“The impact of education digitalization on achieving SDG4: A comparative assessment of Azerbaijan and SDG4 leaders”

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THE IMPACT OF EDUCATION DIGITALIZATION ON ACHIEVING SDG4: A COMPARATIVE ASSESSMENT OF AZERBAIJAN AND SDG4 LEADERS

Abstract

The digital transformation of education is a modern trend, and it is essential to investigate its role in enhancing quality education as one of the Sustainable Development Goals. The purpose of the paper is to confirm the restraining or accelerating impact of education digitalization on achieving SDG4 in Azerbaijan compared with SDG4 leaders. The sample consists of the chosen data of 14 indicators in the education digitalization field (provided by the Statistics Division of the United Nations Department of Economic and Social Affairs, United Nations Educational, Scientific and Cultural Organization Institute for Statistics Data, and the International Telecommunication Union) in 2016–2023 from 10 countries: Azerbaijan (status 'Challenges remain' for SDG4) and nine leading countries (status 'Goal Achievement') according to 2024 SGD Index Rank. To achieve the goal, the Granger causal test and regression analysis (linear modeling for time series and random-effects GLS regression for panel data) using Stata SE 18.0 software were applied. It was confirmed that in Azerbaijan (both separately and within a panel of studied countries), the impact of education digitalization on achieving SDG4 is positive and accelerating (for specific indicators, it is not significant but not restraining). The stronger impact is observed in Azerbaijan compared to the average on the panel level. The key accelerators are school-level Internet access, digital practical skills, and digital literacy, especially proportions of youth/adults who have used arithmetic in spreadsheets, connected and installed new devices, and created electronic presentations (increase in SDG4 achievement indicator by 2.63, 3.5%, and 9.89%).

Keywords digital transformation, ICT skills, Internet access, quality education, sustainable development

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INTRODUCTION

Quality education is one of the Sustainable Development Goals (SDGs). The Statistics Division of UN Department of Economic and Social Affairs (UNDESA) notes that progress toward the 2030 goal on quality education has already been slower than needed before the pandemic, but COVID-19 has had a devastating impact on education, causing learning loss in 4 out of 5 countries. Low levels of information and communication technology (ICT) literacy pose a significant barrier to achieving universal and meaningful connectivity. However, data on digital skills are limited and incomplete, not available across all countries, and rarely across all five skill categories (communication/collaboration, problem-solving, safety, content creation, information literacy) (UNSTATS, n.d.). At the same time, the COVID-19 pandemic has shown that the digitization of education and the implementation of digital learning platforms can have significant benefits. Therefore, digital transformation is considered one of the key measures to achieve SDG4.

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This global perspective finds a clear reflection in the case of Azerbaijan. Like many other countries, Azerbaijan faces ongoing challenges in this area. While assessments of the country's progress toward achieving SDG4 show moderate improvement, current efforts remain insufficient to meet the 2030 targets. One of the main barriers is the low level of digital skills. In particular, satisfactory or even limited level is fixed in cases of the share of primary schools connected to the Internet (68%), lower-secondary schools connected to the Internet (72%), businesses with more than 10 staff using the Internet (51%), and businesses with 0+ staff using the Internet (33%), etc. (ITU, n.d.a).

At the same time, there is not a directly obvious relationship between Azerbaijan's ICT Development Index (IDI) and its SDG4 performance, which is an interesting observation because Azerbaijan's IDI score is relatively high, indicating good ICT infrastructure, but its SDG4 achievement, which focuses on quality education, is significantly lower in comparison to leaders. Thus, the confirmation of the restraining or accelerating impact of education digitalization on achieving SDG4 is a relevant issue that needs specific empirical methods.

1. LITERATURE REVIEW

Education is recognized as a key enabler for achieving all other SDGs. Digital transformation emerges as both a catalyst and a tool for aligning education systems with SDGs. By integrating technology and innovative learning approaches, digitalization contributes to improving the quality of education, which directly influences outcomes through better-trained professionals, increased accessibility to knowledge, and data-driven decision-making. The convergence of digitalization in education and technological advancements is driving transformative changes (Burrell, 2024; Ninassi & Burrell, 2023).

Samusevych et al. (2021) examined the interconnectedness of the economy, education, digitalization, and national security, focusing on how convergence within these domains can enhance socio-economic stability and strengthen national security. The article explored trends and proposed strategies for integrating these elements effectively. The analysis by Artyukhov et al. (2024c) revealed a strong association between educational reforms, outcomes improvements, literacy, and competitiveness. Melnyk et al. (2022) conclude that digital and economic transformations are vital for advancing sustainable development in OECD countries.

Digitalization of education is not merely the adoption of tools but also the integration of advanced technologies, digital tools, and platforms into the education system to enhance teaching, learning, and administrative processes, thereby adapting to the evolving demands of learners, educators, and industries. Imrani and Jafarov (2023) and Jafarov et al. (2023) explored the main paths of sustainable development in education, understanding the varying potential for digitalization in school education, to create a resource framework for the digital learning environment, particularly in the context of education and the broader economy.

Akther et al. (2024) investigate the factors influencing higher secondary teachers in Bangladesh to adopt new teaching technologies. The findings underscore the importance of user-friendly, engaging, and efficient educational technologies, as well as tailored training programs to support teachers. Kalinichenko et al. (2024) conclude that digitization has profoundly impacted Wiki communities by enhancing their capacity for collaboration, governance, and knowledge dissemination. By leveraging advanced tools and addressing challenges like digital inequities and content quality, such communities can continue to thrive and contribute to sustainable development.

Dobrovolska et al. (2023) examined the interconnectedness of knowledge creation, impact, digitalization, and diffusion within the context of higher education. They explored how universities serve as hubs for generating, applying, and disseminating knowledge, highlighting their role in fostering innovation and societal progress. Kuzior et al. (2024) conclude that university-industry R&D collaboration is a critical driver of innovation transfer and startup success. By bridging the gap between academic research and industrial appli-

cation, these partnerships contribute to economic growth, technological advancement, and sustainable development.

