, ridges, hummocky and peripheral sands in the foothills (at the outer foot of the Narat-Tyube ridge) part of Dagestan (16-17 km WNW from the city of Makhachkala) on the Tersko-Sulak lowland plain. Sarykum is the largest isolated sand massif in Russia with an area of more than 2.5 thousand hectares (Gusarov, 2015). Sarykum is considered a striking geomorphological object. The most specific part is characterized by the widespread development of open sands and various forms of aeolian relief. It is divided into large Sarykum (maximum height around 250 m) and small Sarykum (small height, used for the extraction of building materials). The territory of the large Sarykum is under the protection of the Dagestansky Nature Reserve. On the western (large) Sarykum there are several transverse dunes (Fig. 1), the length of the crest of the largest of which is 1200 m. The dunes are formed due to the dispersal of sediments of the Sarykum massif, consisting almost entirely of fine quartz sand (Tulysheva, 2002). Most researchers dealing with the formation of this sand complex associate its formation with the weathering process and aeolian processing of the products of destruction of quartz and weakly cemented sandstones, such as Chokrak and Karagan (Idrisov, 2010). The latter compose the northern slope of the Terek-Sulak trough, represented by the forward ridges - Narat-Tyube, Karaburun, etc. These sandy strata occur throughout the territory of Dagestan, marking the boundary of the orogen and the forward trough.

Figure 1 - Satellite image of the large Sarykum

Despite the sufficient study of Sarykum, a complete geochemical characteristics of the complex has not yet been compiled. Geochemical data can be useful for monitoring the process of desert overgrowth. For example, the basis for this could be the correlation of information on vegetation levels with data on geochemical weathering. In the context of desert overgrowth, such objects are important for assessing biological weathering. Biological weathering occurs under the influence of the vital activity of organisms. Organic processes include the biological dissolution of rocks through bacterial activity, humic acids, and bioerosion or destruction. Changes occur due to the growth of roots, the penetration of shell organisms, lichens, cyanobacteria, algae and fungi into the rocks on which they feed (Haldar, 2020).

Since there is currently no method for assessing biological weathering, indices such as Chemical index of alteration (CIA) (Nesbitt & Young, 1982), Chemical index of weathering (CIW) (Harnois, 1988), Plagioclase Index of Alteration (PIA) (Fedo et al., 1995) and Weathering Intensity Scale (WIS) (Meunier et al., 2013). To calculate the first three indices, the following formulas are used:

$$CIA = \{Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)\} \times 100$$

$$PIA = \{(Al_2O_3\text{-}K_2O)/((Al_2O_3\text{-}K_2O)+CaO^*+Na_2O)\} \times 100$$

$$CIW = \{Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O)\} \times 100$$

In the above equations, the main oxides are expressed in mole fractions, and CaO* is the content of CaO included in the silicate fraction. To quantify the CaO* content, it is necessary to subtract the mole fractions of P_2O_5 from the mole fraction of total CaO. After subtraction, if the remaining number of moles is less than the mole fraction of Na_2O, then the remaining number of moles is considered as the mole fraction of the CaO silicate fraction. If the remaining number of moles is greater than the mole fraction of Na_2O, then the mole fraction of Na_2O is considered to be the mole fraction of the CaO silicate fraction (CaO*).

A different methodology is required to calculate WIS. The general view can be reduced to the form:

$$WIS = (Al_2O_3+Fe_2O_3)\cdot[(Al_2O_3+Fe_2O_3) + Mg_2O + (Na_2O+K_2O+2\cdot CaO)]^{-1}.$$

However, this equation can take into account the silica (SiO_4) component of the sample. To do this, an approach is taken based on the M^+-4Si-R^{2+} system ($M^+ = Na^+ + K^+ + 2Ca^{2+}$; 4Si = Si /4; $R^{2+} = Fe^{2+} + Mg^{2+}$). At these coordinates, the chemical compositions of weathered granitic, mafic and ultramafic rocks define clearly distinct trends that all converge towards the 4Si pole, namely the composition of kaolinites (chlorites are located near the R^{2+} pole). Therefore, the rate of change for a given source rock can be measured by the migration of its chemical composition towards the kaolinite pole:

$4Si\% \; [(4Si_{weathered\ samples} - 4Si_{unweathered\ samples}) \times 100] / (100 - 4Si_{unweathered\ samples})$.

When taking this model into account, the final stage of weathering is reduced to the progressive accumulation of insoluble components R^{3+} ($R^{3+} = Al^{3+} + Fe^{3+}$).

1. METHODOLOGY

Sarykum sandy complex, 34 soil samples were taken from different heights and different levels of vegetation. Of these, 31 samples are presented in the form of fine- and medium-grained sand, 3 samples are material from unweathered cemented layers (points 16-18). Sampling points are shown in Fig. 2. The chemical composition of 32 samples (cont¬ent of main oxides and trace elements) in crushed form was determined by X-ray fluorescence analysis (XRF) using an Axious device Advanced PW 4400 /04 (Philips). Mineral composition was determined using a Tescan scanning electron microscope Mira 3. The chemical composition of the minerals was studied using a BSE detector. The results of mineralogical analysis were processed in the AzTec program Oxford Instruments NanoAnalysis.

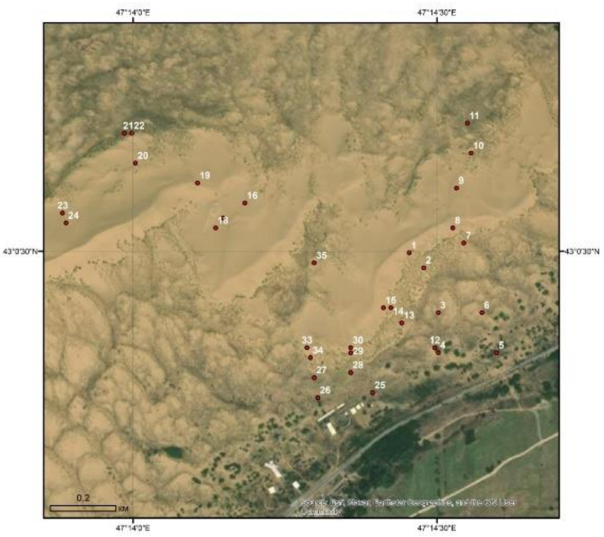

Figure 2 - Sampling points for soil and carbonate crusts.

2. RESULTS AND DISCUSSION

Data on the main oxides are presented in Table 1, data on heavy metals of Sarykum are presented in Table 2.

The data obtained confirm the high content of SiO_2 (63.80 (in unweathered carbonate crusts) - 92.88%, average 88.69 %) in the material. The most common elements are also calcium (2.74-18.64 (in unweathered carbonate crusts)%, average 4.72%) and iron (0.64-2.41%, average 1.46%). The Al_2O_3 content fluctuates around 1%. The content of other basic oxides does not exceed 0.5%. A correlation analysis shows a high negative correlation of calcium with silicon (-0.96), which indicates that Ca is not in compounds with silicates and is represented by calcite and apatites. The content of immobile microelements, such as Cr and Ni, indicates the felsic composition of the original rocks (<150 ppm and <100 ppm, respectively) (Garver et al., 1996). This is also confirmed by the ratios Al_2O_3/TiO_2 and TiO_2/Zr (Hayashi et al., 1997). Thus, for felsic rocks, the Al_2O_3/TiO_2 ratio in mafic, intermediate and felsic igneous rocks is 3-8, ~8-21 and ~21-70, respectively, and the TiO_2/Zr ratio is >200 for mafic igneous rocks, 195 -55 for intermediate igneous rocks and <55 for felsic igneous rocks. In Sarykum samples, the Al_2O_3/TiO_2 ratio averages 18.72, reaching a maximum value of 38.63, while the maximum value for the TiO_2/ Zr ratio is 18.63.

To assess the overgrowth of deserts, 7 areas were selected (points 4-1; 5-8; 11-9; 12-15; 21-19; 22-24; 25.28-30, see Fig. 2), in which the level of vegetation decreases with increasing altitude. Next, the weathering indices used were calculated for each site point and compared with the level of vegetation. Table 3 presents the results of calculations of basic weathering indices (CIA, PIA, CIW), as well as WIS. Thus, according to the data obtained, it can be concluded that the material has a low or moderate degree of weathering, which is confirmed by the results of calculations using three indices (CIA ranged from 61.78 to 65.19, mean 63.92; PIA ranged from 50.75 to 55.56, mean 52.53; CIW ranged from 68.60 to 74.80, mean 72.17), which allows us to draw a conclusion about the compositional maturity of the composition. Thus, the main processes of transformation of the existing material are completed in comparison with the original rock. However, the obtained calculations of the main weathering indices allow us to characterize the predominant type of weathering and do not show a correlation with the level of vegetation, which shows the absence of a general, similar trend in weathering trends. The WIS calculation results, which take into account the silica component SiO_4, turn out to be more representative. This is explained by increased decomposition of aluminosilicate minerals, which may be associated with biological activity. Thus, for all studied areas there is a general trend of an increase in the index with the level of vegetation. The exception is the area with points 4-1, which may be due to high values of Al_2O_3 and Fe_2O_3, which may indicate the presence of a geochemical anomaly. Such anomalies lead to incorrect results.

Table 1 - Content of main oxides in the studied samples of Sarykum (Loi – loss on ignition. Results are presented in % and rounded)

Sample	Loi	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	MnO	K_2O	CaO	MgO	Na_2O	P_2O_5	S	Amount
1	3.93	87.99	1.24	0.10	1.67	0.05	0.18	4.32	0.14	0.27	0.05	0.02	99.95
2	3.39	88.78	1.26	0.08	1.30	0.04	0.18	4.47	0.13	0.27	0.04	0.02	99.96
3	3.24	90.12	1.17	0.09	1.24	0.03	0.18	3.52	0.09	0.23	0.04	0.01	99.96
4	3.75	87.33	1.46	0.09	1.57	0.04	0.23	4.88	0.19	0.32	0.05	0.03	99.94
5	3.48	90.17	1.28	0.10	1.27	0.03	0.21	3.03	0.10	0.24	0.04	0.01	99.97
6	3.90	86.30	1.43	0.10	1.89	0.07	0.21	5.49	0.17	0.30	0.05	0.03	99.94
7	3.58	90.29	1.39	0.11	1.87	0.06	0.21	5.44	0.22	0.29	0.05	0.03	103.53
8	4.98	88.82	1.28	0.10	2.41	0.08	0.18	6.55	0.20	0.26	0.05	0.03	104.93
9	2.39	92.55	1.04	0.06	0.64	0.02	0.15	3.07	0.11	0.04	0.06	0.02	100.15
10	3.35	90.14	1.01	0.07	1.02	0.03	0.14	4.23	0.12	0.04	0.05	0.02	100.21
11	3.25	88.76	1.34	0.10	1.47	0.04	0.22	4.68	0.16	0.09	0.06	0.03	100.21
12	4.90	85.52	1.10	0.05	2.39	0.08	0.21	5.26	0.18	0.21	0.06	0.04	100.00
13	3.56	89.64	0.88	0.03	1.52	0.05	0.17	3.79	0.15	0.15	0.05	0.03	100.01
14	2.62	92.09	0.96	0.03	0.98	0.03	0.19	2.74	0.14	0.17	0.04	0.03	100.01
15	2.98	91.20	0.97	0.03	1.06	0.03	0.19	3.17	0.14	0.18	0.04	0.03	100.01
16	3.61	87.67	1.51	0.13	1.62	0.05	0.25	5.03	0.19	0.10	0.06	0.02	100.23
17	13.47	63.80	1.38	0.13	1.52	0.03	0.24	18.64	0.32	0.31	0.07	0.02	99.93
18	5.64	82.65	1.17	0.08	1.27	0.04	0.20	8.94	0.19	0.10	0.07	0.03	100.38
19	3.11	90.56	0.94	0.04	1.32	0.04	0.19	3.43	0.14	0.17	0.05	0.03	100.01
20	2.68	91.81	0.85	0.03	1.07	0.03	0.17	3.02	0.13	0.16	0.04	0.03	100.02
21	2.82	91.39	1.05	0.06	1.08	0.03	0.21	3.00	0.15	0.18	0.05	0.03	100.02
22	3.02	92.74	1.24	0.09	1.27	0.03	0.20	3.92	0.15	0.27	0.04	0.02	103.00
23	2.91	92.88	1.18	0.09	1.20	0.04	0.19	3.89	0.17	0.27	0.04	0.02	102.88
24	3.74	89.71	0.91	0.05	1.55	0.04	0.19	3.47	0.14	0.14	0.05	0.02	100.01
24	5.45	89.08	1.36	0.11	2.06	0.06	0.22	6.28	0.39	0.29	0.05	0.03	105.39
25	3.75	89.51	1.10	0.05	1.32	0.04	0.22	3.59	0.16	0.19	0.05	0.03	100.01
26	3.04	90.63	1.28	0.06	1.20	0.04	0.27	3.02	0.17	0.22	0.06	0.03	100.01
28	3.12	90.93	0.95	0.04	1.18	0.04	0.20	3.20	0.14	0.16	0.05	0.02	100.02
29	3.20	90.75	0.85	0.02	1.13	0.04	0.17	3.48	0.14	0.16	0.05	0.03	100.01
30	3.64	89.06	1.01	0.03	1.41	0.05	0.19	4.19	0.16	0.19	0.05	0.03	100.01
31	3.62	88.84	0.96	0.04	1.69	0.05	0.17	4.21	0.16	0.18	0.05	0.03	100.01
31	4.34	85.91	1.38	0.13	2.34	0.07	0.21	5.54	0.19	0.08	0.06	0.03	100.29
32	3.34	89.05	1.18	0.10	1.72	0.05	0.19	4.31	0.16	0.06	0.05	0.02	100.23
Min	2.39	63.80	0.85	0.02	0.64	0.02	0.14	2.74	0.09	0.04	0.04	0.01	
Max	13.47	92.88	1.51	0.13	2.41	0.08	0.27	18.64	0.39	0.32	0.07	0.04	
Average value	3.87	88.69	1.15	0.07	1.46	0.04	0.20	4.72	0.17	0.19	0.05	0.02	

