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Impact of technological heterogeneity on economic efficiency and total factor productivity change in developed and developing G20 economies

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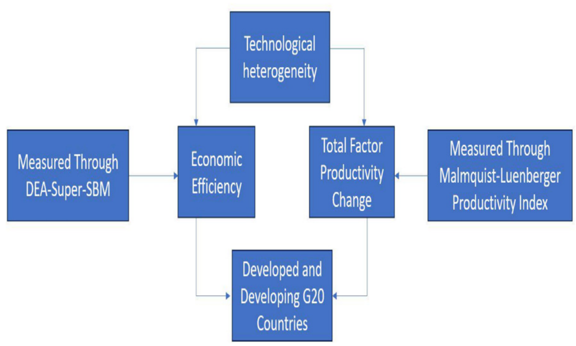
HIGHLIGHTS

- Analyzes economic efficiency and TFPC across G20 economies (1997–2022).
- DEA and Meta-Frontier Analysis reveal technological disparities in G20 countries.
- Efficiency change (EC) drives productivity growth more than technological change.
- Developed economies show optimal efficiency, while emerging economies lag.
- Policy recommendations include investment in R&D and technological collaboration.

GRAPHICAL ABSTRACT



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ABSTRACT

Introduction: The G20 economies, comprising both developed and developing nations, exhibit significant economic efficiency and technological advancement disparities. Understanding these differences is critical for fostering sustainable growth, particularly optimizing resource utilization and narrowing technological gaps.

Objectives: This study evaluates economic efficiency, technological heterogeneity, and total factor productivity change (TFPC) among G20 economies from 1997 to 2022. It distinguishes between developed and developing nations to identify key challenges and opportunities for productivity enhancement.

Methods: We assess economic efficiency using Data Envelopment Analysis (DEA) with the Super-SBM model. Meta-Frontier Analysis measures technological disparities, while the Malmquist-Luenberger Productivity Index (MLI) decomposes TFPC into efficiency change (EC) and technological change (TC).

Results: The mean Meta-frontier efficiency score for G20 countries is 0.9556, indicating a 4.44% improvement potential. Developed economies (e.g., the U.S., Australia) exhibit optimal efficiency, whereas developing nations (e.g., Russia, China, India) lag due to slower technological integration. The Meta-Technology Ratio (MTR) reveals pronounced disparities, with developed economies scoring near 1, while emerging economies range between 0.8 and 0.9. Efficiency change (EC) drives productivity growth more substantially than technological change (TC).

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Conclusion: Narrowing technological gaps, improving resource efficiency, and fostering innovation are vital for sustained economic development, particularly in emerging G20 economies. Policy recommendations include prioritizing R&D investments, technological advancement, and international collaboration to promote equitable and sustainable growth.

Introduction

The optimal allocation of resources, economic efficiency, and growth in total factor productivity (TFP) are fundamental to a country's or region's economic prosperity and welfare [1]. Prudent use of resources boosts production of quality goods and safeguards the environment. This enhances economic stability by preventing shortages and import dependence, while also improving global competitiveness through lower costs [2]. Economic efficiency requires the optimal allocation of resources to maximize social benefits. It reduced waste and decreased costs, resulting in enhanced economic growth and livelihood of people. Efficient economies exhibit a higher propensity for innovation since they continuously seek novel methods and techniques to enhance performance and reduce production costs [3].

Total factor productivity growth quantifies the efficiency with which countries convert their inputs into outputs, and it plays a crucial role in driving long-term economic growth. Higher total factor productivity (TFP) growth indicates the increasing proficiency in utilizing technology and innovations to enhance productivity, enabling the countries to maintain a competitive edge in manufacturing innovative, superior goods and services [4,5]. By integrating the utilization of resources, economic efficiency, and total factor productivity (TFP) growth, economies create the circumstances for sustainable economic development with minimal environmental impact through renewable resources incorporation [6,7]. Additionally, it enhances the resilience of the economies to unexpected interruptions and increases their ability to adjust to fluctuations in the global market. By prioritizing these specific sectors, countries can attain sustainable economic growth, improved ability to compete, and ultimately, enhanced quality of life for their populations [8,9].