Oe et al. (2024) investigate factors affecting student engagement in online learning environments. The study employs Herzberg's motivation-hygiene theory and the concept of flow to analyze how various elements influence learner satisfaction and engagement. Awdziej et al. (2023) examined how the digital maturity of university students influences their sustainable behaviors. Students with higher digital competencies are more likely to engage in actions that support sustainability.

By exploring the analogy between quantum entanglement and brain information processing, Njegovanović (2023) lays the groundwork for developing quantum-inspired approaches to intelligent education. Skrynnyk et al. (2022) explored the application of artificial intelligence in addressing key challenges in education, focusing on how AI-driven tools and systems can enhance learning outcomes, streamline administrative processes, and support the overall digital transformation of the educational sector.

Vorontsova et al. (2020) conclude that state regulation plays a vital role in transforming education systems and their digitalization to achieve sustainable development goals. Persistent challenges such as inequality and resource constraints require further policy innovation and collaboration.

The 2020s brought unprecedented challenges to global education systems due to crises such as the COVID-19 pandemic, armed conflicts, and economic disruptions. These crises underscored the urgent need for the digitalization of education as a means to sustain learning and adapt to rapidly changing circumstances. Filho et al. (2024) report on areas where digital tools have boosted sustainability efforts in higher education after the COVID-19 pandemic. The comprehensive analysis by Artyukhov et al. (2024a) provides valuable insights into the evolution of research themes and collaborative efforts in the study of educational resilience amid armed conflicts. Artyukhov et al. (2024b) present a comprehensive bibliometric analysis of scholarly publications addressing educational crises during the 2020s. Polishchuk et al. (2023) highlight the vital role of the "Ukrainian Science Diaspora" initiative in supporting the scientific community during wartime.

While digitalization enhances educational accessibility, quality, and innovation, financing these advancements is a critical consideration for stakeholders at all levels. Yu et al. (2024) and Yu et al. (2023) highlighted the crucial role of regional socio-economic characteristics (especially in China) in shaping the allocation of financial resources for higher education. Strategic interventions, such as equitable funding models, accountability frameworks, and collaborative efforts, can help mitigate these issues. Vorontsova et al. (2021) highlight a strong correlation between education expenditures and the pace of digitalization in society. Increased investment in education enhances digital literacy, bridging the digital divide.

The intersection of education digitalization, financial literacy, and financial inclusion is a transformative domain that can empower individuals and societies by bridging gaps in financial access, fostering economic stability, and equipping learners with essential skills for the digital economy (Didenko et al., 2023). By addressing knowledge deficits, accessibility challenges, and cultural biases, stakeholders can ensure greater participation in financial systems, driving economic stability and reducing inequality (Kuzior et al., 2022).

Generally, the digitalization of education plays a pivotal role in advancing the SDGs, particularly SDG4 (Quality Education). Ahuja (2023) put attention on leveraging digital innovation to drive progress on SDG4. Kuzior et al. (2023) showed that lifelong learning is indispensable for enhancing a country's competitiveness and innovative potential. It aligns closely with sustainable development goals by fostering economic growth, social equity, and environmental awareness. Makinde et al. (2023) explored the concept of Smart Learning and its role in SDGs achievement within the educational context. Shaibouh and Haji (2024) discuss how university culture mediates the relationship between digital transformation and sustainability outcomes.

Suárez et al. (2023) provided a comprehensive analysis of digital transformation in higher education within Latin America, thereby contribut-

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ing to the achievement of SDGs. The study underscores the need for strategic planning and policy development to effectively integrate digital technologies into education systems. Lim et al. (2022) emphasize the importance of systematically integrating sustainability into higher education curricula to inspire future generations.

Veckalne and Tambovceva (2022) explored the crucial role that education plays in fostering sustainable development and how digital transformation can enhance this role. They discuss the integration of education for sustainable development into various learning contexts and the importance of interdisciplinary approaches. Samiya and Asma (2024) emphasized the importance of a multidimensional approach to measuring and improving the quality of education in institutions. By addressing governance, teaching quality, infrastructure, and student-centric factors, institutions can enhance their educational standards and align with global benchmarks.

The interconnected nature of SDGs and the complexity of sustainability make it challenging to connect these goals to clear educational outcomes. One of the more relevant issues is the creation of evaluation tools that enable educational institutions to track and manage their progress in advancing sustainability in society (Kioupi & Voulvoulis, 2019).

The UNDESA assesses the degree of achievement of a particular goal (including SDG4) based on the generalization of a number of quantitative and qualitative (a certain proportion of indicators is formed via survey analysis) indicators within the Sustainable Development Index pillars and total Index score. ICT access and skills are also assessed, but the digitalization of education is not covered comprehensively. The impact of digitalization on education, the potential to improve the overall level of its quality, and, accordingly, the degree of achievement of SDG4 have not been fully taken into account. Therefore, it is important to prove and formalize this influence.

The purpose of the study is to confirm the restraining or accelerating impact of education digitalization on achieving SDG4 in Azerbaijan compared with SDG4 leaders.

2. METHODS

The information base covers statistical data of the UNDESA, UNESCO Institute for Statistics Data, and the International Telecommunication Union (ITU) as the UN specialized agency for ICT.

The sample of the study includes 10 countries, specifically Azerbaijan (with a status of 'Challenges remain' for the SDG4 score in 2024) and nine leading countries in SDG4 achievement (with a status of 'Goal Achievement') (Sachs et al., 2024). Generally, there are 12 countries with the status of 'Goal Achievement' for SDG4 according to the 2024 SGD Index Rank, but only nine of them are also present in the statistical databases of UNESCO and ITU, which are the source for chosen indicators for this study (Argentina, China, Georgia, Moldova, Peru, Singapore, Thailand, Vietnam, and the United Arab Emirates).