Table 2. Content of heavy metals and Ba in the studied samples of Sarykum (Results are presented in ppm and rounded)

	V	Cr	Co	Ni	Cu	Zn	Rb	Sr	Y	Zr	Nb	Ba	Pb
1	0.0	27.0	4.0	3.0	13.0	34.0	5.6	108.0	7.0	73.0	7.0	66.4	17.0
2	0.0	27.0	6.0	5.0	13.0	29.0	4.6	111.0	8.0	54.0	7.0	25.8	32.0
3	0.0	31.0	6.0	5.0	11.0	27.0	3.5	94.0	5.0	63.0	6.0	5.5	27.0
4	0.0	55.0	6.0	6.0	12.0	34.0	11.9	126.0	6.0	85.0	9.0	76.6	32.0
5	0.0	49.0	5.0	7.0	10.0	32.0	4.6	85.0	8.0	77.0	6.0	96.9	16.0
6	0.0	39.0	3.0	8.0	12.0	41.0	4.6	136.0	7.0	97.0	7.0	188.4	36.0
7	0.0	44.0	5.0	7.0	14.0	41.0	4.6	127.0	8.0	62.0	6.0	46.1	51.0
8	0.0	31.0	12.0	7.0	13.0	41.0	2.5	155.0	9.0	51.0	7.0	46.1	31.0
9	10.0	28.0	5.0	4.0	7.0	28.0	18.0	85.0	6.0	38.0	9.0	60.0	24.0
10	5.0	40.0	2.0	6.0	9.0	30.0	15.0	113.0	6.0	48.0	7.0	110.0	36.0
11	10.0	49.0	6.0	7.0	8.0	36.0	19.0	116.0	7.0	84.0	6.0	100.0	32.0
12	12.0	34.0	5.0	23.8	15.0	28.0	9.0	140.0	12.0	64.0	5.3	98.0	16.0
13	16.0	11.0	2.0	14.0	9.4	26.0	8.0	96.0	8.0	45.0	5.3	88.0	7.0
14	18.0	16.0	0.0	11.2	5.0	16.0	7.0	81.0	9.0	59.0	7.1	94.0	7.0
15	15.0	24.0	4.0	16.8	5.0	20.0	8.0	83.0	8.0	57.0	5.3	87.0	8.0
16	10.0	30.0	10.0	5.0	14.0	38.0	19.0	114.0	7.0	115.0	7.0	100.0	37.0
17	3.0	123.0	3.0	14.0	14.0	38.0	17.0	180.0	9.0	117.0	7.0	70.0	51.0
18	10.0	32.0	6.0	5.0	4.0	34.0	15.0	185.0	10.0	60.0	7.0	80.0	30.0
19	18.0	19.0	3.0	15.4	10.5	22.0	8.0	87.0	9.0	66.0	5.3	105.0	5.0
20	5.0	23.0	1.0	8.4	3.9	19.0	6.0	81.0	9.0	60.0	7.1	79.0	4.0
21	11.0	12.0	2.0	5.6	7.2	22.0	10.0	81.0	10.0	58.0	7.1	113.0	8.0
22	0.0	21.0	10.0	4.0	12.0	35.0	7.7	99.0	6.0	68.0	6.0	5.5	40.0
23	0.0	26.0	8.0	3.0	12.0	31.0	3.5	98.0	7.0	75.0	8.0	66.4	42.0
24	13.0	14.0	4.0	12.6	8.3	22.0	5.0	92.0	10.0	61.0	7.1	117.0	9.0
24	0.0	42.0	9.0	7.0	11.0	40.0	7.7	152.0	10.0	113.0	8.0	86.8	40.0
25	21.0	39.0	2.0	19.6	9.4	25.0	8.0	94.0	10.0	73.0	7.1	76.0	5.0
26	15.0	26.0	1.0	16.8	3.9	21.0	10.0	84.0	9.0	63.0	5.3	119.0	5.0
28	5.0	14.0	5.0	9.8	10.5	20.0	7.0	82.0	9.0	60.0	7.1	75.0	11.0
29	22.0	15.0	1.0	11.2	6.1	19.0	6.0	90.0	9.0	50.0	5.3	107.0	9.0
30	11.0	9.0	5.0	12.6	8.3	23.0	7.0	105.0	10.0	47.0	7.1	92.0	8.0
31	16.0	21.0	3.0	14.7	10.5	24.0	7.5	109.0	9.5	51.0	7.1	64.0	7.5
31	1.0	35.0	9.0	8.0	12.0	39.0	19.0	133.0	8.0	123.0	7.0	140.0	32.0
32	9.0	27.0	9.0	6.0	13.0	38.0	18.0	111.0	9.0	67.0	7.0	10.0	32.0
Min	0.0	9.0	0.0	3.0	3.9	16.0	2.5	81.0	5.0	38.0	5.3	5.5	4.0
Max	22.0	123.0	12.0	23.8	15.0	41.0	19.0	185.0	12.0	123.0	9.0	188.4	51.0
Average value	7.8	31.3	4.9	9.4	9.9	29.5	9.3	110.1	8.3	69.2	6.8	81.7	22.7

Table 3. Results of calculations of the main weathering indices (CIA, CIW, PIA) and WIS .

	CIA	CIW	PIA	WIS
1	63.27	69.66	54.08	0.24
2	63.64	70.00	54.55	0.21
3	64.64	71.78	54.70	0.24
4	62.66	69.52	52.79	0.22
5	64.97	72.73	54.31	0.28
6	63.84	70.44	54.46	0.22
7	63.76	70.56	54.13	0.22
8	64.65	71.11	55.56	0.21
9	82.53	93.69	70.63	0.21
10	82.78	93.51	71.31	0.19
11	76.84	87.93	64.22	0.22
12	63.20	71.97	51.01	0.24
13	65.21	74.47	52.78	0.23
14	64.57	73.93	51.91	0.25
15	64.27	73.29	51.96	0.23
16	76.78	87.96	64.07	0.23
17	61.61	69.00	50.89	0.07
18	74.21	84.99	61.52	0.12
19	64.23	73.65	51.44	0.24
20	63.35	72.58	50.64	0.23
21	64.99	74.48	52.24	0.25
22	62.63	69.66	52.53	0.23
23	61.78	68.60	51.83	0.22
24	65.73	76.15	52.05	0.25
24	62.96	70.10	52.78	0.20
25	64.59	74.12	51.73	0.24
26	64.78	74.83	51.36	0.27
28	64.25	74.31	50.71	0.24
29	63.51	72.60	51.01	0.21
30	64.15	72.93	52.12	0.21
31	64.02	72.26	52.63	0.23
31	78.81	89.54	66.81	0.24
32	79.43	91.08	66.64	0.24

CONCLUSION

Based on the data obtained, a geochemical characterization of the soil of the Sarykum sand complex was carried out. The data obtained are supposed to be used to study the paleoclimatic history of the complex and the origin of the Sarykum material. The study also shows that it is promising to use WIS as a geochemical indicator of desert overgrowth to assess biological weathering. In the future, it is planned to obtain new statistical data and systematize the results obtained.

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Assessing Energy Intensity and Renewable Integration: A Cross-Country Study of Serbia, Hungary, and Croatia

Procena energetskog intenziteta i integracije obnovljivih izvora energije: komparativna studija Srbije, Mađarske i Hrvatske

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Abstract: This study performs a comparative analysis of energy efficiency and renewable energy integration in Serbia, Croatia, and Hungary. Using the most recent harmonised data from the International Energy Agency and the World Bank, the paper examines a set of key indicators: primary energy intensity, total final energy consumption, sectoral distribution (industry, transport, residential), share of renewables in final consumption, and electricity consumption per capita.
The research aims to identify structural differences in energy profiles among the three countries, with particular attention to the influence of differing institutional frameworks - Serbia as a contracting party of the Energy Community versus Croatia and Hungary as full EU member states. The analysis highlights how policy frameworks, energy mix composition, and economic structure shape efficiency outcomes and renewable deployment trajectories. By placing Serbia's performance in a regional comparative context, the study offers insights and policy implications for accelerating Serbia's alignment with EU 2030 energy and climate objectives and the Green Agenda for the Western Balkans commitments.

Keywords: energy efficiency, energy intensity, renewable energy, Serbia, Croatia, Hungary, comparative analysis.

Sažetak: Ova studija sprovodi uporednu analizu energetske efikasnosti i integracije obnovljivih izvora energije u Srbiji, Hrvatskoj i Mađarskoj. Koristeći najnovije harmonizovane podatke Međunarodne agencije za energiju i Svetske banke, rad ispituje skup ključnih indikatora: primarni energetski intenzitet, ukupnu potrošnju konačne energije, sektorsku distribuciju (industrija, transport, stanovanje), udeo obnovljivih izvora energije u konačnoj potrošnji i potrošnju električne energije po glavi stanovnika.
Istraživanje ima za cilj da identifikuje strukturne razlike u energetskim profilima između tri zemlje, sa posebnom pažnjom na uticaj različitih institucionalnih okvira - Srbije kao ugovorne strane Energetske zajednice naspram Hrvatske i Mađarske kao punopravnih zemalja članica EU. Analiza ističe kako politički okviri, sastav energetskog miksa i ekonomska struktura oblikuju rezultate efikasnosti i putanje primene obnovljivih izvora energije. Postavljanjem učinka Srbije u regionalni uporedni kontekst, studija nudi uvide i političke implikacije za ubrzavanje usklađivanja Srbije sa ciljevima EU u oblasti energije i klime do 2030. godine i obavezama iz Zelene agende za Zapadni Balkan.

Ključne reči: energetska efikasnost, energetski intenzitet, obnovljivi izvori energije, Srbija, Hrvatska, Mađarska, uporedna analiza.

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INTRODUCTION

Global efforts to mitigate climate change and enhance energy security have positioned energy efficiency and renewable energy integration as foundational pillars of sustainable development. The European Union (EU) has intensified its ambitions through the revised Energy Efficiency Directive (EED; Directive (EU) 2023/1791), which entered into force on October 10, 2023, and mandates a binding 11.7% reduction in primary and final energy consumption by 2030 relative to 2020 projections (European Parliament & Council of the European Union, 2023a). This revision escalates annual energy savings obligations, rising from 1.3% in 2024-2025 to 1.9% by 2028-2030, embedding the "energy efficiency first" principle across energy and non-energy policies to accelerate decarbonization and reduce import vulnerabilities (European Commission, 2024a). Complementing this, the updated Renewable Energy Directive (RED III; Directive (EU) 2023/2413) targets at least 42.5% renewable energy in gross final consumption by 2030, with an aspirational 45%, emphasizing sector-specific integration in heating, cooling, and transport (European Parliament & Council of the European Union, 2023b).