Different researchers have proved that the advancement of technology is crucial for economic growth. Implementing innovative technology aids in enhancing operational efficiency, resulting in cost reduction and an elevation in the overall quality of products and services [10–12]. As a result, there is an incline in economic output and growth. Emerging technologies stimulate creativity, leading to the establishment of novel sectors and overhauling established economic sectors, resulting in job creation and fostering economic diversification. In addition, it addresses critical issues such as healthcare and environmental sustainability, thereby enhancing overall well-being [13–15]. Moreover, technological progressions allure foreign investments and bolster public services, rendering economies more vibrant and robust. Studies underscore that the effective implementation of advanced technologies, such as digital twins, is pivotal for optimizing resource policy and enhancing ecosystem preservation in energy projects, directly contributing to sustainable development [16]. Further by prioritizing technical advancement, economies can attain sustainable economic growth, enhance quality of life, and maintain competitiveness in the international marketplace [17,18]. Moreover, technological advancement is crucial for reducing emissions and safeguarding the environment. Through the use of cleaner energy sources and more efficient resource utilization, economies can effectively address the issue of climate change and establish a healthier and more sustainable environment for future generations [19].

G20 Countries are collaborating to enhance technological advancement by investing in research and development (R&D) to boost economic efficiency, improve total factor productivity, and address environmental concerns, ensuring a sustainable global future. Their primary focus lies in the development of renewable energy, implementation of smart agriculture techniques, efficient water management, and effective waste reduction strategies, all aimed at optimizing resource utilization and minimizing environmental degradation [20,21]. Through international collaboration and innovation-friendly policies, the G20 prioritizes STEM education to build a skilled workforce, collectively driving a sustainable and prosperous global future [22,23].

The production technology in the developed G20 countries differs significantly from that in the developing G20 countries [24]. Countries such as the United States, Germany, and Japan possess state-of-the-art technologies, and extensive automation, and make substantial investments in research and development, resulting in increased production and efficiency [25,26]. Conversely, countries such as India, Brazil, and Indonesia frequently rely on outdated technologies and labor-intensive approaches due to budgetary limitations and reduced investment in research and development, resulting in decelerated productivity [27]. The G20 forum is actively working to narrow the global development gap by promoting international cooperation, technology exchange, and STEM education. These efforts aim to boost technological capacities, economic efficiency, and productivity growth in developing nations, fostering sustainable economic expansion with minimal environmental impact [28,29]. While the broader themes of technological divergence and productivity are established in the literature, this study makes several distinct and novel contributions. First, it moves beyond theoretical discussion by applying an integrated DEA-Super SBM and Meta-frontier framework to the entire G20, providing the first unified empirical benchmark of economic efficiency and the technology gap ratio between its developed and developing blocs over 25 years. Second, by decomposing the Malmquist-Luenberger Productivity Index, we uniquely identify whether efficiency catch-up (EC) or technological innovation (TC) is the primary driver of progress for each group, offering critical insights that previous aggregate studies have missed. Finally, our use of the Mann-Whitney *U* test provides robust, statistical validation of the performance gap, moving from observational comparison to quantifiable evidence. Consequently, this paper's primary impact lies in its ability to pinpoint the specific sources of the divergence—whether from inefficient adoption of existing technology or a failure to innovate at the frontier—thereby enabling tailored and more effective policy interventions for the world's largest economies.

Despite the measures taken to enhance economic efficiency, productivity growth, and environmental protection through technical advancements and narrowing the production technology gap between developed and developing G20 countries, the success level of this mission is still unexplored and requires further investigation. To this end, this study initially employed DEA-Super SBM to assess economic efficiency in G20 countries over the study period of 1997–2022. It evaluates the efficiency over the study period and distinguishes the efficiency levels of developed G20 countries from those of developing countries. Secondly, the study uses the Meta-frontier Analysis to gauge the production technology heterogeneity (technology gap ratio) in developed and developed G20 Economies. It evaluates the impact of research & development and technological advancement on economic efficiency and the technology gaps in both groups. Thirdly research used MLI (Malmquist-Luenberger Productivity Index) to estimate the Total factor productivity change in G20 countries. TFPC estimation gauges the dynamic change in economic efficiency over the study period. Moreover, total factor productivity change is decomposed into efficiency change (EC) and technology change (TC) to gauge the main determinant (EC or TC) in the TFPC. Finally, to strengthen the study results it applied the Mann-Whitney *U* test to gauge the statistically significant difference between developed and developing G20 countries for economic efficiency, TFPC, and MTR. The rest of the study is presented as follows: Section 2 presents the comprehensive literature review. Section 3 illustrates the methods employed in the study. Section 4 presents the results and discussion. The conclusion and policy implications are presented in Section 5.

