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HUMAN CAPITAL IN THE SYSTEM OF ENSURING THE TECHNOLOGICAL SOVEREIGNTY AND ECONOMIC SECURITY OF RUSSIA

O CAPITAL HUMANO NO SISTEMA DE GARANTIA DA SOBERANIA TECNOLÓGICA E DA SEGURANÇA ECONÔMICA DA RÚSSIA

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Abstract
The article explores the technological sovereignty of Russia as a factor of economic security with an emphasis on the role of human capital in sustainable scientific, technological, and production capacity. The purpose of the study was to quantify the dynamics of technological sovereignty in 2018–2024 and to build a trajectory scenario of its change to 2036. The methodological foundation included statistical analysis, a system of private indicators, their normalization, integral assessment, and scenario modeling. The design model incorporated the indicators of knowledge intensity, patent activity, technological employment, innovative engagement of industry, technological autonomy, and the provision of personnel training and infrastructure. The obtained results indicate a rise in technological sovereignty in 2018–2020, an increase in vulnerability in 2021–2022, and partial

Resumo
O artigo explora a soberania tecnológica da Rússia como um fator de segurança econômica, com ênfase no papel do capital humano na capacidade científica, tecnológica e produtiva sustentável. O objetivo do estudo foi quantificar a dinâmica da soberania tecnológica no período de 2018 a 2024 e construir um cenário de trajetória de sua evolução até 2036. A base metodológica incluiu análise estatística, um sistema de indicadores específicos, sua normalização, avaliação integral e modelagem de cenários. O modelo de projeto incorporou os indicadores de intensidade de conhecimento, atividade de patentes, emprego tecnológico, engajamento inovador da indústria, autonomia tecnológica e provisão de treinamento de pessoal e infraestrutura. Os resultados obtidos indicam um aumento da soberania tecnológica em 2018–2020, um aumento da vulnerabilidade em 2021–2022 e uma adaptação parcial em

adaptation in 2023–2024. The research provides substantiation that human capital is not an auxiliary but a backbone condition for strengthening technological sovereignty, since personnel and research resources define the ability of the economy not only to produce but also to master, scale, and replicate critical technologies.

Keywords: Technological Sovereignty. Economic Security. Human Capital. Innovative Activity. Technological Autonomy. Scenario Analysis. Industrial Policy.

2023–2024. A pesquisa comprova que o capital humano não é um elemento auxiliar, mas uma condição fundamental para o fortalecimento da soberania tecnológica, uma vez que os recursos humanos e de pesquisa definem a capacidade da economia não apenas de produzir, mas também de dominar, escalar e replicar tecnologias críticas.

Palavras-chave: *Soberania Tecnológica. Segurança Econômica. Capital Humano. Atividade Inovadora. Autonomia Tecnológica. Análise de Cenários. Política Industrial.*

1 INTRODUCTION

In modern conditions, technological sovereignty is one of the primary tools for assessing economic security [1-5]. In this, technological sovereignty does not boil down to the domestic availability of individual industries or to the reduction of dependence on the import of individual product groups [6, 7]. Instead, it refers to the ability of the economy to create, develop, master, and reproduce critical technologies using its own scientific, production, organizational, and personnel base. For this reason, technological sovereignty should be viewed as a complex system in which scientific results, industry localization, infrastructure, institutions, and human capital are interconnected. This interpretation is consistent with modern international approaches, in which scientific, technological, and production capabilities are understood as a complex of interdependent elements of the innovation ecosystem, and technological capabilities are seen as the most concentrated and scarce in the global economy [8-11].

The relevance of our research is determined by the fact that against the backdrop of external restrictions, sanctions pressure, structural restructuring of international economic relations, and growing competition for critical technologies, economic security is increasingly dependent on the internal ability of the national economy to ensure the continuity of technological development [12-14]. Insufficient technological sovereignty increases the risks of interruptions in the supply of equipment and components, reduces the sustainability of investment projects, limits the space of budgetary and industrial policy, and increases sensitivity to external shocks. On the other hand, the development of high-tech and knowledge-intensive industries, increased innovation activity, improved staffing, and the expansion of scientific and technological infrastructure create a foundation for sustainable growth and long-term stability [15-18].