These frameworks are especially pertinent to Central and Eastern European nations, where energy intensity - defined as primary energy supply per unit of GDP - averages 50-70% above the EU-27 benchmark of ~2.6 MJ/2021 USD PPP GDP in 2023, stemming from aging infrastructure, and fossil fuel dependencies (International Energy Agency [IEA], 2024a; Eurostat, 2024). In the agricultural sector, which constitutes a significant portion of energy use in rural economies like Serbia's (over 20% of GDP contribution), inefficient machinery and irrigation systems further amplify intensity, underscoring the need for bioenergy and precision farming to align with EU green standards. Croatia and Hungary, as EU members since 2013 and 2004 respectively, face enforceable transposition deadlines by October 2025 for the EED and May 2025 for RED III, driving investments in renewables and efficiency via the Governance Regulation (EU) 2018/1999 and updated National Energy and Climate Plans (NECPs) due in June 2024 (European Commission, 2024b). In contrast, Serbia, a contracting party to the Energy Community Treaty since 2006, aligns progressively with EU acquis through its revised Energy Law (2023) and draft NECP, which targets a 41.21% greenhouse gas reduction from 1990 levels, 43.62% renewables in final consumption, and capped primary/final energy at 6.84/4.34 Mtoe by 2030 (Energy Community Secretariat, 2023a; Ministry of Mining and Energy of Serbia, 2023). Serbia's first renewables auction in 2023 awarded 400 MW wind and 11.6 MW solar, signaling momentum toward 1.3 GW by 2025, though grid constraints and permitting delays persist (Climatescope, 2024; Energy Community Secretariat, 2023b).

The Western Balkans, including Serbia, commit to net-zero by 2050 under the 2020 Sofia Declaration and the Energy Community's Decarbonisation Roadmap, yet face a renewables deployment gap: only 33% of Serbia's 8.5 GW capacity is renewable-dominated by hydropower, compared to Croatia's hydro-led 30.63% share and Hungary's nuclear-constrained 16.41% (Agora Energiewende, 2023; IEA, 2024a). In achieving green goals, Serbia is primarily focused on the development of RES technologies and energy generation from renewable sources. However, as global uncertainty over energy resources grows, and despite the existing moratorium on the use of nuclear energy, interest in reopening this issue is emerging once again (Jovanović & Stojkov Pavlović, 2025). The policy of greening the economy is a way to solve economic and environmental problems that have been present for years, and especially a way to support production and consumption based on less consumption of natural and energy resources and less waste, i.e., less exploitation of natural capital (Andrejević Panić et al., 2024) Recent progress includes Serbia's unbundling of transmission operators and Montenegro's sustained leadership in Energy Community compliance, but regional challenges like lignite reliance (40-95% of electricity in some areas) and underutilized solar/wind potential (1,011 MW wind/897 MW solar installed end-2023) underscore the need for accelerated auctions, storage integration, and cross-border cooperation (Energy Community Secretariat, 2023a; Atlantic Council, 2024). As energy systems become more complex and data-intensive, the application of AI and big data analytics will not only support smarter decisionmaking but also unlock new potentials for cost reduction and performance optimization. Investing in these digital technologies, especially in the context of already cost-competitive renewable energy solutions, represents a strategic pathway toward achieving global decarbonization goals and ensuring long-term energy security (Jovamović & Stojkov Pavlović, 2025).

Despite abundant single-country analyses, such as the IEA's 2022 Hungary review and 2023 Serbia sector insights, comprehensive cross-country comparisons using 2022-2023 data are limited, particularly amid the 2023-2024 surge in renewables (over 560 GW globally added in 2023, with uneven regional uptake) (IEA, 2024a; IEA, 2022). This study bridges that void by scrutinizing macro- and sectoral indicators - energy intensity, final consumption shares, renewables penetration, and per capita electricity use - to illuminate structural disparities. For Serbia, aspiring to EU accession, these insights highlight transferable strategies: Croatia's EU-funded hydro synergies for renewables scaling and Hungary's nuclear baseload for stability, while addressing residential inefficiencies (34.7% of Serbia's final consumption) via building retrofits. By integrating post-2023 policy shifts, the analysis informs equitable transitions, emphasizing that diversified mixes - renewables, nuclear, and efficiency - can cut costs 15% below fossil baselines by 2045 in the Western Balkans (Agora Energiewende, 2023).

1. MATERIALS AND METHODS

The study adopts a comparative quantitative design based on secondary data from internationally harmonized sources: the International Energy Agency's Energy Statistics Data Browser (IEA, 2025) and the World Bank's World Development Indicators (World Bank, 2025). The analysis covers 2022-2023, the most recent years with complete datasets at the time of writing.

Seven indicators were selected (Table 1): Energy intensity of primary energy (MJ/2021 USD PPP GDP), Total final energy consumption (TJ), Sectoral shares of final energy consumption (industry, transport, residential; %), Share of renewable energy in final consumption (%), Electricity consumption per capita (MWh).

All values were normalized where necessary (e.g., purchasing-power-parity adjustment) to ensure cross-country comparability. Descriptive statistics and visual comparison were employed;

2. RESEARCH AND DISCUSSION

This section examines a selected group of energy indicators for Serbia, Croatia, and Hungary. The measures include energy intensity, sectoral distribution of final energy consumption, renewable energy share, and electricity use per capita. Together, they provide a basis for comparing national energy profiles and identifying structural differences across the three countries.

Table 1 - Comparative Energy Efficiency Indicators for Serbia, Croatia, and Hungary (2022-2023)

Indicator	Serbia	Croatia	Hungary
Energy intensity (MJ/2021 USD PPP GDP)	5.02	2.75	3.12
Total final consumption (TJ, 2023)	409317	300987	778485
Industry share of final consumption (%)	22.1	16.3	21.4
Transport share of final consumption (%)	26.8	34.5	26.4
Residential share of final consumption (%)	34.7	30.7	28.6
Renewable energy share in final consumption (%)	25	30.63	16.41
Electricity consumption per capita (MWh, 2023)	5.09	4.484	4.802

Sources: Author's systematization aggregated from IEA (2025) & World Bank (2025)

Serbia records the highest primary energy intensity (5.02 MJ/2021 USD PPP GDP), approximately 80 % above the EU-27 average and 62 % higher than Hungary, the second-ranked country. This elevated intensity reflects both a coal-dominated electricity mix (over 60 % of generation) and persistent inefficiencies in end-use sectors, particularly residential buildings (IEA, 2024a). Croatia exhibits the lowest energy intensity (2.75 MJ/2021 USD PPP GDP), benefiting from a more diversified and less carbon-intensive energy system, while Hungary occupies an intermediate position (3.12 MJ/2021 USD PPP GDP).

Total final energy consumption scales with economic and population size: Hungary consumes roughly 2.6 times more energy in absolute terms than Croatia and almost twice as much as Serbia, consistent with its larger GDP and industrial base. When normalized, however, per-capita electricity consumption remains highest in Serbia (5.09 MWh), followed by Hungary (4.80 MWh) and Croatia (4.48

MWh), suggesting comparatively lower residential and service-sector efficiency in Serbia.

Sectoral distribution further highlights distinct demand profiles. The residential sector accounts for the largest share in Serbia (34.7 %), indicating widespread use of direct electricity for heating and limited district heating or natural gas penetration outside major cities. Transport dominates in Croatia (34.5 %), driven by intensive tourism and transit traffic along the Adriatic corridor. Hungary presents the most balanced structure, with industry, transport, and residential sectors each contributing roughly one-fifth to one-third of final consumption.

Renewable energy penetration shows the sharpest divergence: Croatia reaches 30.63 % of final consumption (well above its 2030 target of 36.4 % under the updated NECP), primarily through hydropower. Serbia achieves 25.00 %, reflecting gradual progress in wind and biomass deployment following its first market-based auctions in 2023. Hungary records the lowest share (16.41 %), despite significant solar additions in recent years, because nuclear power - which supplied nearly 50 % of electricity in 2023 - is excluded from the renewable energy statistic under both EU and Energy Community methodologies (IEA, 2022, 2024a).

Taken together, the indicators in Table 1 underscore that energy efficiency performance is driven not only by economic structure and resource endowment but also by the degree of integration into binding EU regulatory frameworks and the composition of the low-carbon generation mix.

A bar chart visualization (Figure 1) illustrates adoption disparities, emphasizing the need for targeted interventions

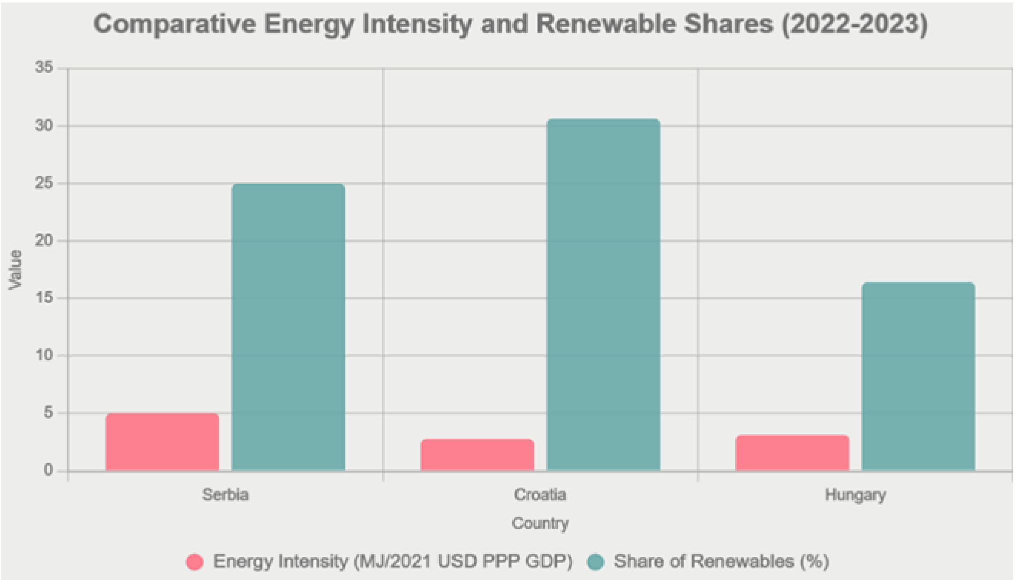

Figure 1 - Energy Intensity and Renewable Energy Share (2022-2023)
Source: Author‘s figure

Serbia exhibits the highest primary energy intensity (5.02 MJ/2021 USD PPP GDP), almost twice the EU-27 average of approximately 2.6 MJ in 2022 (Eurostat, 2024). This reflects persistent structural inefficiencies, particularly in the residential building stock and coal-dominated electricity generation (IEA, 2023). Croatia records the lowest intensity (2.75) and the highest renewable share (30.63%), largely attributable to hydropower and EU-funded incentive schemes (Ministry of Economy and Sustainable Development of Croatia, 2024). Hungary's low renewable share (16.41%) is explained by the dominant role of the Paks Nuclear Power Plant, which supplied nearly 50% of electricity in 2023 while contributing zero percent to the official renewable energy statistic (Hungarian Energy and Public Utility Regulatory Authority, 2024; IEA, 2022b).

Sectoral analysis reveals further divergences. Transport accounts for 34.5% of final consumption in Croatia due to intensive tourism and transit traffic, whereas Serbia's residential sector (34.7%) indicates widespread use of inefficient electric heating and poor building insulation (Statistical Office of the Republic of Serbia, 2024).

CONCLUSION

The comparative examination of Serbia, Croatia, and Hungary confirms that energy efficiency and renewable energy integration are not merely technical issues, but outcomes deeply embedded in institutional, economic, and historical contexts. While all three countries share a common legacy of energy-intensive economies, their current trajectories have diverged significantly due to differing degrees of European integration and strategic choices in the energy mix.

Croatia illustrates how geographical advantages (abundant hydropower) combined with full EU membership and access to substantial cohesion and recovery funding can rapidly advance both efficiency gains and renewable penetration. Hungary demonstrates that a deliberate focus on nuclear power can deliver low-carbon electricity and relative price stability, yet at the cost of slower progress toward binding renewable energy targets. Serbia, still in the pre-accession phase, continues to carry the heaviest efficiency burden, particularly in the residential sector, and remains overly dependent on coal despite recent policy reforms and initial market-based renewable auctions.

These contrasting pathways underscore that there is no single “optimal” model for the region. Instead, success depends on context-specific policy packages that simultaneously address supply-side decarbonisation, end-use efficiency, and social acceptability. For Serbia, the most immediate leverage points lie in aggressive building renovation programmes, removal of administrative barriers to renewable projects, and strategic use of available EU pre-accession assistance and Just Transition resources. Only through sustained implementation of such measures will Serbia be able to narrow the efficiency gap with its EU neighbours and credibly advance toward the 2030 targets of both the Energy Community and the Green Agenda for the Western Balkans.

Ultimately, the experience of Croatia and Hungary offers Serbia not ready-made solutions, but valuable reference points for designing a nationally tailored yet EU-compatible transition strategy that balances energy security, affordability, and climate ambition.

