PROBLEMY EKOROZWOJU/ PROBLEMS OF SUSTAINABLE DEVELOPMENT

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Knowledge-Based Economic Growth: Strategies for Integrating Digital Transformation in Developing and Developed Economies

Rozwój gospodarczy oparty na wiedzy: Strategie integracji transformacji cyfrowej w gospodarkach rozwijających się i rozwiniętych

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Abstract
The aim of the study was to analyse the impact of digital transformation and innovative technologies on economic growth. Regression analysis was employed to identify correlations between innovation expenditure, Internet penetration, gross domestic product levels across 12 countries over the period of 1996-2022. The results indicated that the relationship between research and development expenditure as a percentage of gross domestic product and the level of gross domestic product was significant in most countries. The analysis of China's experience revealed that public investment in the digital economy, as well as the development of artificial intelligence and cloud computing, contributed to industrial modernisation and enhanced public administration. The study confirmed that digitalisation and investment in human capital play a crucial role in shaping the knowledge economy and require a comprehensive approach, including government regulation, the development of innovation ecosystems, the stimulation of digital technologies within the private sector.

Key words: innovation, Artificial Intelligence, financial inclusion, regulatory framework, education sector

Streszczenie
Celem tej pracy jest analiza wpływu transformacji cyfrowej i innowacyjnych technologii na wzrost gospodarczy. Zastosowano analizę regresji w celu zidentyfikowania korelacji między wydatkami na innowacje, penetracją Internetu i poziomem produktu krajowego brutto w 12 krajach w latach 1996–2022. Wyniki wskazały, że zależność między wydatkami na badania i rozwój wyrażonymi jako odsetek produktu krajowego brutto a poziomem produktu krajowego brutto była znacząca w większości krajów. Analiza doświadczeń Chin wykazała, że inwestycje publiczne w gospodarkę cyfrową, a także rozwój sztucznej inteligencji i przetwarzania w chmurze, przyczyniły się do modernizacji przemysłu i usprawnienia administracji publicznej. Badanie potwierdziło, że cyfryzacja i inwestycje w kapitał ludzki odgrywają kluczową rolę w kształtowaniu gospodarki opartej na wiedzy i wymagają kompleksowego podejścia, obejmującego regulacje rządowe, rozwój ekosystemów innowacji oraz stymulację technologii cyfrowych w sektorze prywatnym.

Słowa kluczowe: innowacje, sztuczna inteligencja, włączenie finansowe, ramy regulacyjne, sektor edukacji

1. Introduction

Knowledge-based economic growth refers to a model of economic development founded on the creation, dissemination, and utilisation of knowledge as the primary resource for achieving sustainable growth. Unlike traditional growth models that rely heavily on physical resources, labour, or capital, this paradigm emphasises the role of innovation, education, research, and digital infrastructure in promoting economic progress (De Bem Machado et al., 2022). In the knowledge economy, intellectual capital has become the main driver of productivity and competitiveness in the 20th and 21st centuries. This model is based on the idea that knowledge is an inexhaustible and renewable resource, and that investment and other forms of input into it enable the creation of high-value-added industries, improved labour market adaptability, and increased efficiency of economic processes. Given the spread of this model, it remains relevant to examine how knowledge-based economy is being developed in other countries and how it should be further advanced.

In their study, Jiao and Sun (2021) examined economic development and its impact on economic growth in China. They developed a digital economy index based on the internet development, digital literacy, and industrial efficiency, and assessed its impact on urban economic growth using robust empirical methods, including instrumental variable regression, policy impact analysis, mediation models, and spatial analysis. Their findings indicated that the digital economy significantly promoted urban economic growth in China; however, the mechanisms of economic development at the micro level and the potential for implementing new policies were not addressed. Li et al. (2023) examined national innovation systems and the achievement of the Sustainable Development Goals (SDGs). The study highlighted the importance of cultivating knowledge-based economy capabilities through mission-oriented policies that bring together individuals, enterprises, and countries to achieve SDGs. Scholars noted the significance of a tailored approach based on stages of economic development: the need to focus on knowledge absorption, creation, and dissemination for developed countries; knowledge diffusion for emerging economies; and active knowledge utilisation for developing countries. However, the role of institutions, governance, and incentive issues within the ecosystem was not analysed in the work.

Yu and Yan (2021) in their study, presented a new framework for understanding innovation-driven growth in firms, focusing on the interaction between technological and business model innovations. The results showed that technological innovation had a greater direct impact on growth than business model innovation, and that both types of innovation interacted to enhance this effect. The researchers proposed a *partial co-governance* model, in which firms prioritise technological innovation while also developing a dual innovation system. The study further emphasised the importance of the knowledge base and organisational character for more effective innovation development. However, the study did not consider a sectoral analysis of the SDGs and also overlooked the fact that different knowledge capabilities may have varying impacts depending on the sector or target.

Zhou et al. (2021) considered the impact of technological innovation and industrial structural change on China's economic growth. Through statistical analysis, they found that technological progress has an inverted U-shaped relationship with economic growth, suggesting that China needed to shift from imitation to innovation to sustain development. Moreover, structural upgrading played the most significant role after reaching a turning point in technological progress. However, the mentioned study did not address the role of institutional and policy frameworks in mediating the impact of technological innovation and structural change on economic growth. Lin and Ma (2022), in turn, discussed how digital finance shaped green technology innovation in China. Through statistical data analysis, they drew three main conclusions suggesting that digital finance serves as a key driver of green innovation; various dimensions of digital finance, such as reach, depth of use, and digitisation, have a positive effect on green innovation, with the strongest effects observed in eastern cities, followed by central and western regions; and digital finance alleviates financial constraints, thereby indirectly enhancing green innovation. Although the cited conclusions suggested a significant positive impact of innovation on the financial sector, the article did not explore the long-term sustainability or potential unintended consequences of the impact of digital finance on green innovation, such as digital exclusion, cybersecurity threats, or the carbon footprint of the digital financial infrastructure itself.