The internal limit of such technological independence is ultimately set by human capital. Even with the required financial resources, equipment, and organizational solutions, technological independence remains unattainable without research personnel, engineering competencies, the skills of industrial adaptation of technologies formed on their basis, and the ability of companies and industries to master new technological solutions.

The present study approaches human capital precisely in this sense. Research often defines human capital broadly, not just as a set of knowledge and professional skills but also as the accumulated ability of the economic system to reproduce scientific, engineering, and production abilities and competencies [19-22]. This understanding is particularly crucial in relation to technological sovereignty, because ensuring said sovereignty requires not only staff with appropriate qualifications but also the ability of the state, scientific organizations, universities, and businesses to jointly form a stable circuit of knowledge generation and transfer [23-25]. If this circuit is underdeveloped, technological solutions do not reach the stage of large-scale implementation, and the localization of production remains limited to assembly and, therefore, superficial in essence. Accordingly, even with the expansion of domestic production of certain types of products, the country may remain in a state of dependence on external technology suppliers, i.e., technological dependence [26-28].

In this case, human capital becomes not a concomitant but a determinant of technological sovereignty, enabling design, adaptation, maintenance, modernization, and further development of technologies in the national economy. Without sustainable reproduction of engineering and scientific competencies, technological sovereignty is essentially incomplete and vulnerable. International studies consistently show that innovation, skills, training, and intellectual capital are closely connected with the productivity, capacities, and effectiveness of the adoption of new technologies and, hence, the effectiveness of socio-economic development as a whole [29-30].

For this reason, the question of technological sovereignty appears to be incomplete without due consideration of human capital. Several international works explicitly consider the shortage of specialized human capital as one of the factors undermining technological sovereignty [31-33]. A study on the market for advanced 5G communications in the European Union demonstrates that weak technological sovereignty is associated, among other things, with a lack of specialized human capital and outsourcing key production chain segments [34-36].

The purpose of the present study was to quantify the level of technological sovereignty of Russia, establish its dynamics in 2018-2024, build its trajectory scenario up to 2036, and demonstrate that human capital acts not as an external addition to technological policy but as one of the central factors in reducing technological risks and strengthening economic security.

2 METHODS

The methodology of the study combines statistical analysis, industrial structure comparison, the index approach, and scenario modeling. Technological sovereignty is examined as a multicomponent system combining scientific and technological potential, innovative activity, staffing, technological autonomy, and infrastructure.

The information base consists of official data for 2018–2024 brought to a comparable form. The model included only those indicators that were observed consistently, reflected key aspects of technological sovereignty, were suitable for normalization and economically interpretable, and allowed building a scenario.

The formation of the information base involved searching for comparable time series, verifying the indicators, and converting absolute values into analytical coefficients. Series with gaps, changes in the calculation method, and a weak connection with the subject of the study were excluded.

In addition, we carried out a substantive examination of indicators and coordinated time series between blocks. The final matrix includes the indicators of research and development (R&D), patent activity, technological employment, the share of high-tech industries in GDP, innovation engagement, technological dependence, critical production localization, personnel training, and infrastructure provision (Table 1).

Table 1

Logic behind the inclusion of indicators in the integrated model of technological sovereignty

Assessment block	Key indicators	Analytical function	Connection with human capital
Science and technology	GDP knowledge intensity, patent activity	Characterizes the ability of the economy to generate and formalize new knowledge	Shows the effectiveness of research staff and the quality of scientific potential
Innovative production	Share of high-tech and knowledge-intensive industries in GDP, engagement of the industry in innovation	Reflects the scale of implementation of new technologies and the structural role of high-tech sectors	Shows the extent to which knowledge and skills are converted into production output and value added
Technological autonomy	Technological dependence, localization of critical production facilities, technological autonomy	Assesses the independence of the national economy in providing critical technologies	Indirectly reflects the adequacy of domestic engineering and production competencies
Personnel	Personnel training in industry, technological employment	Characterizes the availability of qualified specialists in the economy and their engagement in R&D	Directly captures the quality and practical orientation of human capital
Infrastructure	Provision of industrial and technological infrastructure facilities	Indicates the presence of the environment for technology development, testing, and implementation	Creates conditions for the effective use of knowledge, personnel training, and the transfer of competencies