The time period (2016–2023) is grounded by the data availability for all investigated indicators in this analysis. The following indicators are chosen and investigated to confirm the restraining or accelerating impact of education digitalization on achieving SDG4:

1. The score of SDG4 achievement within the SDG Index (Sachs et al., 2024; Sdgindex, n.d.);
2. The proportion of primary schools with access to the Internet (UIS, n.d.);
3. The proportion of lower secondary schools with access to the Internet (UIS, n.d.);
4. The proportion of secondary schools with access to the Internet (UIS, n.d.);
5. The proportion of upper secondary schools with access to the Internet (UIS, n.d.);
6. The share of households with Internet access at home (ITU, n.d.c);
7. The proportion of youth and adults who have sent emails with attached files (UIS, n.d.);
8. The proportion of youth and adults who have connected and installed new devices (UIS, n.d.);

9. The proportion of youth and adults who have created electronic presentations with presentation software (UIS, n.d.);

10. The proportion of youth and adults who have used basic arithmetic formulae in a spreadsheet (UIS, n.d.);

11. The proportion of individuals using the Internet for doing an online course (ITU, n.d.c);

12. The proportion of individuals using the Internet (ITU, n.d.c);

13. The level of fixed-broadband Internet basket (% of GNI per capita) (ITU, n.d.c);

14. The level of data-only mobile broadband basket (% of GNI per capita) (ITU, n.d.c).

The data do not require the application of a normalization procedure because they have the same unit of measurement.

To achieve the research purpose, the methods of causal and regression analysis using Stata SE 18.0 software were applied.

The Granger causality test is a statistical method used to determine whether one time series can predict another time series and to understand the relationship between variables over time (Granger, 1969; Granger, 1997). Before running a Granger causality test, it is necessary to create a VAR model that includes the time series tested. A statistical model VAR (vector autoregression) is used to capture the linear relationship between multiple time series data and helps in forecasting systems of interrelated time series. Once the VAR model is established, the Granger causality test is performed to test if past values of one variable can predict the current value of another (Baum et al., 2022; Rossi & Wang, 2019). If the *p*-value of the test is less than a chosen significance level (typically 0.05), the null hypothesis is rejected, and it is concluded that there is Granger causality (Amisano & Giannini, 1997; Hamilton, 1994; Schenck, 2016).

After identifying indicators that cause for changes in the achievement of SDG4, regression analysis methods are used to clarify the direction of influence (negative/restraining or positive/accelerating) and formalize this impact. Linear regression modeling is applied for time series for the investigation of Azerbaijan's case and random-effects GLS regression – for panel data (all sample countries). The Random-effects GLS (Generalized Least Squares) regression assumes that the unobserved individual heterogeneity (the individual differences between countries) is random and uncorrelated with the regressors (independent variables). This makes random-effects models more efficient when the assumption holds true. Coefficients in random-effects models represent the average effect of the predictors across countries while also accounting for differences between countries.

Finally, it would be appropriate to compare the obtained results separately for Azerbaijan and, on average, for the panel of countries (leaders in SDG4 achievement).

3. RESULTS

According to the 2024 SGD Index Rank, Azerbaijan is in the group of countries with the status of 'Challenges remain' for SDG4 (Quality education) (Sachs et al., 2024). The other nine countries from the research sample are leaders in this goal achievement, having the corresponding status of 'Goal Achievement' (Sdgindex, n.d.). In turn, the ICT Development Index (IDI) shows the level of the state of digital connectivity in these countries (ITU, n.d.b). Visualization of comparison analysis of countries' scores and gaps for the above indexes is presented in Figure 1.

On the surface, there is a question about the designation of countries like Peru, Argentina, Georgia, Moldova, and Vietnam as having achieved SDG4 (Quality Education). This can seem surprising given common perceptions of education systems in middle-income countries. However, the Sustainable Development Report 2024 uses specific indicators and thresholds to assess goal achievement. The SDG Index evaluates each SDG using composite scores based on a set of indicators that reflect both access and outcomes. The list of all indicators is given in the Guide to Education Indicators for SDG4 (UIS, 2018). Generally, the

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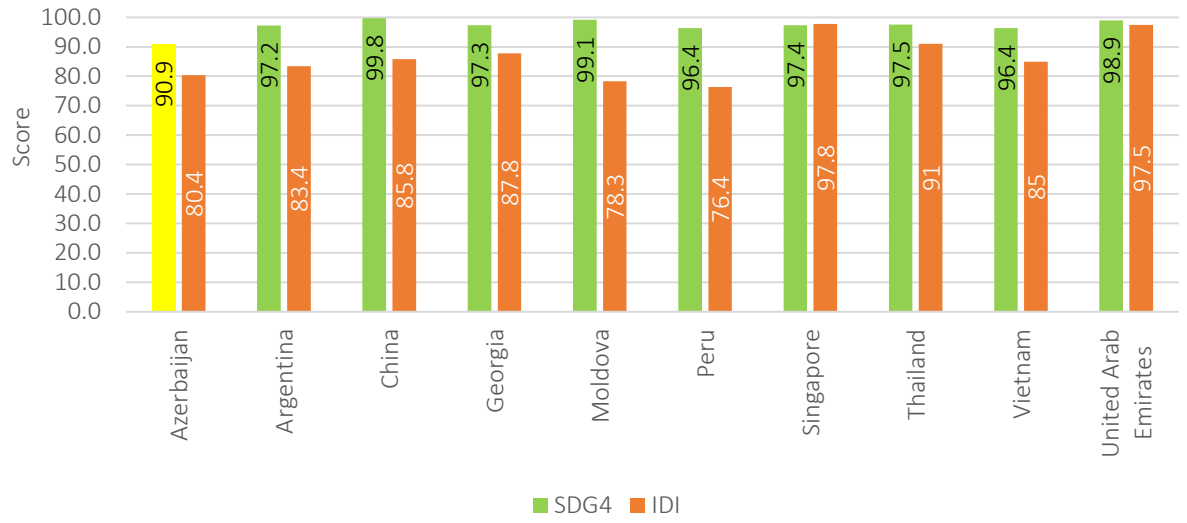
Source: Built by the authors based on Sachs et al. (2024), Sdgindex (n.d.), and ITU (n.d.b).