Phale et al. (2021) concluded in their study that knowledge is a key factor in economic growth and sustainability. Based on statistical data, the researchers demonstrated that five out of eight indicators of the knowledge-based economy, namely government effectiveness, education expenditure, enrolment in higher education institutions, scientific journals, and mobile subscriptions, had a significant positive impact on growth. The cited study also highlighted the crucial role of the development of information and communication technologies, noting that the state should strive to improve public access to innovations in this field. However, the authors did not address the fact that excessive government influence on the sector could result in problems such as corruption, lack of institutional capacity, or resistance to change from various segments of the population, potentially hindering sectoral development.

Suo et al. (2024) explored the relationship between the digital economy and corporate total factor productivity among Chinese manufacturing companies. The researchers showed that knowledge is a critical resource in the digital era, and that companies must strategically manage knowledge and digital integration to remain competitive. Although the study examined moderating influences at the industry level, it is equally relevant to consider these influences at the level of individual firms. Alnasser et al. (2024) assessed the role of digital transformation in Saudi Arabia, stating that technologies such as artificial intelligence, the Internet of Things, and cloud computing have improved operational efficiency, competitiveness, healthcare, education, and entrepreneurship. Nevertheless, challenges, including cybersecurity threats and cultural aversion, remain relevant across economies. While the study acknowledged the impact of technological development on the labour market, it did not assess how digital transformation is altering employment structures, causing job displacement, or increasing the need for large-scale workforce retraining.

Considering the detected gaps, the aim of this study was to analyse the impact of digitalisation processes on economic growth. The objectives of the study were to examine the role of different components in the digital transformation implementation strategy, to identify specific risks and negative consequences associated with such implementation, and to describe the stages of developing a digital transformation strategy. The hypothesis was that countries with higher levels of expenditure on the development of innovative technologies would have higher levels of GDP.

2. Materials and methods

This study utilised information from the website of the World Bank Digital Regulation Platform (2024), in the context of the recommendations provided by the World Bank for the development of a national strategy in the field of digitalisation. Data from the *Made in China 2025* plan (2018) and the *Internet Plus* strategy (2025) were also employed to analyse the state of digitalisation development in China. The study examined the regression relationship between the level of R&D expenditure (as a percentage of GDP) and the level of GDP for 12 countries: China, India, Brazil, South Africa, the United States of America, the United Kingdom, Germany, France, Mexico, Malaysia, Turkey, and Egypt. These countries were selected for the study due to their variation in geographical location and in levels of economic and technological development, thereby allowing for a comprehensive analysis of the relationship between digital transformation and financial advancement.

In the analysed sample, the United States of America, the United Kingdom, Germany, and France were identified as developed countries meeting the criteria of high per-capita income, diversified and advanced economic structure, high human development index (HDI), strong institutional quality, advanced infrastructure, mature financial systems, as well as low poverty rates and strong social protection. Accordingly, India, Brazil, Mexico, Malaysia, Turkey, and Egypt were classified as developing countries striving to achieve high results in the aforementioned domains. As for China, it was identified as the country possessing the characteristics of both developed and developing economies, since its world-class infrastructure and advanced economy co-exist with low per-capita income and persistent regional inequalities. The time period from 1996 to 2022 was selected because it covered the years when the reported indicators of technological development, such as information and computer technology (ICT) infrastructure, digital adoption, innovation capacity, and knowledge-based economy metrics, became widely available across the 12 mentioned countries. The selected timeframe ensured sufficient longitudinal depth for analysing technological trajectories while allowing for cross-country comparability, since earlier years lack standardized datasets that would enable a reliable assessment. The analysis further focused on the impact of specific SDGs, such as digital transformation, industry, innovation and infrastructure, on GDP level. To accomplish research objectives, information from the Our World in Data (2025) platform was used, specifically regarding the country-level R&D expenditures in relation to GDP; while the GDP level data were obtained from the World Bank Group (2024). The method of correlation analysis was applied, using Pearson's correlation coefficient, which was considered sufficient only at >0.6 (0.3 – 0.6 in some cases). The regression equation was deemed significant if the p-value was equal to or less than 0.05 and the t-statistic exceeded the critical value. All calculations were performed using Excel.

3. Results

Knowledge-based economic growth is particularly important for developing economies, as it enables a leap in industrial development. Through strategic investments in technology and human capital, these economies can overcome traditional barriers to growth, such as limited access to natural resources or outdated infrastructure (Díaz-Arancibia et al., 2024). However, success of such a transformation requires comprehensive policies aimed at promoting education reform, developing innovation ecosystems, strengthening intellectual property rights, and ensuring equal access to digital tools and networks.

The benefits of a knowledge-based economy can only be realised through digital transformation. To this end, countries are formulating a national digital transformation strategy (DTS), which seeks to increase transparency in all economic transactions – particularly those involving the state – reduce corruption, improve healthcare and education, promote social inclusion, and support more intelligent resource management (Pu et al., 2023; Abudaqa et al., 2022). Nevertheless, without careful planning, digital transformation can lead to workforce disruptions, cybersecurity risks (including the potential for system hacking and data theft/loss), and environmental concerns such as rising levels of electronic waste and increased energy consumption (Zhou et al., 2021). The selected countries have focused on accomplishing specific SDGs, including digital transformation, industry, innovation and infrastructure, as these are connected to sustainable development. The connection is seen in the fact that sustainable development constitutes a normative framework that emphasizes the integration of economic, social, and environmental dimensions to ensure that present developmental needs are met without undermining the capacity of future generations. SDGs, in turn, serve as an institutionalized articulation of this framework, translating the broad and often abstract principles of sustainable development into a set of 17 structured goals and 169 measurable targets endorsed by the international community (United Nations Development Programme, 2025). While sustainable development functions as the conceptual foundation, SDGs operate as its operationalization, providing a comprehensive and empirically assessable agenda through which states and organizations can systematically plan, implement, and evaluate progress toward long-term sustainability. The interplay between SDGs and sustainable development is taken into consideration, since it is linked to economic development and informs strategic planning to achieve further advancement (Guo et al., 2024).

Developing a national strategy is a complex, multi-stakeholder process that requires significant investment, ethical reflection, and adaptation to an evolving digital landscape. A well-designed strategy provides a clear framework for decision-making, prioritises objectives, allocates resources efficiently, and facilitates collaboration among stakeholders. An effective strategy should also be aligned with policies in other sectors and should be ambitious in scope.