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Influence of toxicity of the environment and physiological state of fish on the bioaccumulation of essential elements in their organs and tissues

Uticaj toksičnosti životne sredine i fiziološkog stanja riba na bioakumulaciju esencijalnih elemenata u njihovim organima i tkivima

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Abstract: The distribution of essential elements among organs and tissues in a number of water bodies with different water toxicity is considered using the example of *Abramis bream brama L*. Models have been constructed for the redistribution of essential elements in the liver and kidney of fish depending on the physiological state. It has been shown that essential elements can serve as markers of the intensity and direction of metabolic processes in the fish body.

Keywords: essential elements, fish, bioaccumulation, physiological state, toxicity of the environment.

Sažetak: Raspodela esencijalnih elemenata među organima i tkivima u brojnim vodenim telima sa različitom toksičnošću vode razmatrana je na primeru deverike (*Abramis bream brama L.*). Konstruisani su modeli za preraspodelu esencijalnih elemenata u jetri i bubrezima riba u zavisnosti od fiziološkog stanja. Pokazano je da esencijalni elementi mogu služiti kao markeri intenziteta i pravca metaboličkih procesa u telu riba.

Ključne reči: esencijalni elementi, riba, bioakumulacija, fiziološko stanje, toksičnost životne sredine..

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INTRODUCTION

In connection with the widespread pollution of water bodies with microelements in recent years, a large number of publications have been devoted to the study of the content of toxic elements in fish organisms. However, during the process of metabolism, the ratio of essential and non-essential elements in various organs and tissues of fish changes. The work (Moiseenko & Kudryavtseva, 1999) noted a decrease in the provision of functionally important organs with essential elements due to toxic water pollution.

Essential elements are required in physiological quantities for biological life due to their participation in metabolic reactions as cofactors or constituents of enzymes (Wood et al., 2012).

The purpose of the work was to study the content of essential elements in organs and tissues depending on the toxicity of the habitat, as well as their redistribution in functionally important organs (liver, kidney) depending on the physiological state of the fish.

1. METHODS

The work was based on previously obtained materials from a survey of bream (*Abramis brama L.*) in the Volga River (Moiseenko et al., 2005, 2005a) and in Lake Silver (Gashkina et al., 2015), as well as new materials obtained in early autumn 2015 г. for the examination of bream in the lake Valdai.

The material was processed using general biological methods (Pravdin, 1966). Hematological analysis was carried out immediately after capture only on live fish. Body mass index (fatness) was calculated according to Fulton, where fishing length was used. To unify the studies, samples of organs and tissues were taken from fish of a similar age composition, with gonads at stages III - IV of maturity in the fall, which allows minimizing age-related, gender and seasonal variations in the content of elements in the body and determines similar endogenous conditions of bioaccumulation. Sample preparation was carried out by wet decomposition in concentrated nitric acid with the addition of hydrogen peroxide. Concentrations of elements in samples of tissues and organs of fish from the lake Valdai and in lake water were determined by mass spectrometry with inductively coupled plasma (X-7, Thermo Scientific, USA) .

The general physiological state of the body was assessed using the morbidity index Z according to the method proposed in (Moiseenko, 2005), according to 3 stages of morbidity: 1 – minor changes in organs and tissues, 2 – clearly visible disorders, 3 – significant pathological changes in the body.

2. RESULTS AND DISCUSSION

The toxicity of the habitat can be determined on the basis of normalizing the concentrations of elements of hazard classes 1-3 to their maximum permissible values for fishery reservoirs (List of fishery standards, 1999). The total indicator of the degree of water pollution for the lake Valdai was 1.2 without exceeding the MPC for any element, and the concentrations of Hg, Cu, Ni, Co and Cr were below the detection threshold. For the Upper and Middle Volga, this indicator averaged 5, exceeding the toxicological threshold for V (1.5 times) and Cu (2 times). For the Lower Volga, the degree of water pollution is higher and equal to 8, with the toxicological threshold exceeded for V (2.5 times) and Cu (2 times), as well as for Sr (1.3 times). The degree of pollution of the lake waters. Silver reaches 40, exceeding the toxicological threshold for Hg (4 times), Pb (2 times), Cu (23 times) and Zn (8 times).

The distribution of essential elements among the organs and tissues of bream from the studied reservoirs is presented in Table 1. Noteworthy is the lower content of Ca in the skeleton and gills of bream from the river Volga. Ca is poorly absorbed from food and enters the fish body mainly from water through the gills and body surface, and the ratio of Ca to Mg in water equal to 3.7 is optimal for the penetration of Ca ions into the fish body (Sorvachev, 1982). The ratio of Ca to Mg in water closest to optimal is observed in lake Silver, while in the water of the Volga River this ratio is greater than 5. Mg, like Ca, forms a depot in muscle, gill and skeletal tissues; its content is relatively uniform in these tissues of bream for all studied water bodies. However, a tendency towards a decrease in its content in the kidney and liver of bream is observed in a number of reservoirs with an increase in the toxicity of the environment.

Na contents are observed in the osmoregulatory organs – kidneys and gills. The increased concentration of Na in water in the Lower Volga does not affect its accumulation in the body. At the lowest concentration of Na in water, bream from Lake. The silver content in all organs and tissues, with the exception of skeletal ones, is higher than in those of the bream of the lake Valdai. The K content is relatively uniform across organs and tissues. At a low concentration of K in water in the Middle Volga, there is a reduced accumulation of it in the liver of fish, which is compensated by a reduced accumulation of Na.

At the concentration of Zn in lake water. When silver is 8 times higher than the toxicological threshold, significant bioaccumulation is observed only in the gills of fish. As the toxicity of the habitat increases, the accumulation of Zn in the liver and kidney of bream decreases. In the lake Valdai concentrations of Cu in water were below the detection threshold, however, in bream it was completely redistributed to the most critical sites of metabolism (liver, kidney). In the lake At Cu concentrations in water many times higher than the toxicological threshold, silver exhibits significant cumulative effects in bream, especially in the gills and liver.

Mn plays an exceptional role in the growth and formation of connective tissue of cartilage and bone, and its maximum levels are observed in the gills and skeleton of fish. The Mn content in the organs and tissues of bream is highly variable in the water bodies under consideration. High concentrations of Mn in water were observed in the Upper Volga; however, increased concentrations were observed only in the muscles and liver of fish. The greatest accumulation of Co is observed in the kidney, as well as in the hematopoietic organ. In the lake Valdai concentration of Co in water was below the detection threshold, but this deficient element was redistributed into the kidney of bream. With an increase in Co concentration in water, an increase in its accumulation in the kidney of bream is observed.

Table 1 - Average and standard deviations of element contents in water, organs and tissues of bream (Ca, Mg, Na and K mg/l and mg/g dry weight, Zn, Cu, Mn and Co µg/l and µg/g dry weights, respectively), caught from the lakes Valdai and Silver, as well as the river Volga.

Water	Water	Liver	Bud	Gills	Muscles	Skeleton
Ca						
Lake Valdai	35.4	0.24± 0.11	0.59± 0.31	117± 45.4	0.89± 0.29	143± 18.7
Upper Volga	27.8	0.44 ± 0.73	0.59 ± 0.77	69.7 ± 5.28	3.6 9 ± 0.96	97.5 ± 14.1
Middle Volga	36.0	0.23± 0.11	0.47± 0.23	79. 6 ± 8.03	3.68 ± 1.09	127 ± 8.76
Lower Volga	34.7	0.13± 0.37	0.39± 0.41	65.5 ± 9.39	2.33 ± 1.35	113± 1 2.4
Lake Silver	15.1	0.35± 0.13	0.67± 0.09	125 ± 33.7	1.57 ± 1.21	153± 17.8
Mg						
Lake Valdai	5.6	0.62 ± 0.04	0.76 ± 0.06	4.33 ± 0.9 4	1.33 ± 0.05	2.67 ± 0.19
Upper Volga	5.9	0.60 ± 0.10	0.6 9 ± 0.06	2.78 ± 0.16	1.37 ± 0.10	2.84 ± 2.62
Middle Volga	6.0	0.45 ± 0.10	0.91± 0.44	3 .23± 0.3 6	1 .27± 0.17	2.25 ± 0.18
Lower Volga	7.3	0.49 ± 0.13	0.6 7 ± 0.09	2.88 ± 0.28	1 .26± 0.11	2.20 ± 0.30
Lake Silver	3.9	0.51 ± 0.10	0.58± 0.09	5.00± 1.49	1 .63± 0.26	3.15± 0.3 6
Na						
Lake Valdai	8.7	1.33 ± 0.06	3 .10± 0.3 6	6.59± 3.14	0.58± 0.12	5.33± 0.78
Upper Volga	3.2	2.78 ± 0.62	5.76± 0.56	5.43± 0.40	1.05 ± 0.16	5.36± 4.81
Middle Volga	3.8	1 .70± 0.51	4.62± 2.12	4.59± 0.86	0.6 9 ± 0.1 9	4.03± 0.37
Lower Volga	14.9	1.83 ± 0.38	4.00± 0.73	5.02± 0.59	0.7 8 ± 0.14	4.20± 0.56
Lake Silver	2.8	4.10 ± 0.9 6	5.76± 0.56	11.4± 5.51	1 .23± 0.05	5.40± 0.43
K						
Lake Valdai	3.1	8.94± 0.36	12.3± 0.62	11.5± 3.81	17.5± 0.61	8.12± 4.96
Upper Volga	1.4	9.19± 1.76	11.1± 1.98	7.37± 1.45	17.1± 1.58	7.17± 4.50
Middle Volga	0.5	4.56± 1.43	12.0± 7.68	5.62± 0.97	11.5± 1.03	2.68 ± 0.55
Lower Volga	2.8	6.21± 1.22	10.6± 1.52	6.46± 0.72	13.2± 1.98	3 .40± 0.82
Lake Silver	2.3	9.00± 1.92	11.3± 1.34	10.9± 5.05	18.0± 0.79	5.54± 0.80
Zn						
Oz. Valdai	2.1	130 ± 20.8	113± 3.38	124± 10.7	19.6± 4.50	86.5± 19.0
Upper Volga	4.1	106± 22.1	9 4.2± 9.06	83.3± 8.36	17.8± 1.93	80.3± 62.5
Middle Volga	1.0	7 9.6 ± 24.6	121± 135	81.2± 6.96	20.0± 3.44	64.7± 7.50
Lower Volga	6.3	110± 37.6	88.2± 11.6	81.4± 5.64	25.0± 4.50	7 1.3± 7.46
Lake Silver	80.5	106± 43.4	7 5.0± 12.4	200± 81.8	13.1± 1.61	80.0± 19.6
Cu						
Lake Valdai	< 0.6	82.1± 41.0	5.16± 0.28	< 0.03	< 0.03	< 0.03
Upper Volga	2.1	51.1± 19.5	5.63± 1.68	2.39 ± 0.24	0.69± 0.14	0.90± 0.59
Middle Volga	1.1	35.5± 28.9	10.6± 18.7	1.95 ± 0.32	0.75± 0.28	0.44± 0.21
Lower Volga	2.0	89.3± 40.2	5.70± 1.65	4.22± 1.13	1.07 ± 0.28	2.55 ± 0.19
Lake Silver	23.1	235± 247	8.74± 1.41	31.7± 31.0	2.57 ± 1.37	1.41 ± 0.79
Mn						
Lake Valdai	26.5	4.96± 1.09	5.25± 0.45	117± 24.4	0.99± 0.42	64.5± 5.24
Upper Volga	108	8.28± 1.50	6.39± 1.41	9 3.3± 22.3	4.57± 1.32	82.2± 101
Middle Volga	34.4	7.51± 2.63	6.19± 4.18	64.4± 16.5	3.12 ± 0.75	54.2± 18.3
Lower Volga	28.4	6.23± 1.69	3 .49± 1.20	28.9± 5.37	1.24 ± 0.58	26.5± 3.57
Lake Silver	34.0	6.93± 1.14	6.47± 1.53	144± 45.1	1.82 ± 2.32	82.9± 6.87
Co						
Lake Valdai	< 0.08	0.10± 0.04	0.59± 0.16	< 0.01	0.06± 0.05	< 0.01
Upper Volga	0.33	0.44± 1.31	0.95± 0.41	0.13± 0.08	0.03± 0.03	< 0.01
Middle Volga	0.17	0.21± 0.10	1 .30± 0.54	0.55± 0.20	0.18± 0.07	0.37± 0.29
Lower Volga	0.90	0.17± 0.08	1.67 ± 0.93	0.34± 0.28	0.15± 0.10	0.19± 0.25
Lake Silver	1.15	0.14± 0.05	1.99 ± 0.52	0.43± 0.20	0.04± 0.05	0.18± 0.04

The physiological state of bream in the studied reservoirs was assessed by the axis of hemoglobin content in the blood (Hb), general morbidity (Z) and body mass index (k) (Table 2). According to (Zhiteneva et al., 1989), the concentration of Hb in the blood of healthy bream is in the range of 92-101 g/l. The Hb content above the upper limit indicates the first response of the hematopoietic system (mobilization of protective functions) to unfavorable conditions or the effects of toxicants, while a decrease in Hb below the norm indicates the development of anemia, destruction of the hematopoietic system, which, as a rule, is accompanied by developing pathologies in the functional important organs (liver, kidneys) of fish (Moiseenko, 1998). The average Hb content in the blood of bream decreases with increasing anthropogenic load on the reservoir. In the Lower Volga there were practically no individuals with Hb concentrations above the upper limit, and more than half of the examined individuals had Hb concentrations below normal, which indicates a significant number of fish with pathological abnormalities in the body. Unfortunately, hematological studies of bream from Lake. There were no silver coins.