Note: Yellow fill – 'Challenges remain', green fill – 'Goal Achievement'(SDG4).

Figure 1. Comparison analysis of scores and gaps for SDG4 achievement and IDI within sampled countries

following indicators are evaluated for SDG4 achievement determination: literacy rate (youth and adult), primary and secondary school completion rates, expected years of schooling, harmonized test scores, school enrollment rates (pre-primary, primary, and secondary), and gender parity in education. When a country meets or exceeds defined thresholds on nearly all indicators for a goal, it can be labeled as having "Goal achieved."

The above countries have shown strong recent performance on key education indicators. Vietnam has outperformed many OECD countries in PISA scores in science and math, with high enrollment and literacy rates. Georgia and Moldova have made substantial reforms to education systems, improving access and literacy. Argentina and Peru have near-universal primary education and high literacy rates despite ongoing challenges in quality and equity. In SDR 2024, their scores for SDG4 are likely driven by universal or near-universal enrollment, high youth literacy, low gender disparities, and standardized test scores (where available) showing minimal gaps in basic proficiency.

Moreover, the status 'Goal Achievement' is not equal 'Perfect System.' The 'Goal achieved' label means that the country meets the international targets set for SDG4, not that its education system is without flaws. Challenges in teacher training, curriculum quality, or regional disparities may still exist. However, statistically, the core SDG4 benchmarks are satisfied.

As for Azerbaijan, it has the status 'Challenges remain' for the SDG4 achievement. While Azerbaijan's IDI score may be relatively high, indicating good ICT infrastructure, its SDG4 achievement, which focuses on quality education, is significantly lower in comparison to other countries in the sample. This situation raises a few important points:

1) despite a higher IDI score, the country may face challenges in effectively leveraging ICT for educational purposes (lack of effective integration of technology into the education system, limited digital literacy, insufficient policy frameworks that support the use of ICT for quality education);

2) while the country may have a strong ICT infrastructure, if there is insufficient teacher training or inequities in access to digital tools, it could negatively impact the quality of education.

Further research is necessary to identify the restraining or accelerating impact of education digitalization on achieving SDG4 based on empirical confirmation.

The main points of descriptive statistics at the time of the last observation (2023) are shown in Table A1 (Appendix A). Internet access in schools is a consistently high mean value across all four education levels (primary to upper secondary). The variation in access to the Internet among primary schools (52.70 to 100) indicates some countries have relatively low access at this level, but for higher levels of education (secondary and upper secondary), Internet access is almost universally available. A high percentage of households have internet access (mean = 85.81), but the variation shows that some countries still have challenges, with household access as low as 55.27% in certain areas. The mean values indicate that broadband Internet pricing varies significantly, with the highest cost for fixed broadband (5.18) and relatively lower costs for mobile broadband (1.31).

There is also a large variation in the use of ICT among youth and adults. While Internet use (ICT6) is highly prevalent across the sample, engagement with more complex ICT activities, such as sending emails with attachments (ICT1), installing new devices (ICT2), and using the Internet for online courses (ICT5), is less widespread. This suggests that while Internet access is high, there may be challenges in ensuring more advanced digital skills are acquired or utilized effectively. The use of ICT tools for educational or professional purposes (e.g., online courses, sending emails with attachments, creating presentations) shows that there is still a need for improvement in developing digital literacy and skills across the population.

These descriptive statistics give a broad understanding of the current state of ICT development and quality education across the sample countries. However, more in-depth analysis is necessary to explore the factors contributing to the discrepancies in SDG4 achievement in relation to digital development.

For this purpose, Granger causality analysis is carried out. Using the vargranger command based on the active pre-applied vector autoregression in Stata SE 18.0, the study obtained the following results for Azerbaijan (as the first country listed in the country sample in this study) (Table A2, Appendix A).

Granger causality test results for Azerbaijan indicate that for most variables, there is bidirectional causality, with statistically significant results in both directions (p-values < 0.05), suggesting that the SDG4 score influences ICT-related factors and vice versa. Both access to ICT in schools and household Internet access are closely tied to SDG4 achievement. As SDG4 progresses, access to ICT in schools and homes, as well as the digital skills of the population, seem to improve, and vice versa.

At the same time, no causality is detected for the indicator of individuals using the Internet for online courses. Both directions for this one show no significant causality (p-values of 0.222 and 0.197, which are greater than the 0.05 significance level). This could imply that online learning, while relevant, is not currently a key driver of overall educational quality in the country, or other factors (like traditional school infrastructure or curricula) may be more influential in Azerbaijan.

A similar procedure was applied to all other sample countries. The results of the causal analysis were obtained, interpreted, and summarized (Table A3, Appendix A).

Household Internet access (I_H) is a significant causal factor for SDG4 in all countries. This emphasizes the importance of broad internet availability at the household level for achieving SDG4 across different contexts. ICT6 (proportion of individuals using the Internet) is also a significant cause of SDG4 in almost all countries, indicating the general importance of Internet usage for educational outcomes. Mobile broadband (MB) appears to have a significant impact on SDG4 in most countries, except in Georgia and Vietnam. There are some countries where specific indicators, like ICT1, ICT2, ICT3, and ICT4 (which measure different aspects of digital skills/literacy), have a more pronounced effect on SDG4 (e.g., Peru and Vietnam). In other countries, these variables show no causality.

Online course participation (ICT5) is mostly insignificant, with only China and Singapore showing a significant relationship. This could suggest that online learning is not yet a primary factor in achieving SDG4 across most of the sample countries, though it may still have potential in some regions.

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Access to ICT in schools (I_EDU1, I_EDU2, I_EDU3, I_EDU4) is significant in many countries but not universally. I_EDU1 (primary schools with Internet access) shows causality in Azerbaijan, China, Moldova, Peru, and Vietnam but not in Argentina, Singapore, or the UAE, suggesting that school access to ICT may vary in its role depending on the country.