The development of such a plan can be presented in a flow chart, as illustrated in Figure 1.

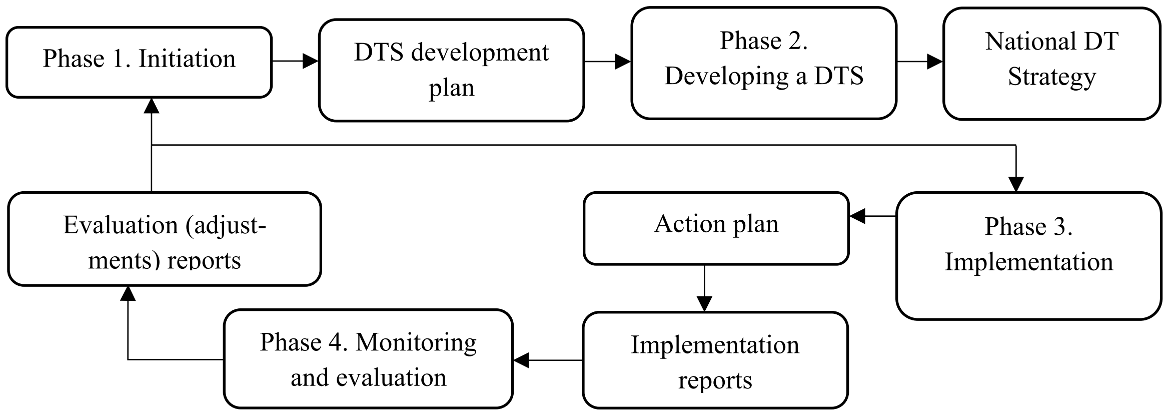

Figure 1. Phases of developing a national digital transformation strategy, source: created by the authors based on World Bank (2024).

The figure suggests that the first phase in developing a national digital transformation strategy focuses on fostering a fundamental understanding among key stakeholders and leaders regarding the importance of the initiative. This phase aims to organise and initiate the strategy's development. A successful digital transformation requires strong political commitment and a clear vision at the highest level: political will ensures the prioritisation of national agendas, mobilisation of resources, and maintenance of strategic focus, while broader political support fosters consensus among political parties and stakeholders. Notable examples include the Coalition Agreement (2025) in Germany and Saudi Vision 2030 (2025) in Saudi Arabia, both of which emphasise digitalisation as a national priority. Simultaneously, governance should be led by a competent and neutral institution with sufficient resources and legitimacy – often a ministry. In preparing the strategy, the lead agency must develop a comprehensive plan outlining key steps, timelines, and resource requirements, while ensuring stakeholder engagement. This plan should align with existing governance processes and be formally approved by a steering committee or the government.

Phase 2, the strategy creation phase, requires the mapping of existing strategies and policies to ensure coherence and alignment with national, regional, and international goals (Setzke et al., 2021). This includes reviewing current strategic documents related to digital transformation, broadband plans, and e-government policies to avoid duplication, resolve conflicts, and identify synergies. A further step in formulating the digital transformation strategy involves conducting a strategic analysis to assess the current digital ecosystem and to identify opportunities and challenges. This includes two key components: a digital landscape analysis, which examines external factors influencing digital transformation, and a digital maturity assessment to evaluate internal capabilities and readiness by identifying strengths and weaknesses. An integrated approach should take into account political, economic, social, and environmental dimensions, using appropriate analytical tools (Wang et al., 2023). Strategic priorities are vital for implementing the overarching long-term vision. In order to assess the progress of the strategy, performance indicators should be established by the state, either independently or based on international experience – namely, the experience of other countries or international organisations (Robertson et al., 2023; Zhang et al., 2023).

Phase 3 of implementation is crucial and requires a systematic approach. It begins once the strategy has been legally approved and the responsible bodies have been appointed. To implement the strategy effectively, it must be translated into detailed short-term plans, often on an annual basis. These plans break down strategic actions into components aligned with departmental and individual goals, thereby enabling effective management and monitoring of implementation. For example, Germany's digital strategy includes 134 specific tasks assigned to various government departments. Adequate funding and stakeholder commitment are essential for successful implementation. While public budgets reflect governmental commitments, private sector participation is critical, as the majority of investment typically originates from private stakeholders. Financial mechanisms, such as government aid, venture capital, and public–private co-financing, alongside economic incentives like tax breaks, help to mobilise resources. Considering the detected links, financial incentives and cooperation with private actors are essential.

Training and education are fundamental components, with governments playing a proactive role in addressing the global digital talent shortage by implementing initiatives to enhance the digital literacy and skills of the population (Bresciani et al., 2021). The final phase focuses on monitoring and evaluation to ensure alignment with the initial goals and to assess the strategy's ongoing relevance. Monitoring tracks progress against predefined indicators, while evaluation identifies the need for adjustments based on relevance and impact. Countries should establish a clear monitoring and evaluation framework, including the definition of indicators, assignment of data collection and reporting responsibilities, and creation of timelines for evaluation activities. The results should be integrated into the planning cycle to support continuous improvement. A key component of any digital transformation strategy is substantial investment in and the development of digital infrastructure (Shcherban et al., 2025; Kengesbayeva et al., 2025). Expanding internet access, particularly in rural and underserved areas, enhances the positive impact of digitalisation on national economic development. Infrastructure development should be accompanied by investment in human capital, notably through the promotion of digital literacy and the acquisition of technical skills. This should apply across the education sector, including both higher and school education. Simultaneously, the development of innovation ecosystems is essential for fostering entrepreneurship and supporting the growth of enterprises whose core activities focus on technological advancement. The establishment of innovation centres and incubators supports research and development in advanced fields such as artificial intelligence. In parallel, governments should incentivise businesses, especially small and medium-sized enterprises (SMEs), which form the backbone of economic development despite increasing market penetration by large corporations, to adopt digital technologies. Governments should offer grants, subsidies, or tax incentives to promote the implementation of tools such as enterprise resource planning sys-

Table 1. Ratio of expenditure on new developments to GDP in selected countries, 1996-2022, source: created by the authors based on Our World in Data (2025).

