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SCIENTIFIC SUSTAINABILITY INDEX AS A TOOL FOR ASSESSING THE RESOURCE BASE OF NATIONAL SCIENTIFIC SYSTEMS: A COMPARATIVE ANALYSIS OF UKRAINE, POLAND, AND LITHUANIA

At the present stage, the competitiveness of countries largely depends on the development of human potential, with science and education as its core components. Their interaction influences socio-political consolidation and supports the formation of an innovation-driven economy, becoming a key factor of economic growth. However, a comprehensive concept for studying scientific and educational potential as a social phenomenon remains underdeveloped. Therefore, its analysis is particularly relevant for defining strategic directions of science and higher education development in Ukraine and the European Union.

This paper provides a comprehensive assessment of the scientific and educational potential of Ukraine in 2010-2025. The sustainability and development prospects of Ukraine's education and science system are examined in comparison with Poland and Lithuania, countries highly integrated into the European Research Area with stable R&D funding. The study relies on data from international statistical databases (World Bank, WIPO, UNESCO, OECD), national higher education quality reports, and innovation indicators, including R&D expenditures and the number of researchers. Relationships between scientific and educational potential and regional macroeconomic indicators, such as gross

regional product and per capita income, are identified, and practical recommendations for strengthening science and innovation policy are proposed.

The findings indicate that Ukraine maintains one of the highest tertiary education enrolment levels in the region, in some years exceeding Poland and Lithuania. Despite demographic shifts and population displacement, the higher education system has shown resilience through rapid digitalization, temporary accreditation procedures, and institutional relocation. Nevertheless, long-term risks persist, particularly regarding the quality of student preparation, as evidenced by international comparative assessments, including PISA 2022.

Keywords: *scientific and educational potential; scientific sustainability; research and development (R&D); national innovation system; higher education.*

General statement of the problem. In the context of the global transformation of scientific and educational systems, the importance of scientific and educational potential as a key factor of sustainable state development is increasing. In 2020-2025, Ukraine found itself in a situation of structural crisis caused by a combination of economic decline, destruction of infrastructure, migration of scientific potential, and the reallocation of public resources in favor of the defense sector. These processes have significantly affected the dynamics of research and development funding, the human resources capacity of science, and the stability of higher education.

Thus, determining the degree of resilience and adaptive capacity of the Ukrainian scientific and educational system in 2020-2025, as well as identifying structural constraints and modernization opportunities in a comparative perspective, makes it possible not only to assess the current state of the national system of science and education, but also to define priority directions for its development in the context of post-crisis transformation and European integration. In particular, the experience of Poland and Lithuania demonstrates that the resilience and competitiveness of a national innovation system are directly correlated with the

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institutional consistency of public policy in the field of research and development funding, the development of human capital, and deep integration into the European Research Area. Systematic participation in supranational research programs, institutional strengthening of the university sector, and sustained growth in R&D investment create a synergistic effect that ensures the long-term modernization of the knowledge economy and enhances the technological competitiveness of the state.

Analysis of recent research and publications. In recent years, the academic discussion of scientific and educational potential has shifted from a "description of resources" (funding, personnel, infrastructure) toward an analysis of the resilience of national innovation systems (NIS) and their capacity to maintain performance under conditions of shock (the COVID-19 pandemic, war, energy disruptions). Within the framework of NIS theory and the knowledge economy, it is emphasized that the effectiveness of science and higher education is determined not only by the volume of R&D expenditure, but also by the quality of institutions, the density of research networks, knowledge transfer mechanisms, and international integration.

Among the foundational works on national innovation systems is [1], which conceptualizes innovation not as the result of isolated activity by firms or research organizations, but as a product of institutional interaction among the state, universities, and business. According to the author, the resilience of a national innovation system depends on the ability of institutions to sustain processes of interactive learning and coordination.

Nelson [2] highlights the role of public policy and institutional architecture in shaping the technological competitiveness of nations. This line of thought is further developed in the "Triple Helix" model [3], where the synergy of universities, industry, and government is viewed as the core of the knowledge economy. Under external shocks, the resilience of the scientific and educational system is determined by its capacity to preserve institutional coordination, sustain R&D investment, and ensure international integration.

Contemporary studies of higher education resilience in Ukraine during wartime constitute a distinct strand in the international academic

debate, focusing on institutional adaptation, quality of instruction, and the transformation of academic mobility. Study [4] analyzes mechanisms of resilience in Ukrainian universities through the experience of students at Lviv University. The authors underscore the importance of everyday adaptation strategies and flexible academic planning. Conceptually, the study draws on the theory of "ordinary resilience," according to which resilience is formed through the use of familiar social and psychological resources under extreme conditions.