With increasing toxicity of waters, there is an increase in the incidence of fish diseases. If the breams of the lake Valdai almost all corresponded to the “norm”, then more than half of the bream from the river Volga, especially on the Lower Volga, and lake Silver were at the 2nd and 3rd stages of the body's disease.

The Fulton or Clark fatness coefficient turns out to be convenient in assessing the physiological status of fish, especially with varying toxicity of the habitat. Because this indicator does not always clearly reflect the fat content of the fish; it is better to use the name – body mass index (k). An increase in the toxicity of the environment is manifested in a trend towards a decrease in body mass index and a significant decrease in its minimum values (Table 2).

Table 2 - Indicators of the physiological state of fish in the surveyed water bodies (Hb - hemoglobin concentration, Z - general morbidity, k - and body mass index, n - number of examined individuals, numerator - average value, denominator - limits of variation, dash - no data)

Water	n	Hb, g/l	Z	k
Lake Valdai	4	103 81-116	0.3 0-1	2.11 2.08-2.17
Upper Volga	14	98 81-118	1.9 0-3	2.24 1.97-2.45
Middle Volga	15	103 82-117	1.9 1-3	2.25 1.91-2.52
Lower Volga	15	87 56-102	2.1 1-3	2.07 1.82-2.17
Lake Silver	5	-	2.2 2-3	1.98 1.75-2.21

To analyze the structure of redistribution of essential elements in the liver and kidney of bream, depending on the physiological state, the apparatus of multivariate linear regression analysis was used Table 3. To establish the generality of responses, multiparameter relationships were obtained in two systems: under more and less homogeneous exogenous conditions of the river Volga and all studied water bodies with strong variability in habitat toxicity.

Changes in the Hb content in the blood of fish are most associated with changes in the Cu content in the liver of breams. The liver plays a major role in the metabolism of Cu, where it is incorporated into ceruloplasmin for transport to other organs or excreted from the body with bile (Wood et al., 2012). Apparently, at the stage of mobilization of the body’s protective functions and increased hematopoiesis, there is intensive transport of ceruloplasmin from the liver, while at the stage of anemia development, Cu accumulation occurs with reduced excretion. There is also a statistically significant change in the K content in the liver and kidneys of bream. In aquarium experiments with long-term exposure of rainbow trout to water with a Cu concentration of 40 μg/l, the following chronic effects were observed: high accumulation of Cu in the liver and gills, an increase in the K content in the liver and its decrease in the blood plasma without changes in the concentrations of Ca and Na, while the increase in K in the liver was explained by a possible connection with Cu excretion in bile (Tellis et al., 2012). In the kidney of bream, with an increase in Hb in the blood, the Mn content significantly increases, which can serve as a sign of activation of the body’s defense systems. Thus, the activity of copper- and zinc-containing superoxide dismutase (SOD) decreases in the series: liver, kidneys, and the activity of manganese-containing SOD decreases in the series: kidneys, liver (Volykhina & Shafranovskaya, 2009). In aquarium experiments, the maximum SOD activity was observed in the kidneys of goldfish in the control and its significant increase during 4-day exposure to water with a high concentration of Mn (Vieira et al., 2012).

Table 3 - The value of t -statistics in models of redistribution of the contents of essential elements in the liver and kidney of bream depending on Hb, Z and k in the river Volga (numerator) and for all studied reservoirs (denominator). Significantly significant values are highlighted in bold; values are insignificant with a dash.

Organ	***r***	**Ca**	**Mg**	**Na**	**K**	**Zn**	**Cu**	**Mn**	**Co**
				Hb					
Liver	0.65 / 0.50	- / -	- / -	1.7 / -	**-2.7** / -1.6	1.4 / 1.3	**-3.0** / **-2.5**	- / -	- / -
Bud	0.66 / 0.63	- / -	- / -	- / -	**-2.6** / **-2.3**	- / -	- / -	**3.0** / **3.3**	- / -
				Z					
Liver	0.45 / 0.56	2.0 / **2.2**	- / -	- / 1.3	- / -	-1.4 / -1.3	- / 1.2	- / -	- / -
Bud	0.35 / 0.65	- / -	- / -	**3.1** / -	- / -	- / -	- / -	-1.8 / **-2.3**	- / -
				k					
Liver	0.64 / 0.64	**-2.4** / **-2.8**	- / -	- / -	- / -	**2.4** / **2.1**	**-3.0** / **-2.9**	- / 1.5	- / -
Bud	0.64 / 0.60	- / -1.4	- / 1.4	-2.0 / -	- / -	1.4 / -	-1.9 / -1.5	**2.6** / **2.3**	-1.7 / -

Models of variation in essential elements depending on the general morbidity of the fish body are more effective when all water bodies are considered (Table 3). In the liver of fish, with increasing stage Z, the Ca content increases, which indicates degenerative processes in hepatocytes. At the cellular level, an increase in Ca content may indicate a change in cellular metabolic processes through signaling systems, which is associated with a violation of the transport properties of cell membranes. “Calcium overload” is associated with an increase in membrane permeability for Ca, with the activation of slow calcium channels and the entry of Ca ions into the cell along a concentration gradient, and in the case of total destruction of membranes, with the continuity of active transport of Ca from the blood into the mitochondrial matrix, competitively displacing Mg ions, which are activators of adenylate cyclase, reducing its activity and, in addition, it activates Ca^{2+} - dependent phosphodiesterase, which enhances the hydrolysis of cAMP (Kirichek & Zubova, 2004). For bream r. Volga, histological studies of the liver of fish at the 3rd stage of disease revealed serious morphofunctional changes, manifested in the form of fatty and hydropic degeneration (Moiseenko et al., 2005).

In the bream kidney, with increasing Z, there is a significant decrease in the Mn content, which may indicate not only a decrease in the antioxidant defense system, but also a decrease in the activity of non-ureotelic type arginase, thereby increasing cytotoxicity. The work (Agadzhanyan et al., 2004) revealed a 4-fold increase in arginase activity in the kidneys of carp compared to other organs (liver, gills, heart, brain) and evidence of activation of arginase by Mn, which is a cofactor of the enzyme, and strong inhibition by Cd. For comparison, the average accumulation of Cd in the kidney was 0.64, 1.28, 1.94, 2.93, 21.0 μg/g dry weight for the lake Valdai, Upper, Middle, Lower Volga, lake Silver respectively. An increase in Na content with an increase in incidence for bream in the river Volga may be a sign of impaired renal excretory function. Histological studies of the kidneys of breams from the river Volga at the 3rd stage of morbidity confirmed serious morphofunctional changes developing according to the type of fibrosis (Moiseenko et al., 2005).

In contrast to the morbidity of the body, with an increase in k, the Ca content in the liver of fish decreases. There is also a significant increase in the Zn content, which means not only activation of development and growth, cell differentiation, repair, but also stimulation of the synthesis of various enzymes and proteins such as metallothioneins, thereby realizing successful adaptive activation of enzymes in response to changes in the environment. In animals and humans, a negative balance is observed against the background of pathological conditions of the body, catabolic states are characterized by a marked increase in Zn losses, but excess Zn intake can induce apoptosis, while physiological amounts of Zn limit the degree of damage caused by oxidative stress and suppress signaling pathways that promote the development of apoptosis (Sheybak, 2016). This phenomenon is clearly visible in the example of reduced accumulation of Zn in the liver and kidney of bream from

Lake Silver (Table 1) with severe water toxicity and a Zn concentration 8 times higher than the toxicological threshold. The decrease in Cu content in fish liver is quite natural. The physiological antagonism of Cu and Zn manifests itself at the level of metallothioneins: if Zn is more active, then Cu forms stronger complexes with this protein (Sheybak, 2016). The availability of Cu for metabolic processes is reduced and it is excreted to a greater extent from the body. An example is the significant accumulation of Cu in the liver of bream from Lake Silver with lower Zn accumulation (Table 1). In the kidney of bream, with increasing k, there is a significant increase in the Mn content, which may indicate high activity of arginase and the antioxidant defense system.

CONCLUSION

The content of essential elements and their distribution among organs and tissues is determined to a lesser extent by their content in water, and to a greater extent by the physiological need and state of the fish's body. However, the general trend is manifested in a decrease in the bioaccumulation of zinc and magnesium in the liver and kidney of bream with an increase in water toxicity.

Essential elements can serve as markers of the intensity and direction of metabolic processes in the body. Models of redistribution of essential elements in the liver and kidney of bream depending on the physiological state were obtained. The generality of the responses is also confirmed when considered under more or less homogeneous exogenous conditions of the river. Volga and all studied water bodies with strong variability in habitat toxicity.

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Digital transformation and quality in the service provision

Digitalna transformacija i kvalitet u pružanju usluga

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Abstract: Digital transformation is becoming a key strategic instrument for improving the quality of services in the modern business environment. Service organizations face accelerated technological changes that impact operational efficiency, customer experience and innovation. The integration of digital technologies significantly changes quality standards, performance measurement methods and user expectations. This paper analyses the concept of digital transformation in the context of quality management, discusses key technologies that enable the improvement of processes and services, and identifies challenges and recommendations for successful implementation. The paper contains a detailed theoretical framework, a review of relevant literature, discussion and conclusions that can serve as a basis for further research and practical application.

Keywords: digital transformation, service quality, management, innovation, technology.

Sažetak: Digitalna transformacija postaje ključni strateški instrument za poboljšanje kvaliteta usluga u savremenom poslovnom okruženju. Servisne organizacije se suočavaju sa ubrzanim tehnološkim promenama koje utiču na operativnu efikasnost, korisničko iskustvo i inovacije. Integracija digitalnih tehnologija značajno menja standarde kvaliteta, metode merenja učinka i očekivanja korisnika. Ovaj rad analizira koncept digitalne transformacije u kontekstu upravljanja kvalitetom, razmatra ključne tehnologije koje omogućavaju poboljšanje procesa i usluga i identifikuje izazove i preporuke za uspešnu implementaciju. Rad sadrži detaljan teorijski okvir, pregled relevantne literature, diskusiju i zaključke koji mogu poslužiti kao osnova za dalja istraživanja i praktičnu primenu.

Ključne reči: digitalna transformacija, kvalitet usluga, upravljanje, inovacije, tehnologija..

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INTRODUCTION

The emergence of digital technologies throughout the history of the last few decades has caused tectonic changes in all sectors of society, and especially in the way services are designed, provided and consumed. From early forms of digitalization, such as electronic documents and databases at the end of the 20th century, to modern forms of automation, artificial intelligence and mobile applications, transformation in the service sector has become an inevitable trend. Digital transformation represents a profound and systemic change in the way organizations operate, use technology and create value for customers. In the service sector, where interaction with the user is a key component, digital technologies are significantly changing the way services are provided, distributed and personalized (Vial, 2019).

The aim of this paper is to analyse the importance and effects of digital transformation in the provision of services, with a special focus on the changes it brings for both service providers and users. The task of the work is to identify technologies that are key to this transformation, to analyse changes in user behaviour. The problem investigated in the paper is reflected in the need for organizations to successfully adapt to accelerated technological changes in order to maintain competitiveness and satisfy increasingly demanding users. Insufficient understanding of digital transformation and its partial implementation often leads to poor results and loss of user trust.

The thesis that this paper seeks to confirm is that digital transformation in the service sector is not only a technical process, but a strategic approach that involves the integration of technology, culture and user experience. Providing services in the digital age requires a new business paradigm based on agility, innovation and customer orientation.

1. LITERATURE REVIEW

Digital transformation implies the process of integrating digital technologies into all aspects of business, which changes the way of working, internal structures, communication with users and delivery of services. It is about a fundamental transformation of business models, and not just about the application of technology for the sake of efficiency.

"Digital" is certainly one of the buzzwords in many industries right now. Everyone is emphasizing how digital they are and how to be digital. Of course, in the wave of this trend, all kinds of things are understood under this term, useful and less useful. Many people confuse digital transformation with digitization, the process in which certain information is transferred from analog to digital form, in simpler terms - the use of digital data or tools instead of paper (CADCAM Data).