Variable	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
China	0.56	0.64	0.65	0.75	0.89	0.94	1.06	1.12	1.21
India	0.64	0.69	0.70	0.72	0.76	0.74	0.73	0.72	0.76
Brazil	1.03	1.04	1.04	1.04	1.05	1.06	1.01	1.00	0.96
South Africa	0.53	0.55	0.57	0.59	0.62	0.64	0.66	0.68	0.73
USA	2.45	2.48	2.50	2.54	2.62	2.64	2.55	2.55	2.49
United Kingdom	1.57	1.54	1.55	1.62	1.61	1.60	1.61	1.58	1.53
Germany	2.14	2.19	2.22	2.35	2.41	2.40	2.44	2.47	2.44
France	2.14	2.15	2.09	2.11	2.09	2.14	2.17	2.12	2.09
Mexico	0.25	0.28	0.30	0.34	0.31	0.32	0.35	0.39	0.39
Malaysia	0.22	0.31	0.40	0.43	0.47	0.56	0.65	0.63	0.60
Turkey	0.45	0.49	0.36	0.46	0.47	0.52	0.51	0.47	0.50
Egypt	0.21	0.20	0.20	0.19	0.19	0.21	0.23	0.25	0.27
Variable	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
China	1.31	1.37	1.37	1.45	1.58	1.71	1.78	1.91	2.00
India	0.82	0.80	0.81	0.86	0.83	0.79	0.76	0.74	0.71
Brazil	1.00	0.99	1.08	1.13	1.12	1.16	1.14	1.13	1.20
South Africa	0.77	0.80	0.79	0.81	0.75	0.66	0.67	0.67	0.66
USA	2.50	2.55	2.62	2.74	2.79	2.71	2.74	2.67	2.70
United Kingdom	1.55	1.58	1.62	1.61	1.62	1.63	1.65	1.58	1.62
Germany	2.44	2.47	2.46	2.62	2.74	2.73	2.81	2.88	2.84
France	2.05	2.05	2.02	2.06	2.21	2.18	2.19	2.23	2.24
Mexico	0.40	0.37	0.40	0.44	0.48	0.49	0.47	0.42	0.43
Malaysia	0.61	0.61	0.70	0.79	1.01	1.04	1.03	1.09	1.18
Turkey	0.56	0.55	0.69	0.69	0.80	0.79	0.79	0.83	0.81
Egypt	0.24	0.26	0.26	0.27	0.43	0.43	0.53	0.51	0.64
Variable	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
China	2.02	2.06	2.10	2.12	2.14	2.24	2.41	2.77	2.95
India	0.70	0.69	0.67	0.67	0.66	0.66	0.65	0.65	0.65
Brazil	1.27	1.37	1.29	1.12	1.17	1.21	1.15	1.15	1.15
South Africa	0.71	0.73	0.75	0.76	0.69	0.61	0.60	0.61	0.61
USA	2.72	2.79	2.85	2.90	3.01	3.17	3.47	3.46	3.50
United Kingdom	1.95	2.27	2.31	2.51	2.70	2.67	2.93	2.91	2.98
Germany	2.88	2.93	2.94	3.05	3.11	3.17	3.13	3.14	3.19
France	2.28	2.23	2.22	2.20	2.20	2.19	2.28	2.22	2.22
Mexico	0.44	0.43	0.39	0.33	0.31	0.28	0.30	0.28	0.27
Malaysia	1.26	1.28	1.42	1.23	1.04	1.00	0.95	1.01	1.07
Turkey	0.86	0.88	1.12	1.18	1.27	1.32	1.37	1.40	1.47
Egypt	0.64	0.72	0.71	0.64	0.69	0.80	0.92	0.91	1.02

tems, e-commerce platforms, and automation technologies that enhance operational efficiency and broaden market access (Li et al., 2023; Sagala and Őri, 2024; Rupeika-Apoga et al., 2022).
Another important aspect of developing the knowledge economy is the creation of a clear and responsive regulatory framework. Policies focused on data protection, cybersecurity, and intellectual property rights are essential for building trust and fostering an environment conducive to innovation. In addition, governments must demonstrate the tangible benefits of digital transformation, primarily through the digitisation of public services via e-government initiatives, which are already widely implemented in various parts of the world. The digitalisation of taxation, healthcare, education, and social security systems enhances transparency, reduces administrative inefficiencies, and improves service delivery, thereby setting a precedent for private sector participation.
Financial inclusion, supported by digital financial solutions, represents another key component of digital transformation. The expansion of mobile banking, digital payment systems, and blockchain-based financial mechanisms enables greater participation in the economy, particularly among previously unbanked populations. Regular monitoring and evaluation mechanisms must be established to ensure the effectiveness of digital transformation initiatives. Moreover, with the active development of blockchain technology, the creation of digital currencies has gained increasing relevance, offering more efficient financial management and providing the state with enhanced capabilities to monitor financial flows.
As part of this study, an analysis was conducted on the relationship between the level of GDP and expenditure on the latest technological developments relative to GDP. The data used for this analysis – specifically the ratio of expenditure on the latest developments to GDP – are presented in Table 1.
Across the 1996–2022 period, the data reveal substantial cross-country variation in expenditures on new technological developments relative to GDP, with advanced economies consistently demonstrating the highest investment intensity and showing differentiated responses to major global shocks such as the 2008 financial crisis and the COVID-19 pandemic.

Table 2. GDP data for selected countries, 1996-2022, source: created by the authors based on World Bank Group (2025).