Authors [5, 6] address the impact of war on the research system and science. In particular, [5] notes that in 2022 approximately 18.5% of active researchers left the country. Study [6] demonstrates how responses to wartime challenges led to the expansion of distance learning, broader international cooperation, and increased participation of Ukrainian students and scholars in foreign programs, largely supported by the EU, the United States, and other Western countries. While the study emphasizes inclusivity risks associated with migration, it also identifies strategic opportunities for strengthening academic mobility through online education, international grants, and partnerships with foreign universities, thereby reinforcing the role of external academic integration in sustaining Ukraine's higher education system.

Authors [7] employ the synthetic control method to quantitatively assess the impact of war on higher education enrollment dynamics in Ukraine. The results reveal statistically significant deviations from expected pre-war trends, confirming the substantial effect of the conflict on the structure of higher education. The study shows that the war has altered not only the current functioning of universities but also the country's long-term educational trajectory.

In [8], the authors demonstrate that collaboration between universities and companies (including those in Poland and Lithuania) enhances the creativity of employees in small and medium-sized enterprises, thereby positively affecting innovation and competitiveness. Differences in the level of creativity and innovation activity among universities in the region are identified, allowing for a better understanding of institutional barriers and the potential for science–education integration. In [9], the technical efficiency of Polish universities in research is assessed using

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the DEA method, revealing key institutional differences and the influence of national funding policy on research outcomes.

Document [10], prepared within the OECD Education Working Papers series, provides a comprehensive analysis of the structure, missions, and profiles of Lithuanian higher education institutions. Based on comparisons with other OECD countries, it evaluates how Lithuanian universities adapt to contemporary educational and research challenges. Lithuanian institutions are shown to participate actively in European initiatives (Erasmus+, Horizon Europe, etc.), which enhances their cooperation potential, academic mobility, and access to international research programs. Quantitative and qualitative data on the development of science and higher education in Lithuania over the past decade are presented in [11], covering institutional structure, legislative changes, R&D funding, requirements for researchers and doctoral candidates, and international integration.

The evolution of Lithuanian higher education from a centralized Soviet model to a diversified and European-integrated system illustrates the role of consistent reforms in strengthening institutional resilience and academic specialization. In contrast to Ukraine, where transformation in 2020–2025 occurs under conditions of military crisis, the Lithuanian experience shows that strategic modernization and European integration can enhance the long-term resilience of the scientific and educational system.

Authors [12, 13] analyze the evolution of Lithuania's higher education system – from a centralized Soviet model to a differentiated structure including universities, professional colleges, and new educational programs. As in Lithuania after the 1990s, Ukraine has undergone institutional transformation involving diversification of higher education institutions, expansion of university autonomy, and integration into the European educational space. However, whereas Lithuanian reforms were primarily aimed at improving efficiency, specialization, and international competitiveness under stable European integration, Ukraine's system in 2020-2025 is adapting under the conditions of external military shock and infrastructure destruction.

Formulating the Goals and Objectives of the Article. The purpose of this article is to provide a comprehensive assessment of the scientific

and educational potential of Ukraine in 2010-2025 under conditions of structural crisis and external military shock. The study aims to identify the level of resilience of the national system of science and higher education, as well as its adaptive mechanisms, in a comparative perspective with Poland and Lithuania.

Within this objective, the research analyzes the dynamics of research and development funding, human resource capacity, innovation activity, and institutional changes in the higher education sector. Particular attention is given to the role of public policy and international integration in shaping the resilience of the national innovation system. The research tasks include identifying structural constraints and determining directions for the modernization of the scientific and educational sphere in the context of post-crisis transformation and European integration.

Presentation of the Main Material of the Study. Ukraine, Lithuania, and Poland demonstrate different models of interaction between higher education and the research system, reflecting both historical legacies and contemporary economic strategies. Fig. 1 presents the dynamics of the share of the population aged 25-34 with tertiary education in Lithuania, Poland, and Ukraine over the period 2010-2024 (for Ukraine, according to available data up to 2021).

The presented graph reflects a steady trend toward the expansion of higher education in all three countries; however, the intensity and stages of this process differ. As shown in the figure, Lithuania demonstrates the highest level of tertiary education attainment throughout the entire period under consideration. During the 2010s, the indicator increased from approximately 44% to 58-59%, after which it stabilized at this level. Such dynamics indicate the consolidation of a mass university education model comparable to that of developed EU countries.