Literature review

DEA has been extensively used to gauge economic efficiency in different countries, regions, and industries [30,31]. Wang and Feng [32] analyzed China's energy, environmental, and economic ('E3′) efficiency from 2002 to 2011. Despite significant economic growth, the country faced high energy consumption and environmental costs. However, the study found encouraging progress in efficiency, driven primarily by technological developments, though challenges in scale and management remained. Overall, China's E3 productivity was on a positive trajectory, indicating potential for greater sustainable development. Sutter and Stough [33] assess the economic efficiency of various US urban areas. By classifying regions by size, they identified specific challenges each faced. The study demonstrated that DEA can generate significant, tailored insights, aiding policymakers in developing targeted strategies for the unique economic needs of different cities and the broader urban system. Halkos and Polemis [34] investigated the economic efficiency of the electricity production industry in the United States utilizing a sophisticated analysis technique known as Window Data Envelopment Analysis (W-DEA). The results indicated that there is a consistent N-shaped trend in global pollutants about economic growth. Li et al. [35] found that green innovation can initially reduce efficiency in Chinese enterprises transitioning to a high-quality development model, particularly when there is inadequate protection for new ideas, low environmental awareness, or ongoing pollution-intensive practices. However, these negative effects were mitigated as companies improved their production methods, gained greater technological autonomy, and operated within competitive markets, ultimately leading to enhanced efficiency. Numerous other studies employed DEA to estimate the economic efficiency in different industries globally [36–42].

Zheng et al. [43] found that environmental regulations in the Yangtze River Economic Belt led to an overall decline in green total factor productivity (GTFP), though the disparities between cities diminished. The impact of these regulations varied by geographical region, with technological innovation playing a crucial role in enhancing GTFP. Ochotnický et al. [44] explored the factors that influenced the growth of total factor productivity (TFP) in 28 European countries. They found that technological innovation had a strong positive impact on TFP, while other factors like human capital, business conditions, and innovation itself had more mixed and less direct effects on productivity. Similarly, Beugelsdijk et al. [45] attributed a significant portion of the economic inequality between EU regions to variations in Total Factor Productivity (TFP), rather than solely to local resources. Yu et al. [46] examined the impact of China's carbon trading system on sustainable total factor productivity (TFP). They found that implementing carbon trading laws had a significant positive impact on TFP. In a similar vein, Ye et al. [47] found that fintech's effect on green productivity in China was positive overall but varied regionally, with the strongest impact in areas with advanced green initiatives. Lastly, Lyu et al. [48] investigated the impact of the digital economy on green productivity in China. They discovered that the relationship followed a U-shaped curve, with progress in green technology being the main driver behind improvements in green productivity. Several research studies used the DEA Malmquist index to estimate the total factor productivity change in different global regions and industries [49–53].

Wang et al. [54] found the Yangtze River Economic Belt's eco-efficiency was stable at 0.599, showing gradual improvement driven by technological advances and the adoption of best practices. Sun et al. [55] aimed to address the issues of environmental degradation and resource scarcity in China by promoting the implementation of a circular economy. The study examined the efficiency of resource recovery and pollution treatment methods, to improve efficiency and reduce emissions. The researchers devised models that integrated game theory with data analysis to assess and pinpoint technological deficiencies throughout China's regions. A continuing fight has been observed between the pursuit of economic expansion, the preservation of the environment, and the recycling of resources. Eastern China has emerged as a leader in technology, while Western China has lagged. Wang and Feng [56] found that advancements in economic efficiency and production technologies played a crucial role in advancing the production process. Czyżewski and Kryszak [57] looked into how small farms in Central and Eastern Europe could boost both their efficiency and sustainability while also meeting economic and environmental goals. Their research showed that farms that were more technically efficient tended to be more sustainable as well. Li and Cheng [58] examined how boosting China's manufacturing sector's carbon emission efficiency could boost economic growth, energy conservation, and emissions reduction. The study found low efficiency and substantial variation across 31 industrial sectors. High-tech industries were most efficient, whereas low-tech industries struggled. Poor management caused the inefficiency, which worsened as businesses grew technologically. Liu et al. [59] concluded that developing countries with high energy usage were more energy efficient, whereas both developed and developing countries with low energy use achieved substantial technological innovations. Moreover, numerous research studies used the DEA-Meta frontier analysis to gauge the technological gap ratio among different global regions [60–62]. While there's been a lot of research on economic efficiency, total factor productivity, and technological differences across industries and sectors in various countries and regions, few studies have focused on measuring these factors using countries as decision-making units. Additionally, the technological gaps between developed and developing economies have not been thoroughly explored. To fill this gap, this study uses different non-parametric methods (outlined in Section 3) to examine economic efficiency, total factor productivity, and technological differences between developed and developing G20 economies.