Country	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Brazil	850	883	864	600	655	560	510	558	669
China	864	962	1029	1094	1211	1339	1471	1660	1955
Germany	2507	2219	2248	2214	1967	1966	2102	2535	2852
Egypt	68	78	85	91	100	97	85	80	79
France	1599	1449	1497	1487	1361	1370	1492	1835	2110
United Kingdom	1420	1561	1654	1688	1666	1650	1786	2054	2422
India	393	416	421	459	468	485	515	608	709
Mexico	432	523	557	631	742	796	811	766	819
Malaysia	101	100	72	79	94	93	101	110	125
Turkey	181	190	276	256	274	202	240	315	409
USA	8073	8578	9063	9631	10251	10582	10929	11456	12217
South Africa	163	169	153	152	152	135	129	197	256
Country	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
Brazil	892	1108	1397	1696	1667	2209	2616	2465	2473
China	2286	2752	3550	4594	5102	6087	7552	8532	9570
Germany	2893	3046	3484	3809	3480	3468	3825	3598	3808
Egypt	90	107	130	163	189	219	236	279	288
France	2192	2318	2656	2927	2700	2646	2870	2683	2816
United Kingdom	2543	2708	3091	2929	2413	2485	2664	2707	2785
India	820	940	1217	1199	1342	1676	1823	1828	1857
Mexico	918	1020	1102	1162	943	1105	1229	1255	1327
Malaysia	144	163	194	231	202	255	298	314	323
Turkey	506	557	681	770	649	777	839	881	958
USA	13039	13816	14474	14770	14478	15049	15600	16254	16881
South Africa	289	304	333	316	330	417	458	434	401
Country	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Brazil	2456	1802	1796	2064	1917	1873	1476	1671	1952
China	10476	11062	11233	12310	13895	14280	14688	17820	17882
Germany	3966	3424	3538	3763	4052	3957	3940	4348	4164
Egypt	306	329	332	248	263	319	384	425	477
France	2861	2442	2470	2589	2782	2723	2648	2966	2796
United Kingdom	3065	2928	2689	2680	2871	2851	2697	3143	3114
India	2039	2104	2295	2651	2703	2836	2675	3167	3353
Mexico	1365	1213	1112	1191	1256	1304	1121	1317	1464
Malaysia	338	301	301	319	359	365	337	374	408
Turkey	939	864	870	859	779	761	720	820	907
USA	17608	18295	18805	19612	20657	21540	21354	23681	26007
South Africa	381	347	324	381	405	389	338	421	407

The United States, Germany, and France maintained stable and comparatively elevated ratios throughout, experiencing only marginal slowdowns around 2008-2009 but quickly returning to an upward trajectory; during the pandemic years, all three countries registered further increases, reflecting countercyclical investments in digitalization, research, and innovation. The United Kingdom followed a similar pattern, with a brief dip after 2008 followed by strong growth, particularly during 2020-2021 when digital infrastructure became a strategic priority. China demonstrates the most pronounced long-term rise among emerging economies, with steady increases even through the 2008 crisis and rapid growth during the pandemic period, indicating sustained policy-driven investment unaffected by global downturns. In contrast, middle-income countries such as India, Brazil, and South Africa show more muted or inconsistent patterns: most experienced only limited disruptions during the 2008 crisis but did not exhibit substantial increases during the pandemic, with India and South Africa continuing gradual declines. Lower-investment economies, such as Mexico, Malaysia, Turkey, and Egypt, display heterogeneous trends, with Mexico and Malaysia weakening after both crises, while Turkey and Egypt show moderate resilience and incremental growth. Overall, the data indicate that advanced economies and China not only maintained but strengthened technological investment during major crises, whereas many developing countries experienced stagnation or contraction, thereby widening the long-term gap in technological investment intensity.
The effect of investing in R&D was further examined in the context of GDP growth rates, as presented in Table 2.
Based on the data presented in Tables 1 and 2, correlation coefficients were calculated for the respective countries. The results are displayed in Table 3.

Table 3. Correlation between GDP level and R&D expenditure as a percentage of GDP in selected countries, source: created by the authors

Country	Correlation
Brazil	0.732
China	0.965
Germany	0.875
Egypt	0.978
France	0.446
United Kingdom	0.549
India	-0.477
Mexico	0.293
Malaysia	0.868
Turkey	0.748
USA	0.900
South Africa	0.336

The study of the above-mentioned data confirmed there was a statistically significant positive relationship between investing in R&D and economic growth rates; however, the intensity of this relationship varied across the countries. Taking into account the threshold level of +0.6 established in the Methodology, it can be concluded that countries such as Brazil, China, Germany, Egypt, Mexico, Turkey, and the United States exhibit a sufficiently strong relationship between GDP levels and R&D expenditure as a percentage of GDP. These countries are the main candidates for identifying a statistically significant relationship between the indicators selected for analysis. The key variables derived from the constructed regression equations are presented in Table 4.

Table 4. Regression equation data for selected countries, source: created by the authors

Countries	Brazil	China	Germany	Egypt	Malaysia	Turkey
Multiple R	0.732	0.965	0.875	0.978	0.868	0.748
R Square	0.536	0.931	0.766	0.957	0.753	0.559
Adjusted R Square	0.518	0.929	0.756	0.955	0.743	0.542
Significance F	1.4E-05	4.6E-16	2.4E-09	1.5E-18	4.7E-09	7.3E-06
P-value (C)	0.00053	1.2E-08	0.00128	0.6657	0.50941	0.17631
P-value (X)	1.4E-05	4.6E-16	2.4E-09	1.5E-18	4.7E-09	7.3E-06
t (C)	-3.97	-8.28	-3.63	-0.44	-0.67	1.39
t (X)	5.38	18.43	9.04	23.45	8.73	5.63
t critical	2.06	2.06	2.06	2.06	2.06	2.06