The science and technology block comprised the following indicators. GDP knowledge intensity (GKI) was determined as the ratio of internal R&D costs (IC) to GDP:

$$GKI_t = \frac{IC_{R\&D,t}}{GDP_t} \qquad (1)$$

The Patent Activity Index (PAI) was calculated as the ratio of the number of invention applications by Russian applicants to the number of organizations performing R&D:

$$PAI_t = \frac{APPL_t}{ORG_{R\&D,t}} \qquad (2)$$

The Intensity of Technological Employment (ITE) was calculated as the ratio of the number of personnel employed in R&D to the number of employees in industry:

$$ITE_t = \frac{PERS_{R\&D,t}}{EMP_{ind,t}} \qquad (3)$$

The structural contribution of high-tech and knowledge-intensive industries was estimated through their share in GDP:

$$ACT_t = \frac{GVA_{HTI,t}}{GDP_t} \qquad (4)$$

The Industry Innovation Engagement Ratio (IER) reflected the ratio of the volume of innovative goods, works, and services to the total volume of dispatched industrial products:

$$IER_t = \frac{INN_{ind,t}}{PROD_{ind,t}} \qquad (5)$$

The technological dependence block included the integrated technological dependence coefficient and the coefficient of dependence in critical commodity groups. In the design model, these indicators were set as proportional values and then used to build the integrated Technological Autonomy Coefficient (TAC). The index of Critical Production Localization (CPL) was determined as the ratio of domestic output of critical goods to domestic demand for them:

$$CPL_t = \frac{PROD_{crit,int,t}}{DEM_{crit,t}} \qquad (6)$$

The TAC was calculated based on the indicators of critical dependence and localization as follows:

$$TAC_t = 1 - \left[\alpha \cdot CTD_{crit,t} + (1-\alpha) \cdot (1 - CPL_t)\right] \quad (7)$$

The design scheme used the value of α = 0.5, implying equal importance of direct import dependence and the localization of critical industries.

The personnel block was fundamental for the study as the block connecting technological sovereignty with human capital. The coefficient of personnel training in industry reflects the share of qualified workers with specialized vocational education. In turn, the intensity of technological employment made it possible to document the involvement of human capital in the research and innovation circuit and not in production in general. Thus, human capital is presented in the model not indirectly but through two independent measurements: the availability of qualified labor and the involvement of personnel in R&D.

The choice of these indicators made it possible to capture human capital in an applied rather than background form. Therefore, the model did not include general educational characteristics of the population, which are not as suited for describing the ability of the economy to ensure technological sovereignty in the production circuit.

This approach is consistent with the conclusions of the OECD and the World Bank that the ability of firms and industries to introduce complex technologies depends not only on access to equipment and infrastructure but also on the quality of skills, training, and organizational capabilities to apply them.

The infrastructure block was described by an indicator of the provision of industry with industrial and technological infrastructure facilities:

$$ITI_t = \frac{OBJ_{infr,t}}{ORG_{prom,t}} \quad (8)$$

where

$OBJ_{infr,t}$— the number of infrastructure objects (industrial parks, industrial and high-tech technology parks, etc.),

$ORG_{prom,t}$— the number of industrial production organizations.