In the first half of the decade, Poland was also characterized by rapid growth in this indicator-from about 35% in 2010 to 45-46% by 2018-2020. Subsequently, the figure stabilized within the range of 44-46%, indicating the completion of the extensive expansion phase of the higher education system and a transition to a stage of qualitative transformation and institutional modernization.

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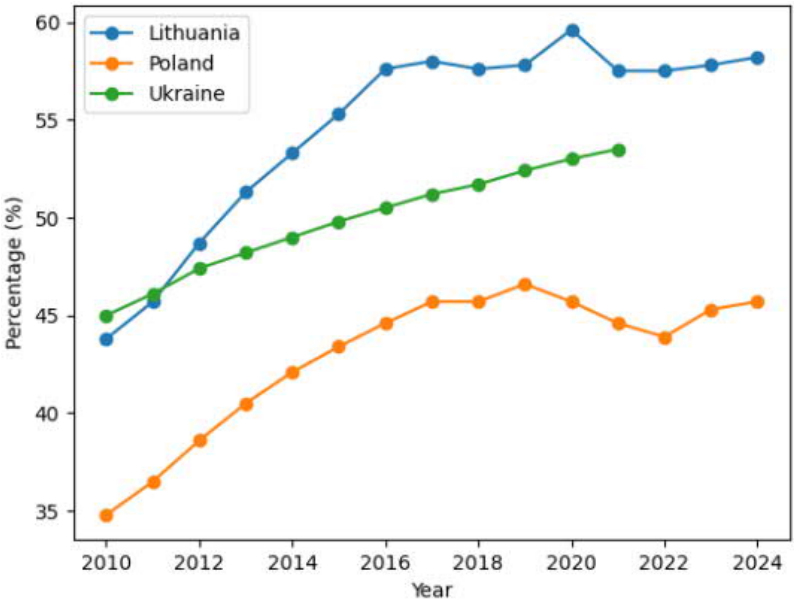

Fig. 1. Population aged 25-34 with Tertiary Education (%)
Source: compiled by the author

Between 2010 and 2021, Ukraine demonstrated a steady increase in the share of young people with higher education-from 45% to more than 53%. This trend confirms the traditionally high social significance of university education and the strong educational engagement of the younger population. Despite subsequent structural challenges, the preceding dynamics reflect a substantial human capital potential.

Thus, in terms of the prevalence of higher education, all three countries possess a significant educational resource capable of ensuring the formation of qualified personnel for scientific and innovative activities.

Substantial differences are observed not so much in the level of higher education attainment as in the ability of national scientific and innovation systems to effectively utilize this human capital to ensure sustainable scientific and technological development.

Ukraine entered the 2020s with chronically low R&D intensity (approximately 0.3-0.4% of GDP), insufficient modernization of research infrastructure, and a high yet demographically unstable level of participation in higher education. Since 2022, these constraints have been compounded by new challenges: the destruction of laboratories and universities, the forced relocation of research personnel, student migration, and the reallocation of public resources toward defense needs. Under these conditions, institutional survival and the continuity of the educational process became the primary priorities, while the long-term innovation strategy temporarily receded into the background. The low level of funding associated with the war has made the sustainable development of research infrastructure particularly difficult.

Poland has demonstrated steady growth in R&D expenditure as a share of GDP in recent years: the indicator increased from approximately 0.6% in the early 2010s to more than 1.5% in 2022-2023. This reflects a consistent public policy aimed at supporting science, internationalizing research programs, and increasing private sector participation in research funding.

Lithuania has consistently invested in science at a level slightly above 1% of GDP, maintaining a stable position compared to other countries in the Baltic region. Although its absolute investment volume is lower than that of Poland, Lithuania shows a relatively stable trend, reflecting sustained funding and integration into European research programs.

Fig. 2 presents the dynamics of indicators characterizing the state of science funding in Ukraine, Poland, and Lithuania as a share of GDP in 2010–2024. The graph displays R&D expenditure as a percentage of GDP and the number of researchers per one million inhabitants. The combination of these indicators makes it possible to simultaneously assess the financial intensity of science and the human resource capacity of the research infrastructure.

It should be noted that Poland demonstrates the most stable and upward trend across both indicators, with a consistent increase in R&D expenditure as a share of GDP throughout the period, accompanied by steady growth in the number of researchers per million inhabitants. The number of researchers rose from approximately 2,400 to more than 3,700

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per million population, representing an increase of about 50-55%. This reflects the formation of a sustainable model for the development of research infrastructure in the country.