Table 4 showed that all the obtained regression equations are adequate, based on selected criteria, in particular, the Adjusted R Square values for all variables are relatively high, exceeding 0.5. Although the threshold value was set at 0.6 within the framework of this study, a level above 0.5 can still be regarded as sufficient to indicate a moderate correlation. Furthermore, the p-values for the independent variable (X) in all equations, as well as the Significance F-values, were below the threshold of 0.05, and the t(X) statistics exceeded the critical value of 2.06.
Despite these generally positive results, it was decided to narrow the scope of subsequent analysis by focusing on fewer countries. Accordingly, China and Germany were selected for further investigation. The selection was based on filtering

out countries whose equations demonstrated certain shortcomings: an Adjusted R Square below +0.6 for Brazil and Turkey; a p-value for the constant (C) above 0.05 for Egypt, Malaysia, and Turkey; and t(C) statistics below the critical value of ±2.06 for Egypt, Malaysia, and Turkey.
The resulting regression equation for China is presented in Formula 1:

$$y = -6451.34 + 8337.964x, \tag{1}$$

where y is the dependent variable (GDP for the selected time period, in USD billion), and x is the independent variable (the level of expenditure on innovation, as a percentage of GDP).
Thus, an increase of one percentage point in innovation expenditure relative to GDP is associated with an estimated increase in GDP of USD 8.3 trillion for China.
The equation for Germany is shown in Formula 2:

$$y = -2193.03 + 2016.835x, \tag{2}$$

where y is the dependent variable (GDP for the selected time period, in USD billion), and x is the independent variable (the level of R&D expenditure, as a percentage of GDP).
Accordingly, an increase of one percentage point in R&D expenditure relative to GDP corresponds to an estimated increase of USD 2.016 trillion in Germany's GDP. This relationship may also be illustrated graphically, as shown in Figures 2 and 3.

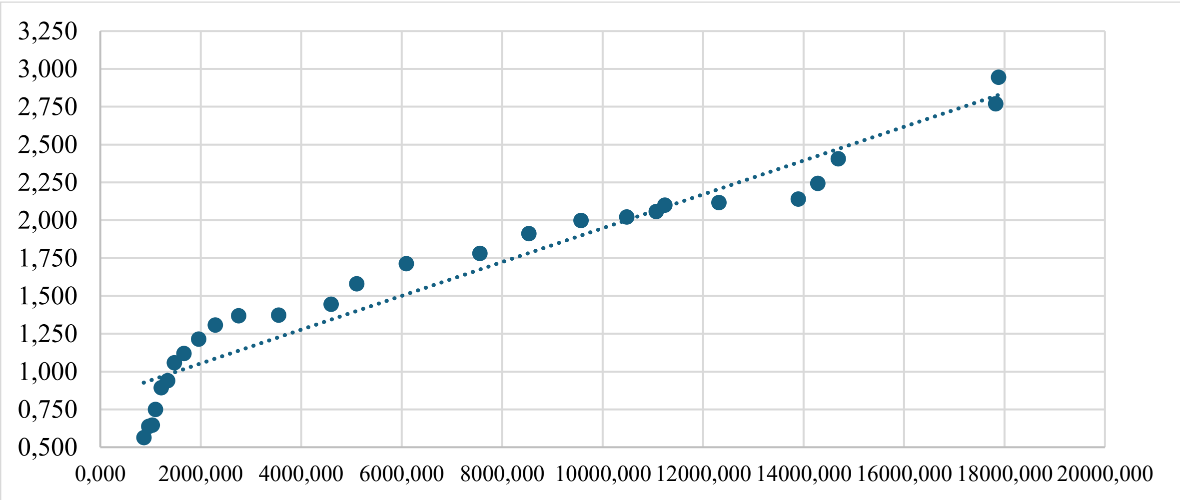

Figure 2. Visualisation of the relationship between GDP (USD billion) and R&D expenditure as a percentage of GDP for China for the period from 1996 to 2022, source: created by the authors

Figure 2 illustrates the relationship between GDP levels and R&D expenditure as a percentage of GDP in China. Although the relationship can be characterised as linear, the figure shows that in the initial segment (up to a GDP level of USD 2 trillion), the slope is significantly steeper compared to later stages. In the case of Germany (Figure 3), the relationship appears more linear overall, albeit with a larger dispersion of values around the regression line.
Specific characteristics of digital system development in China were further examined. The situation in the country represents the case of knowledge-based economic growth driven by digital transformation, situated at the intersection between a developing and a highly developed economy. Over the past two decades, the Chinese government has implemented a systematic strategy to integrate digital technologies into its economic structure through policy directives, infrastructure investments, and the cultivation of an ecosystem that fosters technological innovation. Policy related to the digitalisation of the economy forms the cornerstone of China's broader national strategy. The government actively promotes digital transformation across multiple sectors as a means of stimulating economic growth, improving governance, and enhancing national security. A central focus of China's digitalisation agenda is the development of advanced technologies such as artificial intelligence, big data, cloud computing, and 5G networks. The state invests heavily in research and development, often supporting domestic firms in these sectors through subsidies and tax incentives. China has also prioritised the digital transformation of industry. The *Made in China 2025* plan (2018) promotes the integration of digital technologies into manufacturing and production processes to boost efficiency and foster innovation. Similarly, the *Internet Plus* strategy (2025) seeks to combine internet technologies with traditional industries – such as agriculture, healthcare, and education – in order to improve productivity and competitiveness.