After calculating the private indicators, they were normalized relative to critical and target values. Indicators whose growth means the strengthening of technological sovereignty were normalized using standard linear normalization:

$$z_{i,t} = \frac{x_{i,t} - x_i^{cr}}{x_i^{targ} - x_i^{cr}} \qquad (9)$$

Indicators of the opposite type, the growth of which reflects an increase in threats, were normalized using an inverted form:

$$z_{i,t} = \frac{x_i^{targ} - x_{i,t}}{x_i^{targ} - x_i^{cr}} \qquad (10)$$

Critical values were set as 80% of the historical minimum of the indicator over 2018–2024, and the target values were set at 120% of the maximum level for the same period. This rule made it possible to avoid arbitrary standards while still referencing the achieved values. The integrated Technological Sovereignty Index (TSI) was then calculated as the average of the normalized indicators:

$$TSI_t = \frac{1}{n}\sum_{i=1}^{n} z_{i,t} \qquad (11)$$

The risk indicator was determined as a complementary value:

$$RI_t = 1 - TSI_t \qquad (12)$$

The scenario until 2036 was built using the average annual rate of change in private indicators relative to the targets. For each year, normalization and aggregation were performed anew, making it possible to model not a linear extension of the series but adaptive and then structural growth.

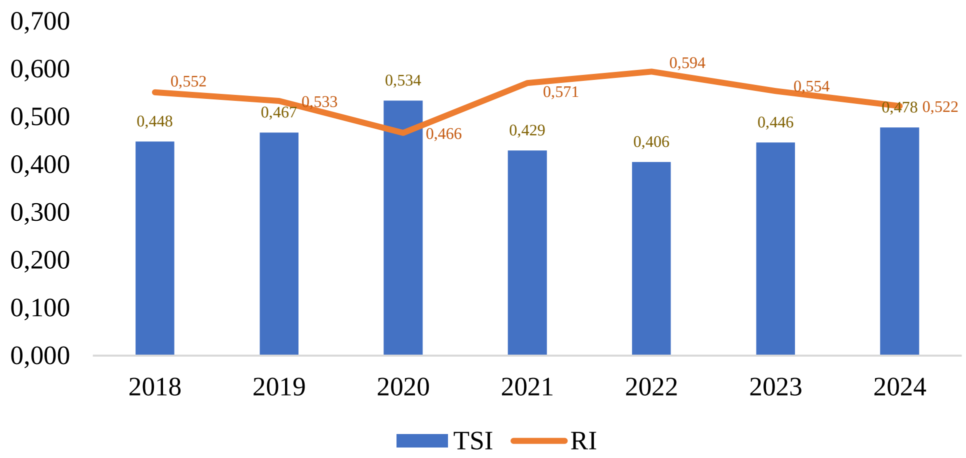
Thus, the research methodology simultaneously addresses three problems: first, obtaining an integrated assessment of technological sovereignty; second, establishing the internal structure of the factors of its change; third, substantiating human capital as an independent element in the mechanism for reducing technological risks and not just a background for industrial and innovation policy.

3 RESULTS

The calculations show that in 2018-2024 the level of technological sovereignty of Russia was in the intermediate zone. During this period, the integrated Technological Sovereignty Index ranged from about 0.41 to 0.53, while the risk indicator was between 0.47 and 0.59. This means that the system under study combined individual growth zones with persisting vulnerabilities. The dynamics of actual values are shown in Figure 1.

Figure 1

Dynamics of the integrated Technological Sovereign Index (TSI) and the risk indicator (RI) in 2018–2024



Source: compiled by the authors according to https://rosstat.gov.ru/

At the first stage, in 2018-2020, technological sovereignty gradually grew. The TSI rose from 0.448 in 2018 to 0.534 in 2020, and the RI decreased from 0.552 to 0.466. This indicates a favorable combination of growth in domestic R&D costs, an increase in the share of high-tech and knowledge-intensive industries in the structure of value added, and increased innovation activity in industry. During this period, the personnel and infrastructure contours did not show sharp spikes, but their stable positive dynamics created the conditions to strengthen the scientific and technological base.