Methods

Super SBM model

In 2001, Tone [63] introduced a new approach to Data Envelopment Analysis (DEA) called the SBM model. Unlike traditional DEA models like CCR and BCC, the SBM model includes slack variables directly in the objective function. This makes it different because it's non-oriented and non-radial, which helps it avoid the biases found in radial or oriented models and better capture the true efficiency. As research continued, it became clear that ignoring undesirable outputs doesn't align with real-world production. To address this, Tone [64] proposed an updated SBM model in 2003 that includes these undesirable outputs in the evaluation process. Here's how the SBM model works.

$$\theta^* = min\frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{i0}}}{1+\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{r0}^g}+\sum_{r=1}^{s_2}\frac{s_r^b}{y_{r0}^b}\right)}$$

$$\begin{aligned} & s.\ t\ \lambda X + S^- = x_0 \\ & \lambda Y^g - S^g = y_0^g \\ & \lambda Y^b + S^b = y_0^b \\ & S^- \geq 0,\ S^g \geq 0,\ S^b \geq 0,\ \lambda \geq 0 \end{aligned} \tag{1}$$

In this context, θ^* represents the efficiency of DMU_0. The variables S^-, S^g, S^b, represent the slack in inputs, desirable outputs, and undesirable outputs, respectively. Here,m is the number of inputs, s_1 is the number of desirable outputs, and s_2 is the number of undesirable outputs. λ is the intensity vector.

The values derived from Eq. (1) fall between 0 and 1. If $\theta^* = 1$ and all the slack values $S^- = 0, S^g = 0, S^b = 0$ this means the DMU is SBM-efficient. However, this model can't distinguish between multiple efficient DMUs. To solve this, Tone introduced the super-SBM (S-SBM) model in 2002 [65], which helps rank efficient DMUs more clearly.

Even so, the super-SBM model doesn't account for undesirable outputs. To address this, we used an improved version of the super-SBM model that includes undesirable outputs, allowing for a better differentiation between SBM-efficient DMUs [66]. If DMU_k is SBM-efficient, it can be defined as follows:

$$\theta_* = \min\frac{1+\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{ik}}}{1-\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{rk}^g}+\sum_{r=1}^{s_2}\frac{s_r^b}{y_{rk}^b}\right)}$$

s.t

$$\begin{aligned} & x_k - \sum_{j=1,\neq k}^{n}\lambda_j x_j + s^- \geq 0 \\ & -y_k^g + \sum_{j=1,\neq k}^{n}\lambda_j y_j^g + s^g \geq 0 \\ & y_k^b - \sum_{j=1,\neq k}^{n}\lambda_j y_j^b + s^b \geq 0 \\ & 1-\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{rk}^g}+\sum_{r=1}^{s_2}\frac{s_r^b}{y_{rk}^b}\right) \geq \varepsilon \\ & \lambda, s^-, s^g, s^b \geq 0 \end{aligned} \tag{2}$$

We can convert the fractional program into a linear programming problem to solve the above model. This requires introducing a variable so that $t\left[1-\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{r0}^g}+\sum_{r=1}^{s_2}\frac{s_r^b}{y_{r0}^b}\right)\right] = 1$. The linear programming formulation is as follows.