Digital transformation is defined as a process of strategic, organizational and technological change that aims to improve processes, services and business models using digital technologies (Westerman et al., 2014). It goes beyond the mere adoption of IT infrastructure and involves changing the culture, structure and behaviour of the organization.

Digital transformation is the moment when a certain technology causes a change in the way a company works and thus creates a competitive advantage in the market. That change can be drastic, and then we talk about disruption, or gradual, when we talk about operational excellence. Digital transformation can be realized in different parts of business: business model, relationship with customers or operations, according to (CADCAM Data).

In short, with digital transformation we achieve tangible results that are reflected in better efficiency and profitability. Some of the results of digital transformation as highlighted by (CADCAM Data) are:

- Cost reduction.
- Higher profits.
- Expansion of products to the global market.
- Better product quality and traceability.

More innovation - people are involved in innovation, improvement and strategy, and routine tasks are left to machines.

1.1. Digital transformation in the services sector

Digital transformation is a process in which digital technologies are fully adopted and implemented. It is an intensive application of digital technology and resources in order to turn these resources into new revenues, a new business model and way of doing business. Digitalization is the use of digital technologies to improve business processes and create an environment for digital business in which information and knowledge play a key role. Digitalization is about technology, and digital transformation is about the customer.

The world is developing new digital technologies. During the last few decades it is noticeable that consumers have changed. They travel more often and are more educated. The demands and expectations that consumers place on manufacturers and service organizations are increasing. Of course, this creates pressure on companies to improve the level of quality of products and services. The use of new technologies made it possible to increase productivity and improve profitability. New technologies affect our identity, our sense of privacy, our free time, the time we devote to work, the way we develop our careers, cultivate our skills, meet people and cultivate relationships with them. When considering the concept of the security of society and the state, it is necessary to highlight its integral character. Integral security implies completeness and indivisibility, representing a unique value that includes all aspects of protection, both at the internal and international level (Đukić et al., 2024).

In IT companies and in certain scientific institutions, there are experts who know IoT and cloud technologies well, develop parts of industrial software and have practical experience. New technologies have an impact on employees by increasing training requirements in the field of information technology, but at the same time the question arises whether artificial intelligence will threaten and increase unemployment. Candidate training in business is the most important thing when introducing new technologies

1.2. Digitalization in the services sector - key advantages

Greater efficiency - One of the key benefits of digitalization in the service sector is increased efficiency. Digital platforms and tools enable process automation, reducing the need for human intervention and speeding up service delivery. For example, online reservations, e-commerce and digital customer services allow quick and easy access to services without physical presence. In this way, digitalization saves time and resources for both service providers and users. It should be noted that the introduction of mobile banking reduces costs and increases accessibility, while carrying the risk of digital exclusion of older users. In the education sector, E-learning platforms increase the availability of knowledge, a possible risk is the digital gap between developed and underdeveloped regions.

Availability - Digitalization also provides greater availability of services. Traditionally, many services were limited by geographic or time factors. However, digitalization removes those obstacles. Now you can access services from the comfort of your home or anywhere else, anytime, with just a few clicks. For example, telemedicine allows patients to receive medical advice and consultations via video call, without the need to physically go to the doctor's office. This accessibility is especially useful in rural areas or for those who are physically challenged. Therein lies the risk: the protection of patient data.

Personalization - Digitalization enables the personalization of services. Thanks to data collection and analytics, service providers can better understand the needs and expectations of their users. Based on this data, I can provide personalized offers and recommendations based on the individual needs of each user. This not only improves the user experience, but also increases the likelihood that the user will use those services again.

Innovations and new business models - Digitalization opens the door to new business models and innovations. The service as such can be completely transformed by digital technologies. For example, artificial intelligence (AI) and chatbots can be used to provide automated and personalized customer support. Blockchain technology can improve security and transparency in the financial services sector. The Internet of Things (IoT) can be used to monitor and manage various services, such as smart homes or smart cities. Digitalization is driving innovations that change the way we do business and use services. The modern business environment is characterized by accelerated digitalization, which changes the paradigm of service provision. The quality of services, once based on traditional standards, is today increasingly defined through digital channels and technologies. Digital transformation implies the strategic integration of technologies into business processes, with the aim of improving efficiency, innovation and user satisfaction (Porter & Heppelmann, 2015).

Table 1. Digital dimensions of service quality

Dimension	Traditional approach	Digital approach
Velocity	Limited by working hours	Availability 24/7
Personalization	Standardised services	AI messages
Safety	Physical verification	Biometrics, Blockchain
Availability	Location limited	Global connectivity

In the world economy, the service sector is of increasing importance, bearing in mind that it generates large revenues, as well as the largest possible participation in income creation and employment growth. The service sector has a strong influence and importance for the economy of every country. Also, the service sector contributes to the growth of employees and the growth of the social gross product, it has a strong influence in the formation of the needs and desires of consumers on the market. The changes that occurred in the world economy contributed to the growth of the service sector, which became the key to new development.

1.3. Digitalization challenges

Data security is becoming increasingly important as digitalization increases the risk of data theft or misuse. Efforts should be made to protect privacy and ensure that data is stored securely. Also, digitalization can lead to job losses in certain sectors that are sensitive to automation. It is important to understand these challenges and adapt to maximize the potential of digitalization.

Digitalization also provides opportunities for process improvement and resource optimization in the service sector. Through the application of smart analytics and "big data" technologies, service providers can gain greater insight into their operations.

Data analysis can identify patterns and trends that can help better resource planning, reduce waste, and improve overall operational efficiency. For example, in the logistics sector, digitalization enables tracking and managing the transportation and storage of goods in a way that minimizes costs and optimizes service delivery.

Another important advantage of digitalization in the service sector is the improvement of customer experience. Through digital channels, users can quickly and easily access information, perform transactions and communicate with service providers. Chatbots and virtual assistants provide instant support and answers to customer questions. Personalized recommendations and promotions can be based on user activity history and preferences. All this results in more satisfied users, greater loyalty and a better reputation for service providers.

1.4. Technologies that enable digital transformation

The World Trade Organization (WTO) report lists the technologies and trends of the Fourth Industrial Revolution, ranked by importance: Internet of Things, Big Data analytics, three-dimensional printing, advanced (autonomous) robotics, smart sensors, augmented reality, cloud computing, energy storage, artificial intelligence, nanotechnology, synthetic biology, simulation, human-machine interface, mobile devices, cyber security, quantum computing, horizontal and vertical integration, (Porter & Heppelmann, 2015) .

The Internet of Things (IoT) has many different definitions, and one of the shortest is that it is a global network that connects smart things. The term "Internet of Things" was included in the Oxford Dictionary only in 2013. IoT is considered a collection or set of objects (devices) that can be controlled and provide information via a wireless connection over the Internet, most often using a mobile application for monitoring or control. In other words, the term IoT refers to the connection of everyday objects/devices to the Internet and/or to other devices with the aim of providing users with simpler, more precise and "smarter" use of those devices. However, IoT is a broader concept that includes devices, infrastructure and applications in addition to communication. "Things" can further be defined as real/physical or digital/virtual entities that exist and move in time and space, and that can be identified. Things are usually identified by an assigned identification number, name and/or location address. Offering applications to users takes place through software platforms (IoT platforms) that integrate things and continuously collect their data. For this purpose, there is a need to process a large amount of data (Big Data), often in real time, as well as to unify and uniquely record data collected from different sources. The implementation of IoT implies the collection of a large amount of data, the analysis of which solves the problems of the system from which the data was taken. Three types of communication related to IoT are (Mehmedaj, 2023):

- communication of things with people,
- communication between things,
- communication between devices.

It is known that the Fourth Industrial Revolution rests on the automation of business processes, which is happening in parallel with industrial automation and factory automation. It represents the overlapping of two independent and historical economic development trends:

- progress in the development of information technology, predictive analysis and automation of administration and
- advances in machine automation.

The leading new paradigm is communication between devices (machine to machine - M2M), but not only between machines in the factory, but also between all existing devices and systems. Industry is considered to have multiple reasons for introducing networked software into machines and products in the classic industrial division of design, production and support of products and services. Networked programs in products or services provide benefits in the following areas (Westerman et al., 2014):

- Communication between devices can result in additional efficiency and safety in production. M2M uses sensors and various measurements during communication, including the exchange of temperature data over communication networks, to the application of programs that transform raw data into meaningful information.
- Maintenance and improvement, if possible in the form of preventive maintenance, which enables greater reliability and speed of operation of various machines, such as coffee machines or sensors in turbines or engines.

- Involvement and interaction with users enables the exchange of user data through various devices such as refrigerators, televisions, and vacuum cleaners, thus enabling the creation of new value and shaping of new ways of providing services.

Artificial intelligence and robotics are an integral part of current and upcoming changes. Today, industry without the application of robotics is unthinkable. The role of robots in production is particularly important. Changing their position and role represents the basic idea of future changes, that is, it is believed that intelligent machines that learn independently, that are adaptable and can take into account their environment, should naturally cooperate with people.

For now, robots in manufacturing serve only as assistants, but according to the vision of the Fourth Industrial Revolution, robots and humans in the future should collaborate and complete tasks together. It should be emphasized that, although robots are given a greater role, the central idea is that they adapt to humans, and not the other way around.

Another change brought about by digitalization is the way data is collected. For many years, companies made decisions based on data taken from traditional sources, such as production reports, internal reports, market research reports, and the like. Today, there are many more data sources available, including data generated by sensors in smart products, as well as data from browsers or social networks, (Davenport & Ronanki, 2018).

Analysis of large amounts of data (English: Big Data Analytics) provides new solutions to companies in the form of advertising, monitoring modern trends and opportunities in international markets without investing significant resources in local marketing, as well as in the form of more efficient optimization of procurement, production and distribution activities. However, collecting and storing large amounts of data is not what makes Big Data technology special. It is precisely the possibility of processing and analysing the collected data for further use that makes this technology extremely valuable.

The technologies that are the bearers of the digital revolution have developed with the help of three trends in programming, communications and data processing. Those three trends include (Cao, & all 2019):

- Moore's law,
- Gilder's law,
- Digitalization of information.

Moore's Law is associated with programming and computing, more specifically with the industry of monolithic integrated electronic circuits, whose progress enables more advanced forms of computing and programming. It was originally created in 1965 at the very beginning of the electronic age and this law claims that the number of components in an integrated circuit will double every year. This means that the processing capacity of the integrated circuit will also double every year. Later, the law was revised to say that processing capacity would double every two years.

Another trend is related to the growth of the amount of information that can be transmitted by modern communication networks. Gilder's law predicts that the total amount of data to be transferred, that is, the capacity of the communication system, will grow at least three times faster than the computing power. The high capacity of the communication system means that data can be transferred between two nodes in the system at high speed - almost instantly.

The third trend of the digital revolution is the ability to collect, store and convert data from analog to digital form, so that this data can be processed and transmitted via optical cables to a wide global public. This trend enables the use of large computing power, programming capabilities and fast, comprehensive communication systems.

The fourth industrial revolution and digital technologies will certainly affect the economic environment in terms of reshaping the industrial sectors and companies that form the basis of the modern global economy. New patterns of innovation are being built to drive the technological changes underlying industrial revolutions. Innovation systems at the time of the Fourth Industrial Revolution will become integrated across different scientific and technical disciplines and will include other domains such as education.

2. DIGITALIZATION AS A NEW INDUSTRIAL REVOLUTION

Digitalization is at the centre of the new industrial revolution. As a basic feature of the new revolution, which will be more comprehensive than any previous one, we can single out the reduction of barriers between the market and inventors thanks to the application of new digital technologies. In addition, an increasing role of artificial intelligence and robotics is foreseen. The development of digital technologies has changed the way people, the entire society and the economy function, and has contributed to the creation of a new form of digital economy.

In such an economy, new business models based on networking are being developed, and data is becoming extremely important for value creation. Global platforms that enable the application or development of technologies on a global level also contribute to the development of the digital economy, and include social networks, greater mobility, cloud computing, analysis of large amounts of data, and the like.

The digital economy, according to (Kuruzovich, 2013), requires an adapted regulatory framework. It is based on cross-border data flows, network effects and mobility of intangible assets. Fully digitized businesses have opportunities to avoid certain regulatory rules in different jurisdictions. This covers a wide range of activities and areas - from taxation and governance, market competition, labour market standards, to transport and accommodation. Disregarding or avoiding certain local or national rules is often a part of business models that belong to the digital economy.

The impact of digitalization on a country will depend on the readiness of individuals, companies and the economy as a whole to use the benefits that this kind of transformation brings.