A phase of increased vulnerability formed starting from 2021. The TSI dropped to 0.429 in 2021 and to 0.406 in 2022, while the RI rose to 0.571 and 0.594, respectively. This essentially means that the adaptation capacities of the national system failed to fully compensate for the growth of external restrictions, the restructuring of supply chains, and the deterioration of technological autonomy parameters. Of particular importance in this phase is the fact that the personnel block did not act as a source of a quick compensatory effect: the indices of personnel training and technological employment reacted much slower than the parameters of external dependence and innovation activity. In other words, in the shock conditions, human capital turned out to be an inertial resource that could not be promptly increased in response to technological restrictions.

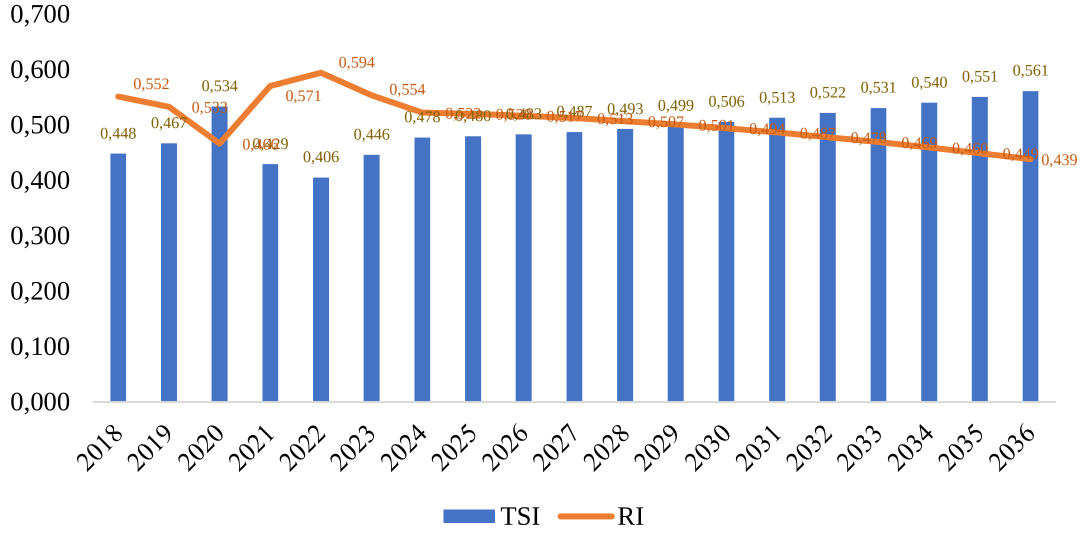
Partial adaptation is observed in 2023–2024. In this period, the TSI increased to 0.446 in 2023 and 0.478 in 2024, while the RI dropped to 0.554 and 0.522, respectively. This improvement is associated with an increase in the innovative engagement of industry and the share of high-tech and knowledge-intensive industries, as well as an acceleration of infrastructure provision. However, the 2020 level was not achieved. This means that restoration processes had already been launched, but the personnel, technological, and structural gaps had not yet been fully filled as a result.

The dynamics identified are asymmetric: the indicators of technological dependence, innovation engagement, and partially infrastructure change the fastest, while the personnel and research blocks remain more inertial. Therefore, measures to localize and expand infrastructure alone do not provide a rapid transition to a sustainably higher level of technological sovereignty.

The scenario to 2036 shows a moderately positive but not breakthrough trajectory. In the baseline scenario, the TSI rises from 0.478 in 2024 to 0.480 in 2025, 0.487 in 2027, 0.506 in 2030, and 0.561 in 2036. Respectively, the RI decreases from 0.522 in 2024 to 0.439 in 2036. The most important period is 2025-2030, when the foundation for the transition from adaptive recovery to more sustainable vulnerability reduction is laid down (Figure 2).

Figure 2

Dynamics of the integrated Technological Sovereignty Index (TSI) and the risk indicator (RI) in 2018–2036



Source: compiled by the authors according to https://rosstat.gov.ru/

In substance, the scenario assessment shows that human capital will remain one of the most inertial components of the model. Even with the growth of TSI, workforce training and technological employment increase more smoothly than engagement in innovation and infrastructure performance. This means that long-term reinforcement of technological sovereignty cannot be achieved only through localization or building up infrastructure. Aside from that, it requires the sustainable reproduction of skilled personnel, research teams, and mechanisms for transferring knowledge to industry.