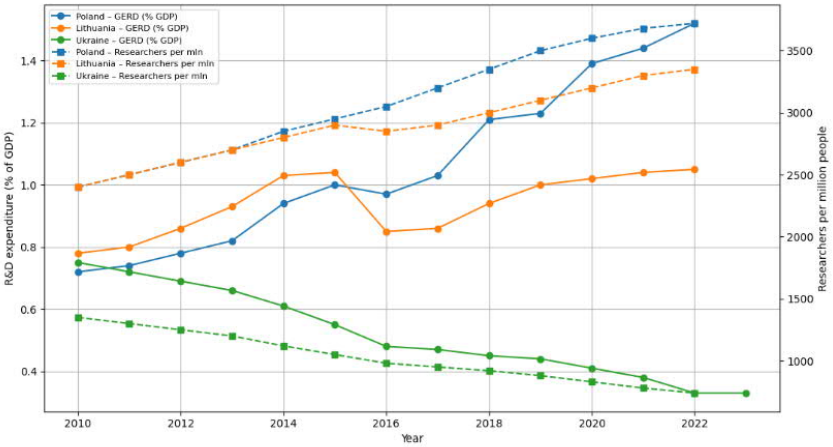

Fig.2. Trends in R&D Expenditure and Research Personnel in Ukraine, Poland and Lithuania (2010–2024)

Source: compiled by the author

During the same period, Lithuania exhibited more moderate yet stable dynamics. R&D expenditure increased from about 0.8% of GDP to approximately 1.0-1.05%, corresponding to growth of around 25-30%. The number of researchers rose from roughly 2,400 to more than 3,300 per million inhabitants, indicating an increase of about 35-40%.

A comparison of these indicators for Lithuania suggests a relatively balanced model: the system does not exhibit sharp fluctuations but maintains a stable level of research infrastructure.

In Ukraine, over the period under consideration, the share of research expenditure in GDP shows a downward trend. R&D expenditure declined from approximately 0.75% of GDP to about 0.33%, representing a reduction of more than 50%. The number of researchers decreased from around 1,350 to about 740 per one million inhabitants, indicating a decline of roughly 45%.

The simultaneous decline of both indicators points to a structural weakening of research infrastructure: reduced funding is accompanied by a contraction of research institutions. This reflects the limited investment base of science and heightened risks of losing scientific potential, particularly under conditions of macroeconomic and institutional shocks.

It should be noted that in Poland and Lithuania, increased funding is accompanied by growth in the number of researchers, indicating the functioning of a mechanism for the reproduction of scientific potential. In Ukraine, the opposite trend is observed, suggesting a weakening of the institutional resilience of the research system.

Fig. 3 presents a comparative graph of the dynamics of research infrastructure efficiency in the three countries, calculated per 0.1% of GDP allocated to R&D.

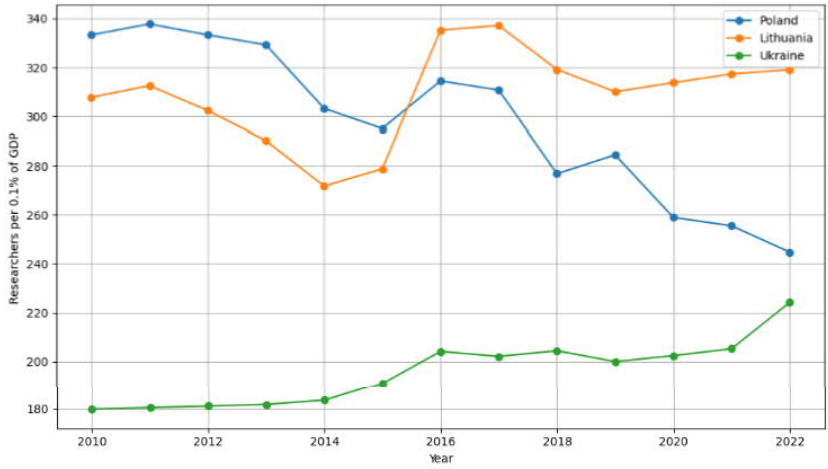

Fig.3. Trends in Research Infrastructure Efficiency (Researchers per 0.1% of GDP R&D), 2010–2024.

Source: compiled by the author

Fig. 4 presents the dynamics of the Scientific Sustainability Index (SSI). The index values are scaled from 0 to 1 using the mi-max normalization method, which makes it possible to compare countries within a unified relative range.