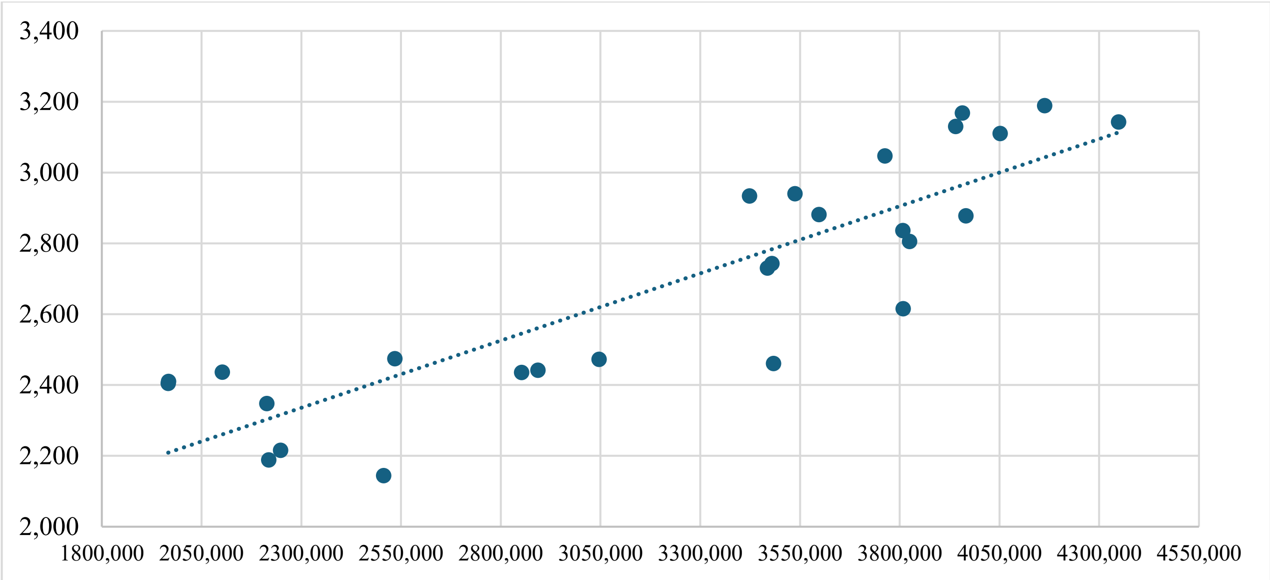

Figure 3. Visualisation of the relationship between GDP level (USD billion) and R&D expenditure as a percentage of GDP for Germany for the period 1996-2022, source: created by the authors

In the field of governance, digitalisation plays a key role in modernising public administration (Matkarimov et al., 2024). The Chinese government has introduced e-government platforms to streamline services, increase transparency, and enhance citizen engagement. Moreover, digital tools are widely deployed to monitor and maintain social stability, as seen in the extensive use of surveillance technologies and the implementation of the controversial social credit system. A foundational pillar of China's digital transformation strategy is its substantial investment in research and development. China ranks among the world's largest investors in this area, placing particular emphasis on artificial intelligence, quantum computing, semiconductors, and big data analytics. The state maintains a central role in directing technological progress by providing generous subsidies, tax relief, and funding to strategically important sectors (Saktaganova et al., 2025; Panteghini, 2009). At the same time, it retains strict control over data flows and internet regulation, resulting in a distinctive model in which digitalisation advances within a tightly regulated framework.

China's digital transformation is also evident in the development of its smart infrastructure, particularly in the telecommunications sector. The country's digital economy is supported by a highly dynamic entrepreneurial ecosystem. A significant rise in technology-focused enterprises has been observed, particularly in cities such as Shenzhen, Hangzhou, and Beijing. Chinese technology companies have developed advanced artificial intelligence applications, automated industrial processes, and blockchain-based solutions, thereby enhancing efficiency across logistics, finance, and public administration. One of the most ambitious elements of China's digital transformation is its drive for industrial digitalisation, particularly in the domains of smart factories, artificial intelligence, and robotics. This initiative aims to enhance manufacturing efficiency, especially within the electronics, automotive, and high-tech industries. The government actively supports the formation of digital industrial clusters by offering financial and policy incentives to enterprises that adopt advanced automation technologies (State Council…, 2025).

Despite these advancements, China faces several structural challenges. Chief among them is substantial government intervention in the private sector, which can diminish its dynamism. Furthermore, the regulatory environment – particularly regarding data security and intellectual property rights – generates uncertainty for both domestic and foreign investors. Ongoing restrictions imposed by Western countries on access to semiconductor and artificial intelligence technologies may also lead to unintended consequences.

In addition, a growing digital divide persists, particularly between coastal urban centres and less developed inland regions, limiting the equitable distribution of digital economic benefits. Nevertheless, China has largely succeeded in leveraging digitalisation to boost productivity, improve public service delivery, and stimulate the emergence of new economic sectors. However, the long-term sustainability of this model will depend on the country's ability to manage geopolitical tensions, achieve technological self-sufficiency, and develop a regulatory framework that effectively supports innovation-driven development.

4. Discussion

Knowledge-based economic growth provides developing economies with a pathway to overcome traditional structural barriers by strategically investing in technology and human capital. A well-designed digital transformation strategy enhances transparency, strengthens economic inclusiveness, and improves the quality and efficiency of public services. Nonetheless, achieving these outcomes requires government support, advanced infrastructure, and a supportive regulatory environment. China exemplifies a high-quality case of digital transformation, having directed significant resources toward artificial intelligence, 5G networks, industrial automation, and advanced manufacturing. While China's trajectory has been broadly positive, it is not without challenges: regional disparities, skills gaps, and the high cost of research and development remain important constraints. Moreover, external shocks, including the 2008 global financial crisis and the COVID-19 pandemic, have intermittently tested the resilience of China's innovation system. Notably, during the pandemic period, technological investment accelerated, reflecting both a policy-driven prioritization of digital infrastructure and the strategic role of innovation in sustaining economic activity under crisis conditions.

The present study identified several key drivers of innovation in China, including active government support, sustained investment in research and development, and the continuous expansion of digital infrastructure. These findings are consistent with Brodny and Tutak (2022), who analysed digitalisation across European Union (EU) member states using ten indicators to assess technological adoption and its correlation with economic variables. Their study highlighted that while cloud computing has been widely adopted by EU enterprises, emerging technologies such as artificial intelligence and 3D printing remain less prevalent, particularly in newer member states. Moreover, the study observed a significant disparity in digitalisation levels between the *old* and *new* EU member states, with Denmark, Finland, and Belgium ranking highest, and Hungary, Bulgaria, and Romania trailing behind. Influencing factors included GDP per capita and investment in innovation, while the GDP level itself appeared to have limited direct impact on technological advancement. In comparison, China's innovation-led growth is more strongly shaped by government intervention, which directs investment toward strategically important sectors and accelerates the dissemination of new technologies across the economy. This contrast illustrates that, while both China and the EU benefit from innovation-driven development, the role of state policy is considerably more pronounced in the Chinese context.

Xholo et al. (2025) further examined the complex interplay between digitalisation, education, and gross national income (GNI). Their study found that while investments in education and digital technologies are essential, they can exert negative effects on GNI in the short term due to the high initial costs and delayed realization of economic returns. In contrast, institutional quality demonstrated a strong positive impact on GNI, highlighting the importance of governance and effective regulatory frameworks in enabling innovation-driven growth. The present study complements these findings, revealing a positive correlation between GDP and R&D expenditure as a percentage of GDP across 12 countries, including China. This positive relationship contrasts with the short-term negative effects observed in Xholo et al. (2025), suggesting that the efficiency of investment and the strength of institutional support are critical factors determining whether innovation translates into immediate economic gains.