Argentina and Georgia are notable for showing few significant causality relationships with SDG4 compared to other countries. In contrast, Vietnam, Peru, and Moldova show a larger number of significant relationships, indicating stronger links between ICT indicators and SDG4 achievement.

Totally, there is clear global recognition that Internet access, both at home (I_H) and through mobile broadband (MB), plays a vital role in improving education quality (SDG4). The importance of ICT skills (e.g., email use, device installation, creating presentations) is mixed, with some countries showing a strong relationship between digital skills and educational outcomes. Online learning is still not a dominant driver of SDG4 achievement globally, though it may hold more promise in certain countries (e.g., China and Singapore).

These findings suggest that infrastructure (like Internet access) is crucial, but digital skills development and school-level ICT access also play important roles that may differ across regions.

After identifying indicators that are causes for changes in the achievement of SDG4, the next step in the research is to clarify the direction of influence (negative/restraining or positive/accelerating) and formalize this impact. For this, regression analysis methods are used. For Azerbaijan, linear regression models were built (Table 1).

In the first model, $P>|t|$ = 0.002 is statistically significant. R-squared = 0.8264 is very high, indicating that I_EDU1 explains 82.64% of the variation in SDG4 achievement. Prob > F = 0.0018 means that the overall model is significant. Therefore, primary school access to the Internet has an accelerating impact on SDG4 achievement in Azerbaijan. The coefficient suggests that for every 1% increase in the proportion of primary schools with Internet access, the SDG4 score increases by 0.68%. Similarly, an increase in the proportions of Internet access for pedagogical purposes in lower secondary schools, secondary schools, and upper second-

Table 1. Regression modeling of the impact of education digitalization on achieving SDG4 in Azerbaijan

Regression model	P>|t|	R-squared	Prob > F
SDG4 = 0.68·I_EDU1 + 43.09	0.002	0.8264	0.0018
SDG4 = 0.64·I_EDU2 + 42.59	0.002	0.8273	0.0017
SDG4 = 0.67·I_EDU3 + 38.41	0.002	0.8286	0.0017
SDG4 = 0.7·I_EDU4 + 32.7	0.002	0.8292	0.0017
SDG4 = 1.14·I_H – 9.62	0.011	0.6895	0.0107
SDG4 = 9.23·IB + 69.19	**0.431***	**0.1063***	**0.4306***
SDG4 = 6.39·MB + 76.7	**0.283***	**0.1882***	**0.2828***
SDG4 = 1.06·ICT1 + 21.9	0.000	0.9186	0.0002
SDG4 = 3.5·ICT2 + 29.45	0.000	0.8920	0.0004
SDG4 = 9.89·ICT3 + 15.96	0.000	0.9157	0.0002
SDG4 = 2.63·ICT4 + 24.13	0.000	0.8898	0.0004
SDG4 = 1.53·ICT6 – 43.05	0.001	0.8637	0.0008

Note: * the model is not statistically significant and it is not adequate; SDG4 – the score of SDG4 achievement within SDG Index; I_EDU1 – the proportion of primary schools with access to the Internet for pedagogical purposes; I_EDU2 – the proportion of lower secondary schools with access to the Internet for pedagogical purposes; I_EDU3 – the proportion of secondary schools with access to the Internet for pedagogical purposes; I_EDU4 – the proportion of upper secondary schools with access to the Internet for pedagogical purposes; I_H – the share of households with Internet access at home; IB – the level of fixed-broadband Internet basket; MB – the level of data-only mobile broadband basket; ICT1 – the proportion of youth and adults who have sent emails with attached files (e.g. document, picture, video); ICT2 – the proportion of youth and adults who have connected and installed new devices; ICT3 – the proportion of youth and adults who have created electronic presentations with presentation software; ICT4 – the proportion of youth and adults who have used basic arithmetic formulae in a spreadsheet; ICT6 – the proportion of individuals using the Internet.

ary schools is positively related to better SDG4 outcomes (on average, SDG4 score increase is by 0.64%, 0.67%, and 0.7%, respectively).

There is a significant and positive relationship between household Internet access and SDG4 achievement. The coefficient of 1.14 suggests that for each 1% increase in households with Internet access, SDG4 score increases by 1.14%. This is one of the strongest indicators of SDG4 achievement.

Models with broadband and mobile Internet indicators are not significant, suggesting that the level of fixed-broadband Internet basket and mobile broadband basket do not significantly influence SDG4 achievement in Azerbaijan.

Built models with digital skills indicators are statistically significant. The impact of the proportion of youth/adults who have sent emails with attachments is highly significant (the positive coefficient of 1.06 suggests that as more individuals can send emails with attachments, SDG4 achievement improves). This emphasizes the importance of basic digital skills.

The proportion of youth/adults who have used arithmetic in spreadsheets, connected and installed new devices, and created electronic presentations are also accelerators of SDG4 achievement. Regressor coefficients of 2.63, 3.5, and 9.89 mean the large positive influence in comparison with previous indicators – increase in SDG4 score by 2.63, 3.5%, and 9.89% in case of a 1% change in the indicator value, accordingly. This indicates that practical digital skills, digital literacy, and presentation skills are crucial for educational outcomes.

Moreover, the last model highlights the importance of the proportion of individuals using the Internet (Internet access in general) as an enabler for educational progress (a potential positive increase of SDG4 score is by 1.53%).

Given the cross-country differences identified as a result of causal analysis, it is also appropriate to substantiate and assess the impact of the studied factors on average at the level of the panel of sample countries. For this task, panel data regression modeling is used, in particular, random-effects GLS regression (Table 2).