$$\theta_* = \text{min}t + \frac{1}{m}\sum_{i=1}^{m}\frac{S_i^-}{x_{i0}}$$

s.t

$$\begin{aligned} & t - \frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{S_r^g}{y_{r0}^g}+\sum_{r=1}^{s_2}\frac{S_r^b}{y_{r0}^b}\right) = 1 \\ & tx_0 - \sum_{j=1,\neq 0}^{n}\Delta_j x_j + S^- \geq 0 \\ & -ty_0^g + \sum_{j=1,\neq 0}^{n}\Delta_j y_j^g + S^g \geq 0 \\ & ty_0^b - \sum_{j=1,\neq 0}^{n}\Delta_j y_j^b + S^b \geq 0 \\ & \Delta, S^-, S^g, S^b \geq 0 \end{aligned} \tag{3}$$

In model (3), $\Delta, S_i^-, S_r^g, S_r^b$ are the transformed versions of the intensity and slack variables from the model (2), which are $\lambda, s_i^-, s_r^g, s_r^b$, respectively. By solving model (3), we can find the optimal values for all the slacks and t. If all the slacks are zero and $\theta^* = 1$, the DMU being evaluated is considered efficient. If that's not the case, the DMU is classified as inefficient.

Meta-frontier model

Meta-frontier models help evaluate the efficiency of Decision-Making Units (DMUs) across different frontiers, offering a more meaningful comparison than just using one unified frontier [67]. These models also make it possible to estimate the technology gap for DMUs within specific group frontiers, compared to the overall frontier that applies to all DMUs [68]. This technology gap is measured using the Meta-Technology Ratio (MTR). The MTR for group i is defined as [69,70].

$$MTR = \frac{GTE_i}{MTE} \tag{4}$$

In this context, GTE_i represents the Group Technical Efficiency (GTE) for group i, based on the technology level specific to that group. This means it only considers DMUs within the same group. On the other hand, MTEMTEMTE stands for Meta Technical Efficiency, which reflects the technology level across all evaluated DMUs, encompassing all groups.

The Meta-Technology Ratio (MTR) shows how closely a group's technology matches the overall *meta*-frontier technology. Since MTE is always less than or equal to the to GTE_i, the MTR will never exceed one. A higher MTR means that the group's technology is closer to the *meta*-frontier level [71]. If a group's MTR is one, it means there's no gap between the two frontiers (as shown in Fig. 1). This makes the MTR a useful measure for understanding technological differences between regions. In practice, closing the technology gap within a group can be done through various strategies, such as advancing technology or improving management practices [72].

The Malmquist-Luenberger productivity measurement

ML productivity indices are designed in a way that's similar to traditional Malmquist indices, but instead of using Shephard distance functions, they rely on directional distance functions. As described by Chung et al. [73], the ML productivity index for the period between t and $t+1$ is defined like this:

$$ML_t^{t+1} = \left[\frac{\left(1+\overrightarrow{D}_o^{t+1}\left(x^t,y^t,b^t;y^t,-b^t\right)\right)}{\left(1+\overrightarrow{D}_o^{t+1}\left(x^{t+1},y^{t+1},b^{t+1};y^{t+1},-b^{t+1}\right)\right)} \times \frac{\left(1+\overrightarrow{D}_o^{t}\left(x^t,y^t,b^t;y^t,-b^t\right)\right)}{\left(1+\overrightarrow{D}_o^{t}\left(x^{t+1},y^{t+1},b^{t+1};y^{t+1},-b^{t+1}\right)\right)}\right]^{\frac{1}{2}} \tag{5}$$

This can be divided into two main components, namely:

$$\text{MLEFFCH}_t^{t+1} = \frac{1+\overrightarrow{D}_o^{t}\left(x^t,y^t,b^t;y^t,-b^t\right)}{1+\overrightarrow{D}_o^{t+1}\left(x^{t+1},y^{t+1},b^{t+1};y^{t+1},-b^{t+1}\right)} \tag{6}$$

$$\text{MLTECH}_t^{t+1} = \left[\frac{\left(1+\overrightarrow{D}_o^{t+1}\left(x^t,y^t,b^t;y^t,-b^t\right)\right)}{\left(1+\overrightarrow{D}_o^{t}\left(x^t,y^t,b^t;y^t,-b^t\right)\right)} \times \frac{\left(1+\overrightarrow{D}_o^{t+1}\left(x^{t+1},y^{t+1},b^{t+1};y^{t+1},-b^{t+1}\right)\right)}{\left(1+\overrightarrow{D}_o^{t}\left(x^{t+1},y^{t+1},b^{t+1};y^{t+1},-b^{t+1}\right)\right)}\right] \tag{7}$$