Factors that influence the level of maturity of a country's digital ecosystem include (Lotinac, 2024):

- network infrastructure (Broadband), which is determined by international, national and local telecommunications networks, public availability and affordability of such services,
- the sector of information and communication technologies and innovations, including the business sector, focused on the production of software applications, the production of components and services based on information and communication technologies (ICT) (business processes, analytical processes, etc.),
- users, which includes individuals, businesses, government and machines - all of which must be connected together.

2.1. Changes in the behaviour of users of the services

Digital users expect speed, accessibility and personalization. It requires organizations (Mehmetaj, 2023):

- Access to services through mobile applications;
- Transparent communication;
- Possibility of independent management of services (self-service).

Successful digital transformation depends on a large number of factors, but certainly the first prerequisite is putting it "on the agenda". If digital transformation is just a buzzword (terms from certain fields that are often used, especially in the media), and is used without a clearly defined strategy and goals, then failure in its implementation is almost certain. Clear communication of the digital transformation strategy to all employees should be a priority for all companies that are aware that it is necessary for successful adaptation to market challenges and changes.

Another important prerequisite for the successful implementation of digital transformation is the degree of digitalization of the company, i.e. the speed of adoption and application of innovative technologies and tools that replace analog processes. If there is already a commitment to following digital trends and implementing various digital tools, the process of digital transformation will be simpler. Change of corporate culture, i.e. adapting outdated patterns of behaviour to the digital age is also considered a very important prerequisite for the success of digital transformation, according to (Doz, & Kosonen, 2010).

2.2. Measures for improving digital competitiveness

Through digital transformation, companies can significantly improve their efficiency and provide new sources of income, however, they must be aware that it is important to fully approach digital transformation, allocate significant resources, encourage engagement at all levels of the company and ensure organizational determination. Below are the measures that companies should take in order to improve their own digital competitiveness (Vial, 2019):

- *Priorities for digital transformations*. Awareness of the importance of digital transformation is the first step towards taking concrete steps to design a strategy.
- *Development of a digital transformation strategy*, i.e. a vision of the desired future. Understanding the need, creating a clear vision of the desired future and steps to achieve it. It is important that all actors are familiar with the digital transformation strategy and that they are aware of their role in the process, so that everyone is directed towards the same goal.
- *Hiring experts*. Digital transformation requires the engagement of quality and educated personnel.
- *Implementation of an appropriate digital transformation management structure*. Hiring

executives who will provide strategic guidance and lead the organization through the digital transformation process.

- *Creating a digital culture*. Changing the corporate culture and familiarizing all employees with the importance of digital transformation as a strategic business direction.
- *Quality management of human resources*. Quality management of existing staff and attracting new key people are crucial for creating a digital culture among employees and a functional ecosystem.
- *Greater agility and better preparedness for unforeseen situations*. Organizations that have been digitally transformed are better prepared for all environmental shocks. The crisis caused by the COVID-19 pandemic has fully proven that investing in digital transformation pays off.
- *Developing cooperation and partnerships*. Digital transformation often requires collaboration with different partners due to potential lack of knowledge and resources. Using experts in areas where the organization lacks expertise can prevent the risk of digital transformation failure.

3. ADVANTAGES OF DIGITAL TRANSFORMATION

One of the most significant advantages of digital transformation is the elimination of tasks that save employees time through automation. Software such as robotic process automation tools can perform tasks that previously required staff time and attention. A software solution can automate the manual process of performing a variety of tasks such as collecting customer data, sending emails (for example, related to service or status updates), procurement tasks, invoicing, time tracking and payroll, according to (Lešnjak, 2024).

Automation of business processes, according to (Lešnjak, 2024), is a springboard for building a holistic process of digital transformation. Automating tasks doesn't have to be expensive thanks to innovative software solutions that help companies de-risk their digital transformation investments. Automation brings greater accuracy, reduces the error rate and costs of completing tasks because there is no need for employees to be involved. Instead, it is possible to engage staff in critical tasks that require high-level decision-making or creativity.

More importantly, digital transformation has enabled customers to access services and support using their preferred method of interaction. Software solutions can bring true multi-channel support and allow users to easily contact businesses via phone, live chat, e-mail, mobile app or support forums. Because all these channels are digital, it is possible to offer customers more touch points, easily track interactions and improve feedback collection to provide even better service. The processes that drive software solutions according to (Lotinac, 2024) open the door to greater visibility of what works well and what should be improved. Because digital tools can collect and process data in real time, they enable managers to easily recognize patterns and identify opportunities for improvement.

3.1. Challenges of digital transformation

When considering the challenges of digital transformation at the enterprise level, Lešnjak (2024), points out that many organizations are still struggling with older, so-called legacy technologies that cannot be easily replaced. Projects dedicated to upgrading such systems and making them compatible with new digital technologies require significant resources - both in terms of manpower and budget.

The adoption of new technologies requires a culture of risk-taking within the organization. This high risk stems from the high initial investment and long-term returns. Many firms do not like this approach because they are generally risk-averse - they prefer to invest in low-risk projects with short-term returns. Cyber-attacks also play an important role in the world of digital technologies. With the number of attacks increasing every day, companies are losing a lot of money and effort to prevent them. The main problem with such attacks is that new threats are being developed every day that are used in order to control business, he points out (Lešnjak, 2024).

Another of the most significant obstacles to the adoption of digital technologies is the lack of standards in the use of IT technologies. There is no unique way to identify or use them. Therefore, the technology can be used in different ways and integrate complicated systems between the manufacturer and its supply chain, and between different departments within the same organization. Another challenge is the resistance of existing employees to change. They don't want anything to move them out of their comfort zone. This requires managing the change process and "unfreezing" the existing state in order to make the necessary changes. It will also require the recruitment of change agents who believe in the idea of change and help the management to convince its employees of the change and improve their working conditions, (Lešnjak, 2024).

CONCLUSION

Digital transformation is no longer a choice, but a necessity. In the service sector, it means providing value to users in a new way - faster, better and more affordable. Successful transformation requires a strategic approach, investment in technology and human resources, as well as a willingness to continuously learn and adapt.

Digital transformation in the service sector is much more than just the modernization of business processes - it is a fundamental strategic shift that includes technological innovation, changes in organizational culture, as well as redefining the relationship between service providers and users. Through this transformation, organizations move from traditional business models to digitally based approaches that enable greater agility, efficiency and competitiveness in an increasingly dynamic market environment.

The work showed that the key advantages of digital transformation are greater availability of services, automation of processes, personalization of user experience and improvement of the quality of decision-making through analytics and the use of large data sets (Big Data). The integration of technologies such as the Internet of Things (IoT), artificial intelligence (AI), and cloud computing and digital twins (Digital Twin) enables companies to better understand market needs, react faster to changes and create innovative services with added value.

On the other hand, the work also recognizes a number of challenges brought by digital transformation - from the need for professional staff and high investments, through problems with inherited technologies, all the way to issues of data security and ethical dilemmas that appear in the context of automation and replacement of human work. Managing these challenges requires a holistic approach, strategic clarity, but also flexibility and readiness for organizational changes.

In conclusion, the future of the service sector largely depends on the ability of organizations to accept digital transformation not only as a technical process, but as a complete change of business paradigm. Those who successfully connect technology, people and processes will be in a position to shape the market, not just adapt to it. Digital transformation, if carried out thoughtfully and planned, has the power to create a smarter, more efficient and inclusive society in which services are available to everyone - anytime and anywhere.

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Adaptation and anthropogenic evolution of animals under conditions of technogenic provinces

Adaptacija i antropogena evolucija životinja u uslovima tehnogenih provincija

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Abstract: Problems concerning microevolutionary transformations in animal populations are considered. It is shown that genetic variation is the main factor providing the basis for adaptation to environmental changes, including toxic pollution. The selection pressure of a toxic factor gives an advantage in survival to more resistant genotypes in animal populations, which eventually leads to the reduction of their genetic diversity and potential for adaptation to other natural or anthropogenic stress factors. Microevolutionary transformations follow the pattern of r-selection, i.e., occur in favor of smaller, earlier maturing individuals capable of expending a greater proportion of their energy resources for reproduction.

Keywords: technogenic province, microevolution, population, genetic diversity.

Sažetak: Razmatraju se problemi koji se tiču mikroevolucionih transformacija u životinjskim populacijama. Pokazano je da je genetska varijacija glavni faktor koji pruža osnovu za adaptaciju na promene u okruženju, uključujući toksično zagađenje. Selekcioni pritisak toksičnog faktora daje prednost u preživljavanju otpornijim genotipovima u životinjskim populacijama, što na kraju dovodi do smanjenja njihove genetske raznolikosti i potencijala za adaptaciju na druge prirodne ili antropogene faktore stresa. Mikroevolucione transformacije prate obrazac r-selekcije, tj. dešavaju se u korist manjih, ranije sazrevajućih jedinki sposobnih da potroše veći deo svojih energetskih resursa na reprodukciju.

Ključne reči: tehnogena provincija, mikroevolucija, populacija, genetska raznolikost.

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INTRODUCTION

Environmental pollution leads to the formation of technogenic biogeochemical provinces, which create extreme conditions for their inhabitants. Their formation can occur as a result of volley emissions or constant flows of elements and substances with toxic properties into the environment. Economic activity, changing the living conditions of animals, is not at all aimed at changing the evolution of organisms in nature, however, it has a very noticeable impact on many aspects of the evolutionary process, primarily at the microevolutionary level (Altukhov, 2003). Environmental pollution in modern conditions is one of the leading abiotic factors affecting animal populations. Recently, examples have increasingly appeared in biology showing that animals respond to anthropogenic pollution with active adaptive and microevolutionary transformations (Altukhov, 2003; Bezel, 2006; Korosov & Pavlov, 1988; Moiseenko, 2002; Chesser & Sugg, 1996; Depledge, 1996; Newman, 1995; Staton et al., 2001). The evolution of populations under changing environmental conditions can occur quickly and dramatically. However, in the world literature devoted to anthropogenic evolution there is no general information on this problem. Industrial melanism in butterflies and acquired resistance to pesticides in insects are the most frequently cited examples of evidence for anthropogenic microevolution. At the same time, the literature on genetic adaptation and the evolution of tolerance in living organisms to the effects of toxic substances is very extensive.

The purpose of this work is to form an idea of how changes in the population that occur under the influence of high concentrations of toxic elements in technogenic provinces can affect genetic diversity and what consequences the selective pressure of environmental pollution can lead to..

1. BREEDING FOR TOLERANCE

Despite existing in a polluted environment, many organisms were able to successfully reproduce, develop and grow. Tolerance can be defined as the individual ability of individuals to resist the effects of such concentrations of toxic substances that lead to suppression or death of intolerant individuals (Chesser & Sugg, 1996).

The phenomenon of adaptation to survival in toxic conditions has been established in many examples with aquatic and terrestrial animals. P.L. Klerks (1990), based on a literature review on the formation of resistance to metals in aquatic organisms, came to the conclusion that many researchers do not distinguish between acclimatization and genetic adaptation. In his works, he showed that the settlement of metal-polluted biotopes by benthic organisms occurred as a result of their acclimatization with subsequent genetic adaptation, and emphasized that adaptation is formed through genetic selection of resistant individuals. He explains the increased stability of benthic communities in estuaries that were exposed to cadmium pollution more than 30 years ago by genetic adaptation. An increase in genetic tolerance to Cu and Pb was also demonstrated in the isopod Asellus meridianus living in rivers exposed to mining wastewater (Hauser et al., 2003). In chironomids (Chironomus riparius) living in metal-polluted environments, the LC50 was 13 to 250 times higher than in laboratory animals cultured in a clean environment (Newman, 1995). Individuals of the population of predatory centipedes (Chilopoda) living in places polluted with heavy metals (Zn, Cd and Cu) were more resistant to the action of metals compared to insects taken from unpolluted habitats, which was confirmed by further experiments with animals introducing metals into food insects taken from contaminated and background habitat conditions (Bezel, 2006). These data confirmed the adaptation of the population to pollution and increased tolerance to the effects of metals in surviving individuals. Similar examples have been described for small mammals. A.V. Korosov and B.K. Pavlov (1988) compared two populations of forest voles: one of them existed on the slopes of Khamar-Daban, subject to long-term pollution by emissions from a pulp and paper mill, the other - in unpolluted habitats. Long-term technogenic impact (more than 18 years) led to a change in the genotypic structure of the population, which for a number of generations survived in conditions of toxic environmental pollution, i.e. was characterized by greater survival of individuals upon further introduction of toxic substances into food compared to voles taken from unpolluted habitats.