4 DISCUSSION

The findings provide several more general conclusions important to the scientific debate on technological sovereignty. First, technological sovereignty reflects a dynamic balance between the zones of growth and vulnerability. Improving scientific, technological, and infrastructure parameters does not guarantee risk reduction with persisting personnel limitations and external dependence.

Second, human capital serves a double function, ensuring the current operation of high-tech industries and at the same time acting as a mechanism for the adaptation and absorption of technologies. Therefore, personnel training and technological employment are recognized in the study as central elements of technological sovereignty.

Third, the analysis shows that human capital affects technological sovereignty not linearly but through several channels at the same time. The first channel is research: without a sufficient number of R&D employees and stable patent activity, it is impossible to maintain the trajectory of domestic scientific and technological development. The second channel is industrial: without qualified engineering and production personnel, it is impossible to scale localization and master complex production processes. The third channel is adaptation: in the face of external shocks, it is trained personnel that make it possible to rebuild technological and organizational chains quickly. This multichannel role of human capital generally aligns with broader international assessments suggesting that complex innovation systems evolve based on the interdependence of scientific, technological, and production capacities.

Fourth, Russian results fit well into the international agenda, where technological sovereignty is linked to security, sustainability, and the ability of the state to coordinate scientific, industrial, and personnel policies. Without such coordination, TSI growth remains limited even with improvements in some indicators.

Finally, international empirical studies also show that the deficit of specialized human capital is one of the key factors of technological vulnerability. Consequently, the dependence observed in Russia is not private but rather systemic.

Nevertheless, the findings need to be interpreted considering the limitations. First, the integrated index cannot substitute industry analysis. Second, the personnel indicators used in the study only partially reflect the quality of specialist training and in-house training. Third, the scenario until 2036 shows a probable but not the only possible trajectory.

Despite these limitations, the proposed approach allows human capital to be incorporated into the internal structure of technological sovereignty instead of being viewed as an external background element. Further research should address the industry and regional decomposition of the model, as well as analyze personnel reproduction mechanisms in high-tech sectors.

In this way, our research clarifies the very category of technological sovereignty. The results suggest that it should describe not only the ability to produce individual critical goods domestically but also the ability to reproduce the knowledge, personnel, organizational practices, and infrastructure conditions needed for continuous technological development. In this sense, human capital is not a separate social supplement to technological policy but one of its central productive forces.

5 CONCLUSION

The conducted study has shown that the technological sovereignty of Russia in 2018–2024 developed unevenly. The 2018–2020 period was characterized by increased technological resilience; 2021–2022 saw an increase in vulnerability; and 2023–2024 became the period of partial adaptation and recovery. By 2024, the integrated Technological Sovereignty Index did not return to the local maximum of 2020, which indicates significant persisting structural constraints.

Scenario assessment up to 2036 suggests the possibility of gradually strengthening technological sovereignty, although without reaching the zone of complete removal of technological risks. Even the target version retains a noticeable residual level of vulnerability. This means that economic security in the long term will be determined not only by the growth rate of the high-tech sector but also by the ability of the state and business to consistently reproduce the scientific, personnel, and infrastructure prerequisites of technological development.

In practice, this necessitates a transition from a policy of compensating for external constraints to a model of reproducing technological capacities that will combine educational, scientific, industrial, and infrastructure policies into a single strategy for technological sustainability.

The key scientific and practical conclusion is that human capital needs to be considered as a backbone element of technological sovereignty. Without a sufficient number of researchers, engineers, qualified production specialists, and mechanisms to continuously update competencies, neither the sustainable development of R&D, nor deep localization, nor the effective development of technologies in industry is possible. Therefore, the policy for strengthening technological sovereignty has to simultaneously address science and technology, industry, and personnel. It is this coordination that creates the basis for reducing technological risks and strengthening economic security in the medium and long term.

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