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The methodology for calculating this index is based on the aggregation of two core indicators: the share of gross domestic expenditure on research and development in GDP and the number of researchers per one million inhabitants. The normalized value of the indicator for each country *c* and year *t* is determined according to the following formula.

$$GERD_{c,t}^{norm} = \frac{GERD_{c,t} - GERD_{min}}{GERD_{max} - GERD_{min}},$$

$$R_{c,t}^{norm} = \frac{R_{c,t} - R_{min}}{R_{max} - R_{min}}$$

where $GERD_{c,t}$ – Gross Domestic Expenditure on R&D,

$GERD_{min}$, $GERD_{max}$ – respectively, the minimum and maximum values of this indicator within the sample,

$R_{c,t}$ – Researcher per million people,

R_{max}, R_{min} the – extreme values of the number of researchers during the specified periods.

Under the assumption that, in the baseline model, funding and human resource capacity are considered equally significant, equal weights are applied, and the resulting index formula takes the following form:

$$SSI_{c,t} = 0.5 \cdot GERD_{c,t}^{norm} + 0.5 \cdot R_{c,t}^{norm}$$

The value $SSI_{c,t}$ of range from 0 to 1, with higher values indicating a stronger resource base of the scientific system relative to other observations in the sample.

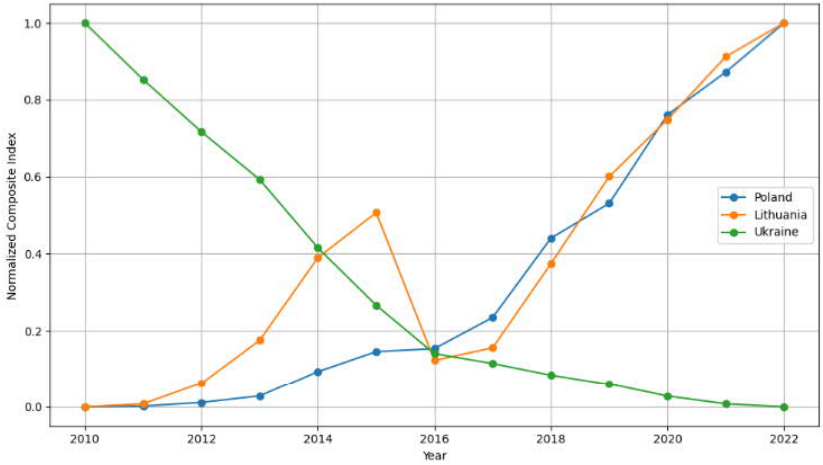

Fig.4. Scientific Sustainability Index (Composite Measure, 2010-2024 The index is calculated using GERD (% of GDP) data from the World Development Indicators database [14], OECD [15], and UNESCO Institute for Statistics [16]).

Source: compiled by the author

The graph shows that in 2010 Ukraine recorded the highest relative value of the index, which is explained by its initially higher parameters compared to the minimum values in the sample. However, a steady decline is observed as early as 2012-2013. After 2014, the downward trend becomes more pronounced, and by 2022 the index value approaches the lower bound of the scale. This reflects a systemic reduction in the share of R&D expenditure in GDP and a significant decrease in the number of research personnel. As a result, by the end of the period, Ukraine occupies the least sustainable position among the countries under consideration.

In contrast to Ukraine, Poland demonstrates a pronounced upward trend. From 2010 to 2015, the index increased gradually, after which the growth accelerated, particularly during 2016-2020. By 2022, Poland reached one of the highest index values in the sample. This indicates a systemic strengthening of the country's research infrastructure.

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Lithuania is characterized by a smoother and moderately volatile trajectory. In 2010-2015, its index values exceeded those of Poland and ranged between 0.57 and 0.70, pointing to a relatively strong resource base at the beginning of the period. A temporary decline is observed in 2016-2017; however, the index subsequently resumes growth. By 2021-2022, Lithuania reaches a level of 0.82-0.88, reflecting a high level of research personnel availability alongside moderate funding dynamics. Despite this positive trend, Lithuania remains slightly below Poland in terms of the final composite index value.

Overall, the graph illustrates the divergence in scientific resource sustainability among the countries: the strengthening positions of Poland and Lithuania against the backdrop of Ukraine's systemic weakening. The trajectories reflect differences in public policy regarding science funding and the dynamics of research personnel. Thus, the visualization confirms the emergence of a persistent gap between Central and Eastern European countries in terms of the resource parameters of their scientific systems. It should be noted that this index measures resource sustainability and does not capture overall scientific performance.