Table 2 summarizes the results of a panel regression analysis examining the impact of vari-

Table 2. Regression modeling of the impact of education digitalization on achieving SDG4 on the panel level

Regression model	P>|z|	R-squared	Wald chi2(1)	Prob > chi2
SDG4 = 0.18·I_EDU1 + 87.63	0.000	0.2110	15.39	0.0001
SDG4 = 0.28·I_EDU2 + 77.75	0.000	0.3306	24.85	0.0000
SDG4 = 0.3·I_EDU3 + 76.19	0.000	0.3114	26.23	0.0000
SDG4 = 0.31·I_EDU4 + 75.15	0.000	0.2604	25.64	0.0000
SDG4 = 0.04·I_H + 100.67	**0.168***	**0.0008***	**1.90***	**0.1676***
SDG4 = 0.25·IB + 103.21	**0.554***	**0.0025***	**0.35***	**0.5537***
SDG4 = 0.04·MB + 103.84	**0.953***	**0.0022***	**0.00***	**0.9526***
SDG4 = 0.13·ICT1 + 98.5	0.001	0.1137	10.49	0.0012
SDG4 = 0.23·ICT2 + 99.19	0.000	0.0010	48.07	0.0000
SDG4 = 0.16·ICT3 + 100.72	0.005	0.0273	7.86	0.0050
SDG4 = 0.25·ICT4 + 97.62	0.000	0.0322	55.06	0.0000
SDG4 = 0.09·ICT5 + 102.61	**0.244***	**0.0201***	**1.35***	**0.2444***
SDG4 = 0.07·ICT6 + 98.04	**0.064***	**0.0290***	**3.44***	**0.0636***

Note: * the model is not statistically significant, and it is not adequate. SDG4 – the score of SDG4 achievement within SDG Index; I_EDU1 – the proportion of primary schools with access to the Internet for pedagogical purposes; I_EDU2 – the proportion of lower secondary schools with access to the Internet for pedagogical purposes; I_EDU3 – the proportion of secondary schools with access to the Internet for pedagogical purposes; I_EDU4 – the proportion of upper secondary schools with access to the Internet for pedagogical purposes; I_H – the share of households with Internet access at home; IB – the level of fixed-broadband Internet basket; MB – the level of data-only mobile broadband basket; ICT1 – the proportion of youth and adults who have sent emails with attached files (e.g. document, picture, video); ICT2 – the proportion of youth and adults who have connected and installed new devices; ICT3 – the proportion of youth and adults who have created electronic presentations with presentation software; ICT4 – the proportion of youth and adults who have used basic arithmetic formulae in a spreadsheet; ICT6 – the proportion of individuals using the Internet.

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ous education digitalization indicators on the achievement of SDG4 across 10 countries, including Azerbaijan, Argentina, China, Georgia, Moldova, Peru, Singapore, Thailand, Vietnam, and the United Arab Emirates.

Strong positive effects were found for the following variables:

- I_EDU1 (primary schools with Internet access) could lead to a 0.18% increase in SDG4 score if this indicator's value increases by 1%);
- I_EDU2 (lower secondary schools with Internet access) (0.28% increase);
- I_EDU3 (secondary schools with Internet access) (0.3% increase);
- I_EDU4 (upper secondary schools with Internet access) (0.31% increase);
- ICT1 (youth and adults sending emails with attached files) (0.13% increase);
- ICT2 (youth and adults installing new devices) (0.23% increase);
- ICT3 (youth and adults creating presentations) (0.16% increase);
- ICT4 (youth and adults using arithmetic formulae in spreadsheets) (0.25% increase).

These factors all show significant positive relationships with SDG4 achievement, with I_EDU3 and I_EDU4 showing the most notable effects.

Non-significant relationships are with I_H (household Internet access), IB (fixed-broadband basket), and MB (mobile broadband basket), which showed no significant relationships with SDG4. ICT5 (online courses) and ICT6 (general Internet use) also did not show significant results in this panel regression.

From these results, it is clear that Internet access in schools (especially primary and secondary levels) and the development of digital skills among youth and adults are crucial factors in improving SDG4 achievement.

When comparing the regression results for Azerbaijan (Table 1) with those for the panel of countries (Table 2), several important similarities and differences emerge in how digitalization indicators affect SDG4 achievement. The effect in Azerbaijan is much stronger than in the panel of countries for I_EDU1, I_EDU2, I-EDU3, and I_EDU4. This could suggest that Internet access in schools has a more direct or pronounced effect on SDG4 in Azerbaijan compared to other countries in the sample. In addition, this could reflect the unique circumstances in Azerbaijan, where secondary education might be more digitally integrated than in some countries in the panel.

ICT-related activities (such as sending emails, creating presentations, using spreadsheets, etc.) also have stronger effects in Azerbaijan, indicating that digital skills development is more impactful for SDG4 in Azerbaijan. However, some indicators like ICT5 (using the Internet for online courses) are insignificant in the panel, suggesting that online learning might not have the same role across all countries, or it might be a less important driver of SDG4 in some countries. In Azerbaijan, ICT5 is not a cause of the change in the SDG4 score.

The household Internet access indicator plays a significantly stronger role in Azerbaijan, explaining a large portion of the SDG4 variation. For the panel, the effect is almost negligible, suggesting that household Internet access may not have the same direct impact on SDG4 across different countries. As for the fixed broadband Internet basket and mobile broadband basket, the paper offers a similar conclusion: fixed broadband and mobile prices do not have a statistically significant impact on SDG4.

4. DISCUSSION

Challenges and opportunities in achieving SDG4 have been extensively analyzed (Ferguson & Roofe, 2020; Schmidt & Tang, 2020), but such analyses were based solely on existing literature and case study experiences in implementing education for sustainable development activities. Instead, this study examined the impact (restraining or accelerating) of 14 indicators characterizing education digitalization on achieving SDG4, which was empirically validated, formalized, and quantified.

As the accelerated adoption of digitization in Azerbaijan's education sector is considered a pressing issue, Hajiyeva et al. (2023) examined the key areas of digitization in education in Azerbaijan. They highlighted the characteristics of the digital educational environment, the need to integrate information technologies that support change, modern tools for information and communication, databases, and the provision of up-to-date telecommunications equipment throughout the entire digitization process of education and educational content. However, their outcomes are mostly descriptive and qualitative, unlike the quantitative and formalized results obtained in this study through the use of causal and regression analysis and modeling.