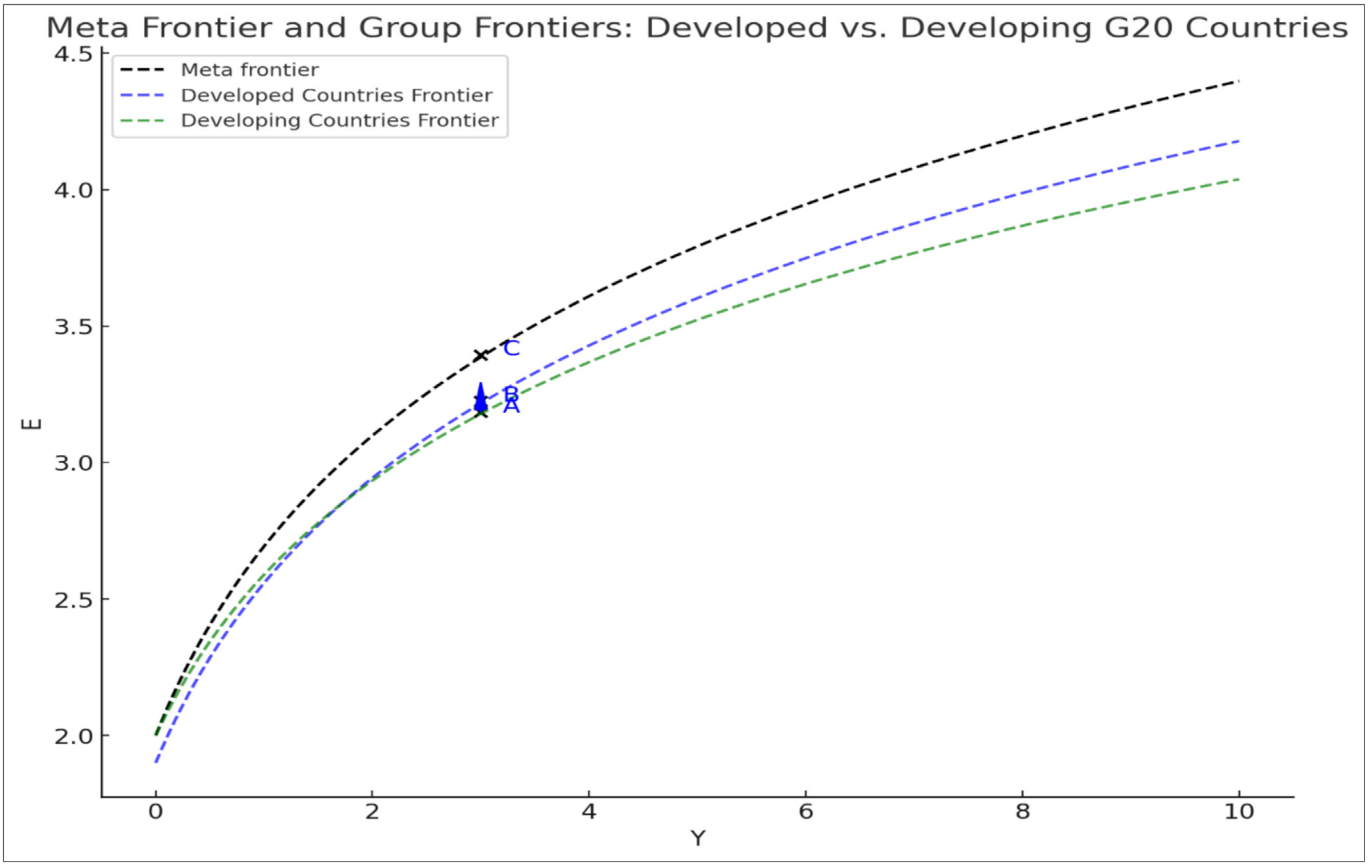

Fig. 1. Meta-frontier and Group-frontier presentation.