The ability to survive in polluted conditions is regulated by various mechanisms. For example, the mechanism of animal resistance to metals is associated with the ability of individuals to change the rate of their absorption or excretion, induce metallothioneins, bind or sequester metals, as well as differences in the sensitivity of enzymes to the inhibitory effects of metals (Moiseenko, 2002). Individuals preadapted to the activation of these functions receive an advantage for survival and reproduction. It should be noted that the evolution of tolerance does not always occur, and often weakened organisms from contaminated areas turn out to be as sensitive or even more sensitive to toxic factors than from uncontaminated habitats (Chesser & Sugg, 1996).

Thus, the response of animal populations to pollution-induced selection pressure will lead to the survival of some genotypes and the elimination of others. Under conditions of long-term selection pressure from pollution, local ecotypes can be formed. Enhanced functions of detoxification and elimination of ecotoxicants can be used as a biomarker to determine the long-term effects of toxic exposures on aquatic animal populations.

2. MUTATIONS

Heritable changes in the DNA genome, or mutations, are the source of genetic variability in natural populations. Mutations can appear spontaneously or gradually develop under the influence of a changed environment. Genotoxic agents cause spontaneous mutations, manifested in replication, recombination and instability of chemical bonds in DNA, which in turn can lead to phenomena such as the formation of structural isomers, loss of amino groups, base incompatibility during DNA replication. The toxicant can directly affect the DNA molecule through interaction with nucleotides, or indirectly - through induction of replication (Cajaraville et al., 2003; Hauser et al., 2003; Shugart & Theodorakis, 1994).

M.P. Cajaraville et al. (2003) revealed changes in DNA structure in fish, especially marine species, under the influence of oil spills, mercury intoxication, or the influence of other metals or organic xenobiotics. The consequences of DNA structure disorders are manifested in a wide range, including restructuring of the functioning of enzymes (enzymes), protein metabolism, production of cell-damaging toxins, inhibition of cell growth, accelerated tissue aging, suppression of the immune response, decreased fitness, increased incidence of diseases and the development of cancer. Many mutations are not inherited (somatic) and do not disrupt the genetic pool; over time, they are removed from the population. These include mutations leading to carcinogenic consequences that cause various neoplasms. Whereas mutations in the reproductive organs (reproductive gametes) can be inherited.

Thus, environmental pollution increases the mutation load on populations. Although it is very difficult to assess the consequences of mutations, it is obvious that mutation processes lead to changes in allele frequencies in the structure of the genetic pool, and this will inevitably affect the fitness of individuals and populations as a whole. Unfavorable mutations are quickly removed by selection, but recessive mutations, invisible to selection, can accumulate over generations, creating a genetic load. Mutation load, to one degree or another, reduces the viability of the population (Altukhov, 2003).

3. CHANGING THE GENE POOL

The condition of the body is a function of genetic characteristics and environmental factors. Based on the above facts, it is obvious that two key factors will influence the genetic pool of the population in the conditions of its existence in the newly formed technogenic provinces: 1) targeted selection of tolerant genotypes and 2) accumulation of recessive mutations.

Some animals, carriers of rare mutations and genotypes, may be under the influence of eliminating factors, while others are beyond their influence. As a result, the former become increasingly rare and may even completely disappear from the gene pool, while others remain in the population. In conditions of a general decrease in population size under the influence of a toxic factor, the frequency of occurrence of resistant genotypes will increase, and in the future they will become the main basis of natural selection in the process of restoration and subsequent increase in population size.

Having different tolerance to the action of a toxic factor, individual subpopulation groups react differently to its influence, which can result in serious structural changes. A critical drop in numbers due to toxic pollution causes the inclusion of compensatory mechanisms at the ecological and physiological level, which contribute to the restoration of density and stabilization of population processes (Shilova & Shatunovsky, 2005). The influence of high elimination of individuals during their intoxication will be compensated by the known laws of maintaining population size (Altukhov, 2003; Gilyarov, 2003; Moiseenko, 2002).

Under conditions of constant or periodic toxic effects on the population, the importance of resistant genotypes in the population will increase as the only genetic option that ensures selective success under these conditions. Mechanisms that increase the intensity of reproductive processes in residual populations (in this case, from tolerant individuals) are well known (Shvarts, 1980). The response of a population to pollution is identical to the action of any factor affecting its density. Under conditions of selection pressure from pollution, local ecotypes can be formed as a consequence of the “bottleneck effect”, i.e. the effect of the emergence of genetic variability (such as genetic drift) in a population that has gone through a stage of sharp population decline (Chesser & Sugg, 1996). Traits that become inherent in a group of individuals after passing the bifurcation point - the “bottleneck” - are more likely to be multiplied in the subsequent development of the population. In the case of massive releases of toxic substances, a drop in the number of individuals in the population occurs in a short period of time. Under these conditions, only those members of the population survive who have in their genotype features that provide their carriers with greater resistance to the action of the toxic factor. At the Institute of Plant and Animal Ecology of the Ural Branch of the Russian Academy of Sciences, model calculations were performed under given conditions: the gene pool of the population includes N genotypes. With 97% of the death of animals under the influence of pesticides on the animal population, 1% of animals survive due to natural resistance, 2% are accidentally surviving animals. When the population size is restored to its original value, the proportion of resistant animals increases to 25%, with double action of pesticides - up to 77%, with three times - up to 98% and subsequently remains at the level of 99%. However, the actual accumulation of resistance in a population will be slower, since resistance in a natural population may occur in a much smaller proportion.

It is known that the combination of the mutation process and selection causes directional changes in the population (Altukhov, 2003). The response of genetically heterogeneous populations to an environmental stress factor is expressed in a change in the distribution of population parameters. As a result, a population may acquire new alleles or change the frequencies of certain alleles, which will ultimately serve as a source of genetic variation and microevolutionary processes. Allele frequencies can change due to mutation, selection, migration and genetic drift.

There is still debate about whether there is a special gene for resistance (tolerance) in the natural population? Detoxification is carried out by various mechanisms, and therefore can be encoded in different genes (Depledge, 1996). For example, C.H. Walker et al. (2001), based on a summary of literature data, describe possible mechanisms of evolutionary selection in insects that ensure their resistance to insecticides: 1) behavioral - increased sensitivity and avoidance; 2) strengthening of detoxification functions (DDT - dihydrochlorinase, carbomates - microsomal monooxidases, organophosphorus compounds - glutothione transferases and esterases); 3) decreased sensitivity to damage (for example, decreased sensitivity of acetylcholisterase in the nervous system); 4) decreased cellular permeability. Above we gave other examples of increased resistance in organisms, such as induction of metallothioneins, increased activity of functional oxidases, sequestration, decreased permeability, or increased excretion of ecotoxicants. The process of developing resistance to the action of a toxic agent is polygenic and various survival mechanisms may be responsible for it, so a clearly defined locus of tolerance has not been identified. Since sustainability is polygenic, the evolutionary process can go in different directions simultaneously, which is confirmed by the historical record of intensive speciation after crisis situations on the Planet.

4. “PAY” FOR ADAPTATION

Pollution creates extreme living conditions for organisms, the resistance of which manifests itself as a protective function of the body against the adverse effects of environmental factors. This protection reduces the rate of death, but may come at the cost of reducing the effectiveness of other functions. The presence of life cycle invariants and a strict relationship between individual parameters leads to the fact that an increase in fitness due to a change in one trait entails a “payback”, manifested in a change in another trait and a decrease in the fitness of the same organisms in slightly different conditions. Survival in a subtoxic environment can lead to a decrease in adaptability in general, and subsequently to the destruction of the population when experiencing other extreme conditions, i.e. selection of a resistant genotype will reduce adaptability to other extreme environmental factors (Newman, 1995).

Tolerance may be characteristic of a narrow, specific range of phenotypes and may be accompanied by a loss of genetic diversity. A decrease in genetic variability in the population as a whole can lead to a limitation in the fitness and ability of the population to respond to changes in “traditional” natural - climatic factors (Bezel, 2006; Shugart & Theodorakis, 1994; Staton et al., 2001). Numerous facts confirm the possibility of sustainable long-term existence of natural populations under conditions of significant toxic stress. G.S. Weis et al. (1999) showed that methyltolerant embryos were less adaptable to salinity variations. The development of tolerance to methylmercury resulted in a decrease in genetic diversity among individuals in the population, reducing their ability to withstand natural stress factors or other types of pollution.

Metal tolerance in organisms occurs through the selection of individuals well adapted to reduce metal uptake, induce metallothioneins, and bind and excrete metals. As a result, a deficiency of essential (vital) microelements can form in the body, which develops in organisms that are resistant to the effects of toxic metals. This may partly explain the decrease in the body’s resistance to changes in other environmental factors (Hauser et al., 2003). An example of an increase in population resistance to a toxic factor, accompanied by a decrease in the population’s adaptability to other environmental factors, is given by V.S. Bezel (2006) using the example of studying the bentgrass plant (Agrostis tenuis), which indicates the universality of this phenomenon not only for the animal, but also for the plant world.

Thus, selection can increase the resistance of a population to toxicants, but in the future it can lead to a reduction in genetic diversity. Selective selection leads to a reduction in genetic variability within a population and reduces the population’s adaptability to natural or anthropogenic stressors in the future.

5. SPEED AND DIRECTION OF ADAPTIVE CHANGES

E.I. Kolchinsky (1990) identifies a decrease in their size and a transition to a short reproduction cycle as the main directions of anthropogenic micro-evolutionary transformations of animal populations. Genetic adaptation occurs more quickly in populations with a short life cycle and a high rate of population growth. Based on the general laws of evolution, it can be assumed that jlyb genetic and environmental factors will promote and accelerate the selection of tolerant species, while others will inhibit the acquisition of tolerance in species exposed to pollution:

Genetic factors: mutations - the acquisition of genetic variability, which will be affected by selection; dominance - tolerance controlled by dominant alleys will be selected faster; mono- and polygenic - selection will act more quickly under monogenetic control; fitness - selection occurs more quickly in the case of large differences between tolerant and sensitive individuals.

Ecological factors: time and speed of reproduction of generations - short-cycle species with a rapid population growth rate can more quickly respond to selective pressure; population sizes - small populations may have less genetic variability; mating - influence the recombination of the tolerant genotype; emigration/immigration - associated with an intolerant genotype will evolve slowly; living conditions (microhabitat) - selection will proceed more slowly if sensitive species find refuge from the effects of a toxic agent (microhabitats, shelters); developmental stages - sensitive developmental stages will influence the effectiveness of selection.

Whether a population will eliminate or adapt to anthropogenically induced stress depends on the speed and strength of its action, the severity of the stressor attack, as well as the population's ability to adapt. The polygenomic tolerance system in species allows for rapid changes in gene frequencies and, therefore, rapid response by evolutionary changes to environmental changes.

Changes in the life cycle strategy of fish caused by toxic water pollution are united by the concept of life cycle types formed by r- and K-selection (Pianka, 1981). In stable, weakly susceptible to change conditions, K-selection operates, therefore, the organisms formed by it are characterized by a long life span, large size, late maturation and cyclical reproduction. Populations formed by r-selection exist in variable conditions and are characterized by smaller sizes, early maturation, high decline in older age groups and, accordingly, a small frequency of spawning. With r-selection in populations of one species, individuals mature earlier, are smaller in size, and spend more energy resources on reproduction. When exposed to unfavorable environmental factors, changes in the life cycle strategy corresponding to r-selection acquire adaptive value. There is no doubt that the toxic factor is also unfavorable. Under the influence of anthropogenic factors, the ecological structure of the population undergoes the most significant changes.

CONCLUSION

To summarize the scientific facts, we can conclude that microevolutionary transformations occur in animal populations under the influence of pollution. The selection pressure of the toxic factor leads to the survival of more resistant genotypes. Environmental pollution also increases the mutation load on populations. Genetically based tolerance is inherited. Two key factors will influence the genetic pool of a population in conditions of its existence in conditions of pollution: 1) directed selection of tolerant genotypes and 2) accumulation of recessive mutations. It is known that the combination of the mutation process and selection causes directional changes in the population. As a result, a population may acquire new alleles or change the frequencies of certain alleles, which will ultimately serve as a source of genetic variation and microevolutionary processes. Reduction of genetic diversity can increase the resistance of populations to a certain type of pollution, but reduce the adaptive capabilities of the population as a whole to other stress factors or types of pollution. However, the questions of how the influence of the emerging technogenic provinces in the modern biosphere will affect the genetic structure of the population, what long-term consequences disturbances at the molecular-cellular and organismal level will lead to, have not yet been fully clarified and are extremely important in theoretical ecology.

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ECOLOGICA

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Под покровитељством

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РАЗВОЈ ИНОВАТИВНИХ ТЕХНОЛОГИЈА У 4. И 5. ИНДУСТРИЈСКОЈ РЕВОЛУЦИЈИ

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