Conclusions. The presented results demonstrate a pronounced divergence in the scientific systems of Ukraine, Lithuania, and Poland: Poland is implementing a model of intensive expansion characterized by simultaneous growth in funding and research personnel, while Lithuania maintains a model of moderate yet efficient development with a high concentration of research staff per unit of funding.

Unfortunately, Ukraine is currently experiencing a decline in both financial and human scientific resources. A key priority for Ukraine should be the gradual increase of R&D expenditure as a share of GDP. Raising this indicator to 0.8-1.0% of GDP in the medium term would contribute to stabilizing the scientific resource sustainability index. The observed reduction in the number of researchers represents a critical factor. Therefore, necessary measures should include programs for the return of research personnel, comprehensive support for early-career researchers, the establishment of competitive remuneration conditions, and the stimulation of international scientific mobility with effective reintegration mechanisms. Given that in EU countries a significant share

of R&D expenditure is financed by the business sector, the development of public–private partnership mechanisms in Ukraine could increase overall investment in science without imposing excessive pressure on the state budget.

The results of the Scientific Sustainability Index calculation indicate that the most vulnerable component of Ukraine's scientific system is its human capital. In wartime conditions, this problem acquires a systemic character due to forced migration, infrastructure destruction, and reduced funding. In the short term, the primary objective should be to prevent the irreversible loss of research capacity through targeted protective grants for research teams in strategically important areas, flexible remote working arrangements for displaced scholars, and expanded cooperation programs with European research organizations.

More broadly, the findings confirm that the resilience of a national scientific system depends not only on the level of resource provision but also on the institutional consistency of public policy, the effectiveness of human capital reproduction mechanisms, and the degree of international integration. The proposed Scientific Sustainability Index may serve as a tool for monitoring resource dynamics and evaluating the effectiveness of science and higher education policy.

Thus, for Ukraine, the key challenge lies not only in restoring lost scientific positions but also in forming a new model of scientific and technological development. The implementation of these measures will ensure the long-term sustainability of the national scientific system and its full integration into the European Research Area.

ІНДЕКС НАУКОВОЇ СТІЙКОСТІ ЯК ІНСТРУМЕНТ ОЦІНЮВАННЯ РЕСУРСНОЇ БАЗИ НАЦІОНАЛЬНИХ НАУКОВИХ СИСТЕМ: ПОРІВНЯЛЬНИЙ АНАЛІЗ УКРАЇНИ, ПОЛЬЩІ ТА ЛИТВИ

На сучасному етапі конкурентоспроможність держав визначається рівнем розвитку людського потенціалу, ключовими складовими якого є наука й освіта. Їхній взаємозв'язок суттєво впливає на соціально-політичну консолідацію суспільства, а

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практичне застосування знань формує інноваційну економіку та стає важливим чинником економічного зростання. Водночас цілісна концепція дослідження науково-освітнього потенціалу як соціального феномена досі не сформована. Це зумовлює актуальність його аналізу для визначення стратегічних напрямів розвитку науки й вищої освіти в Україні та країнах Європейського Союзу.

У статті здійснено комплексну оцінку науково-освітнього потенціалу України у 2010-2025 рр. Проаналізовано стійкість і перспективи розвитку національної системи науки й освіти у порівнянні з Польщею та Литвою - країнами з високим рівнем інтеграції до Європейського дослідницького простору та стабільним фінансуванням R&D. Дослідження базується на даних міжнародних статистичних баз (World Bank, WIPO, UNESCO, OECD), національних звітах із забезпечення якості вищої освіти та показниках інноваційної активності, зокрема витратах на дослідження і розробки та чисельності дослідників. Визначено взаємозв'язки між науково-освітнім потенціалом і регіональними макроекономічними показниками- валовим регіональним продуктом і доходами населення.

Результати свідчать, що Україна зберігає один із найвищих рівнів охоплення вищою освітою в регіоні, у окремі роки перевищуючи показники Польщі та Литви. Попри демографічні зміни та міграцію населення, система продемонструвала стійкість завдяки цифровізації, тимчасовим процедурам акредитації та релокації закладів. Водночас зберігаються довгострокові ризики, зокрема щодо якості підготовки вступників, що підтверджується результатами міжнародних досліджень, включно з PISA 2022.

Ключові слова: *науково-освітній потенціал; наукова стійкість; дослідження та розробки (R&D); національна інноваційна система; вища освіта.*

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