Comparative analyses across regions provided additional insight; for example, Bąk et al. (2022) observed that countries that joined the EU earlier generally exhibit higher levels of development in knowledge-based economy components, whereas those acceding after 2004 tend to lag behind. This pattern underscores the influence of long-term institutional frameworks and accumulated technological capacity on innovation outcomes. While EU member states typically rely on private sector-led innovation and prioritize green investments, China emphasizes strategic state-led development, technological self-reliance, and national security. These divergent approaches highlight how institutional and policy contexts shape the pace, scale, and focus of technological advancement, even when the broader objective of innovation-led economic growth is shared.

The impact of major global crises on technological investment provides a further layer of understanding. The 2008 global financial crisis temporarily slowed investment in some countries, particularly those with weaker fiscal positions, but advanced economies largely maintained their R&D intensity, signalling resilience. In contrast, developing countries often experienced stagnation or decline in technological investment during this period. The COVID-19 pandemic reinforced these dynamics: advanced economies and China increased investments in digital infrastructure, artificial intelligence, and industrial automation to mitigate the economic shock, whereas many middle- and lower-income countries struggled to sustain pre-pandemic levels of innovation due to fiscal constraints and supply chain disruptions. These observations underscore that while innovation is a driver of growth, its resilience during crises depends on both policy orientation and institutional capacity.

Additional studies further confirm the relationship between knowledge-based growth and economic performance. Mohamed et al. (2022) demonstrated that in developing countries, indicators such as mobile phone penetration, internet access, foreign direct investment, and international trade significantly influence economic growth. Political stability, anti-corruption measures, and the adoption of new technologies amplify these effects. Similarly, Jonida (2024) highlighted that technological innovation contributes not only to economic expansion but also to environmental sustainability by promoting renewable energy adoption and reducing carbon emissions. These findings suggest a synergistic relationship between innovation, green growth, and overall economic development, further reinforced by state policies that facilitate investment access, improve patent systems, and support scientific workforce training.

Mohamed et al. (2021) examined Qatar's transition from a hydrocarbon-dependent economy to a diversified, knowledge-based model. The study emphasized the importance of investing in gas technologies, hydrogen production, and high-tech sectors, alongside human capital development and gender inclusion. By adopting China's approach to innovation and stra-

tegic investment, resource-dependent economies like Qatar can accelerate knowledge-based growth and achieve sustainable economic diversification. Indeed, China itself evolved from reliance on low-cost manufacturing and raw material exports to a technology-intensive economy, underscoring the transformative potential of strategic innovation policies.
Education emerges as a central enabler of innovation-driven development. The present study highlights that improvements in workforce quality, combined with investments in training and human capital, facilitate the implementation of advanced technologies and strengthen the innovation ecosystem. Hu et al. (2021) similarly emphasised the role of education, social well-being, and knowledge-oriented cooperation in fostering urban competitiveness and regional development. By accumulating human, environmental, and relational assets, cities can create a cycle of innovation, attracting talent, stimulating creativity, and supporting long-term sustainable growth. Both the current study and prior research converge on the conclusion that education and human capital development are fundamental policy priorities for achieving resilient, knowledge-based economies.
The findings of this study reinforce the hypothesis that innovation-led development is a critical driver of GDP growth in both developing and developed countries. Investments in cutting-edge technologies, particularly when supported by strong institutional frameworks, facilitate long-term economic performance and contribute to sustainability objectives. However, the analysis also highlights the challenges and obstacles that can impede progress. High initial costs, skills shortages, regional disparities, and the impacts of external shocks such as the 2008 financial crisis and the COVID-19 pandemic can delay the realization of economic benefits from innovation. Countries with proactive policy measures, government supervision, and targeted investment, including People's Republic of China, are better able to maintain growth trajectories during such crises, demonstrating the resilience of knowledge-based development models.
In conclusion, the present study, in conjunction with the reviewed literature, confirms that knowledge- and innovation-driven development significantly enhances economic performance, particularly when supported by effective governance, strategic policy intervention, and investments in human capital. The analysis of China, EU member states, and other developing economies illustrates that while the general mechanisms linking innovation to growth are similar, institutional frameworks, policy priorities, and crisis resilience critically shape outcomes. Consequently, for developing countries seeking sustainable economic growth, the combination of digital transformation, strategic R&D investment, human capital development, and institutional strengthening emerges as essential. Furthermore, external shocks such as financial crises and pandemics reinforce the need for adaptive and resilient innovation policies that can sustain technological momentum and secure long-term economic and social benefits.

5. Conclusions

In summary, the transition to a knowledge-based economy driven by digital transformation presents both significant opportunities and notable challenges for emerging economies. Strategic investments in technology, human capital, and digital infrastructure enable countries to overcome traditional barriers to economic development. However, this process also demands substantial government effort in formulating effective policies, establishing robust governance structures, and engaging in careful planning to mitigate the potential risks that may arise during implementation. The study also found that expanding internet access – particularly in rural and underserved areas – plays a vital role in maximising the benefits of digitalisation.
The case of China highlights both the successes and complexities of government-led digital transformation. Through policy initiatives such as Made in China 2025 and Internet Plus, the country has succeeded in integrating digital technologies across various sectors, thereby enhancing productivity, improving public service delivery, and reinforcing national security. Although China's rapid advancements in artificial intelligence, big data, and 5G networks suggest that the country is poised to become a global leader in digital transformation, the long-term sustainability of this model will depend on its ability to balance strong state control with a dynamic and innovative market environment.
This study also conducted regression and correlation analyses to assess the relationship between different indicators of innovation development and economic growth. These analyses confirmed the existence of such a relationship, particularly in the case of China, where a statistically significant correlation was found between R&D expenditure (as a percentage of GDP) and the level of GDP. Future research should focus on the detailed analysis of each core component of the knowledge economy in China – especially the field of artificial intelligence, which has gained increased relevance in light of the emergence of DeepSeek, a Chinese AI model promoted as more affordable, accurate, and efficient than ChatGPT.

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