Méndez et al. (2022) also paid attention that enhancing the digital skills of teachers, students, and schools plays a key role (accelerating impact of digital competence) in achieving SDG4 of the 2030 Agenda, which focuses on improving education quality and providing learning opportunities for all. However, a validated online questionnaire was distributed to schools and high schools in the Community of Madrid, gathering responses from 97 teachers who were teaching remotely using digital tools during the COVID-19 lockdown that helped raise awareness of the importance of improving digital competence among educators. The results highlight the evaluation of the used technological tools (digital platforms, online classes, and videos being rated as the most useful, while online tests and forums were considered less beneficial) (Rangel-Pérez et al., 2021).

However, the above research methods and results are again more qualitative and are not based on the confirmation of proposed hypotheses, modeling, and assessing empirical data.

Kitto et al. (2023) also used causal modeling. They addressed the 'theory vs. data' problem in education, using artificial intelligence and learning analytics methods (alignment with theoretical concepts of the sciences can complicate data interpretation, etc.). However, this current paper used not only causal but also regression analysis and modeling. This allowed for more formalized and validated results.

Li et al. (2025) studied the causal relationship between digital literacy and students' academic achievement. The 35 effect sizes collected were analyzed using comprehensive meta-analysis. In this current study, other indicators and relations were analyzed.

Horobet et al. (2022) studied the relationship between education, digitalization, and financial development from 1996 to 2019, focusing on the differences between advanced and emerging European economies. The authors used a Bayesian VAR framework to analyze variables related to education, digitalization, and financial development, along with several endogenous factors to account for cross-country variations in nominal GDP growth, unemployment, and trade openness. They reveal that education plays a central role in the financial development–education–digitalization nexus, while financial development and digitalization are identified as lagging variables. Instead, this paper targeted education–digitalization–sustainable development nexus.

Therefore, the results of this study do not duplicate previously formed scientific achievements but rather supplement and develop them, based not only on a conceptual but also on an economic and mathematical basis.

The paper, while providing valuable insights into the relationship between education digitalization and SDG4 achievement, does have several limitations that could affect the robustness and generalizability of the findings. The analysis focused only on countries leading in SDG4 achievement compared to Azerbaijan; future studies could include lower-performing countries. Data comparability may be limited due to differences in collection methods, definitions, and reporting standards. The study covers a limited time period and may not accurately reflect temporal trends in digitalization or progress toward SDG4. The indicator list, while broad, was subjectively selected. Other influential factors – such as socio-economic conditions, political stability, teacher training, and educational policies – were not included in the regression models but may impact SDG4 outcomes.

These limitations should be considered when interpreting the findings, and future research might explore the impact of additional variables, more sophisticated modeling techniques, and broader geographical representation to offer a more comprehensive understanding of the relationships between digitalization and SDG4.

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CONCLUSION

The research purpose was to confirm the restraining or accelerating impact of education digitalization on achieving SDG4. It was substantiated that in Azerbaijan, as on average in all sample countries, the impact of the increase in the level of digitalization of education on the achievement of SDG4 is positive and accelerating. However, for some indicators, this impact was identified as insignificant in quantitative terms (however, not negative/restraining).

In Azerbaijan, improved Internet access in schools – especially at the upper-secondary level – has positively influenced SDG4 scores (up to 0.7%). Household Internet access boosts scores by 1.14% on average. Digital skills (e.g., using spreadsheets, installing devices, and creating presentations) are even stronger drivers, with certain competencies raising SDG4 score by up to 9.89% per 1% increase in use. In contrast, general broadband access alone shows little impact, highlighting that connectivity must be paired with digital literacy and school-level integration to enhance educational outcomes.

These results suggest that the key drivers for improving SDG4 achievement are school-level Internet access, digital practical skills, and digital literacy.

The digitalization of education has a stronger and more direct impact on SDG4 achievement in Azerbaijan than on the panel of countries leaders in achieving this Goal, particularly in terms of school Internet access and the development of digital skills among youth. The panel of countries, while showing some significant relationships, has weaker overall effects.

The variations in results can likely be attributed to differences in digital infrastructure, policy priorities, and the stage of digital transformation across countries. The obtained results highlight the importance of tailored strategies based on country-specific conditions to effectively achieve SDG4.

An important implication of these findings is the potential value of investing not only in infrastructure but also in teacher training and curriculum reform to embed digital skills in everyday learning. Enhancing the digital readiness of educators and aligning digital content with national education goals could further amplify the positive impact of digitalization. Moreover, intersectoral coordination – particularly between education, ICT, and labor ministries – may help ensure that digital education initiatives are aligned with broader development priorities.

The study has some limitations, i.e., the selected list of countries and indicators, limited time, and chosen research methods. Azerbaijan may have more targeted or recent investments in education digitalization, leading to stronger impacts. The panel countries may have different levels of development, infrastructure, and policies related to education and digitalization, leading to more heterogeneous impacts of the variables on SDG4.

Further research should investigate the interactions between digitalization indicators to assess whether their combination produces a synergistic effect on SDG4 achievement, incorporate additional variables, employ advanced modeling approaches, and expand the geographic scope to deepen the understanding of how digitalization drives progress toward SDG4.

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APPENDIX A

Table A1. Descriptive statistics in terms of the studied indicators for the formed sample of countries in 2023

Variable	Mean	Min	Max
SDG4	97.0914	90.8623	99.7810
I_EDU1	87.9567	52.7044	100.0000
I_EDU2	92.0016	68.5532	100.0000
I_EDU3	92.3816	69.3266	100.0000
I_EDU4	92.8067	70.1575	100.0000
I_H	85.8123	55.2702	100.0000
IB	2.12200	0.42000	5.180000
MB	0.70800	0.16000	1.310000
ICT1	33.8916	17.1821	97.70000
ICT2	18.1706	6.35000	87.40000
ICT3	19.2178	7.42140	56.50000
ICT4	23.7508	9.53580	84.40000
ICT5	15.8978	2.55000	57.96860
ICT6	83.1430	63.5349	100.0000

Note: SDG4 – the score of SDG4 achievement within SDG Index; I_EDU1 – the proportion of primary schools with access to the Internet for pedagogical purposes; I_EDU2 – the proportion of lower secondary schools with access to the Internet for pedagogical purposes; I_EDU3 – the proportion of secondary schools with access to the Internet for pedagogical purposes; I_EDU4 – the proportion of upper secondary schools with access to the Internet for pedagogical purposes; I_H – the share of households with Internet access at home; IB – the level of fixed-broadband Internet basket; MB – the level of data-only mobile broadband basket; ICT1 – the proportion of youth and adults who have sent emails with attached files (e.g. document, picture, video); ICT2 – the proportion of youth and adults who have connected and installed new devices; ICT3 – the proportion of youth and adults who have created electronic presentations with presentation software; ICT4 – the proportion of youth and adults who have used basic arithmetic formulae in a spreadsheet; ICT5 – the proportion of individuals using the Internet for doing an online course; ICT6 – the proportion of individuals using the Internet.

Table A2. The results of Granger causality test for the case of Azerbaijan

Equation (result)	Excluded (cause)	chi2	df	Prob > chi2
SDG4	I_EDU1	9.536	2	0.008
I_EDU1	SDG4	5,340.4	2	0.000
SDG4	I_EDU2	13.249	2	0.001
I_EDU2	SDG4	497.28	2	0.000
SDG4	I_EDU3	12.201	2	0.002
I_EDU3	SDG4	154.42	2	0.000
SDG4	I_EDU4	10.626	2	0.005
I_EDU4	SDG4	48.651	2	0.000
SDG4	I_H	1760.1	2	0.000
I_H	SDG4	7.1527	2	0.028
SDG4	IB	11.17	2	0.004
IB	SDG4	6.2128	2	0.045
SDG4	MB	747.87	2	0.000
MB	SDG4	13.639	2	0.001
SDG4	ICT1	36.016	2	0.000
ICT1	SDG4	72.942	2	0.000
SDG4	ICT2	20.954	2	0.000
ICT2	SDG4	23.371	2	0.000

Table A2 (cont.). The results of Granger causality test for the case of Azerbaijan

Equation (result)	Excluded (cause)	chi2	df	Prob > chi2
SDG4	ICT3	34.054	2	0.000
ICT3	SDG4	71.393	2	0.000
SDG4	ICT4	19.713	2	0.000
ICT4	SDG4	23.174	2	0.000
SDG4	ICT5	3.0119	2	0.222
ICT5	SDG4	3.245	2	0.197
SDG4	ICT6	19.62	2	0.000
ICT6	SDG4	7.244	2	0.027

Note: SDG4 – the score of SDG4 achievement within SDG Index; I_EDU1 – the proportion of primary schools with access to the Internet for pedagogical purposes; I_EDU2 – the proportion of lower secondary schools with access to the Internet for pedagogical purposes; I_EDU3 – the proportion of secondary schools with access to the Internet for pedagogical purposes; I_EDU4 – the proportion of upper secondary schools with access to the Internet for pedagogical purposes; I_H – the share of households with Internet access at home; IB – the level of fixed-broadband Internet basket; MB – the level of data-only mobile broadband basket; ICT1 – the proportion of youth and adults who have sent emails with attached files (e.g. document, picture, video); ICT2 – the proportion of youth and adults who have connected and installed new devices; ICT3 – the proportion of youth and adults who have created electronic presentations with presentation software; ICT4 – the proportion of youth and adults who have used basic arithmetic formulae in a spreadsheet; ICT5 – the proportion of individuals using the Internet for doing an online course; ICT6 – the proportion of individuals using the Internet.

Table A3. Generalized results of causal analysis for all sample countries

Cause of SDG4	AZE	ARG	CHN	GEO	MDA	PER	SGP	THA	VTN	ARE
I_EDU1	yes	no	yes	–	yes	yes	–	no	yes	–
I_EDU2	yes	yes	yes	–	yes	no	–	yes	yes	–
I_EDU3	yes	yes	yes	yes	yes	no	–	yes	yes	yes
I_EDU4	yes	yes	yes	yes	no	no	–	–	yes	–
I_H	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
IB	yes	no	yes	yes	yes	yes	yes	yes	no	yes
MB	yes	yes	yes	yes	yes	yes	yes	yes	no	no
ICT1	yes	–	–	yes	–	yes	yes	no	yes	no
ICT2	yes	–	–	no	–	yes	no	no	yes	no
ICT3	yes	–	–	no	–	yes	yes	no	yes	yes
ICT4	yes	–	–	no	–	yes	yes	yes	yes	no
ICT5	no	–	yes	yes	–	no	yes	no	–	no
ICT6	yes	yes	yes	yes	yes	no	yes	yes	yes	yes

Note: '–' causality wasn't confirmed if certain indicator was omitted because of collinearity; AZE -Azerbaijan; ARG – Argentina; CHN – China; GEO – Georgia; MDA – Moldova; PER – Peru; SGP – Singapore; THA – Thailand; VTN – Vietnam, ARE – United Arab Emirates; SDG4 – the score of SDG4 achievement within SDG Index; I_EDU1 – the proportion of primary schools with access to the Internet for pedagogical purposes; I_EDU2 – the proportion of lower secondary schools with access to the Internet for pedagogical purposes; I_EDU3 – the proportion of secondary schools with access to the Internet for pedagogical purposes; I_EDU4 – the proportion of upper secondary schools with access to the Internet for pedagogical purposes; I_H – the share of households with Internet access at home; IB – the level of fixed-broadband Internet basket; MB – the level of data-only mobile broadband basket; ICT1 – the proportion of youth and adults who have sent emails with attached files (e.g. document, picture, video); ICT2 – the proportion of youth and adults who have connected and installed new devices; ICT3 – the proportion of youth and adults who have created electronic presentations with presentation software; ICT4 – the proportion of youth and adults who have used basic arithmetic formulae in a spreadsheet; ICT5 – the proportion of individuals using the Internet for doing an online course; ICT6 – the proportion of individuals using the Internet.

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