Eqs. (5) and (7) calculate the geometric means by comparing the results from period t with those from the period $t+1$ as reference points. The first part, MLEFFCH, focuses on how output efficiency has changed between these two periods. The second part, MLTECH, looks at how technology has evolved during the same time frame.

If ML_t^{t+1} is greater than 1, it means productivity has improved; if it's less than 1, productivity has decreased. The $MLEFFCH_t^{t+1}$ index from Eq. (6) compares how close observations are to their frontiers in periods t and $t+1$. A value greater than 1 means the observation is closer to the frontier in the period $t+1$, while a value less than 1 means it's further away. The MLTECH $tt+1$ index from Equation (7) measures changes in the production of both good and bad outputs. If MLTECH $tt+1$ is greater than 1, it shows technical progress, whereas a value less than 1 indicates technical regression [74,75]. Table A1 further explain the parameters and variables for Eqs. (1) to (5).

Mann-Whitney U test

The Mann-Whitney U test, also known as the Wilcoxon rank-sum test, is a statistical method used to compare two independent groups and see if there's a significant difference between them. It's especially helpful when the data doesn't follow a normal distribution or when other tests, like the t-test, can't be used due to certain assumptions not being met. Unlike tests that rely on raw data points, the Mann-Whitney U test compares the ranks or order of the values, making it a good choice for small sample sizes or ordinal data. This test was introduced by Henry B. Mann and Donald R. Whitney [76], in 1947 as an alternative for analyzing data that doesn't fit traditional models. In our study, we use the Mann-Whitney U test to examine whether there are significant differences in economic efficiency, total factor productivity, and MTR between developed and developing countries. Based on this approach, we've proposed the following three hypotheses.

H1: The distribution of economic efficiency is at the same level across developed and developing G20 countries.

H2: The distribution of MLI is at the same level across developed and developing G20 countries.

H3: The distribution of MTR is at the same level across developed and developing G20 countries.

This integrated methodology is uniquely suited to the G20′s economic heterogeneity. It improves upon standard analyses by simultaneously: 1) ranking efficient nations with Super-SBM, which accounts for slack in undesirable outputs like CO2; 2) using the *meta*-frontier to quantify the technology gap between developed and developing blocs; and 3) deploying the MLI to decompose productivity growth into efficiency catch-up and technological innovation. This allows our study to move beyond measurement and provide targeted policy recommendations on whether a country should prioritize management practices, technology transfer, or indigenous innovation. Recent application of this very methodology to G20 efficiency evaluation, technological heterogeneity and productivity growth estimation confirmed its high relevance [8,77].

Variable selection and data collection

Ensuring the appropriate selection of inputs and outputs in Data Envelopment Analysis (DEA) is crucial for obtaining significant and accurate results [78]. Failure to capture essential inputs or outputs, or the inclusion of insignificant variables, might lead to inaccuracies in the efficiency evaluations, so deviation from the actual frontier. Appropriate selection facilitates the analysis to accurately differentiate between high and low performers and guarantees the reliability and relevance of the data utilized. Therefore, the careful and accurate selection process is crucial to guarantee that the insights obtained from the DEA [79]. The selection of variables in this study is grounded in established economic theory and prior literature, capturing the fundamental factors of production: labor, capital, energy, and technological knowledge [80]. Labor is represented by the total labor force, capital is proxied by gross fixed capital formation, energy is measured by primary energy consumption, and technology is captured by research and development (R&D) expenditure. The production process yields a desirable output, the Gross Domestic Product (GDP), and an undesirable by-product, CO_2 emissions, allowing for an efficiency assessment that incorporates environmental sustainability. Data for the G20 member countries from 1997 to 2022 were primarily sourced from the World Bank's World Development Indicators (WDI) and Our World in Data (OWID) repositories to ensure consistency. Specifically, GDP, gross fixed capital formation, labor force, and R&D expenditure were obtained from WDI, while primary energy consumption and CO_2 emissions were sourced from OWID. To construct a balanced panel dataset, missing values, particularly in early years for R&D, were addressed using linear interpolation, deemed appropriate for the stable nature of such macroeconomic data. All monetary values are in constant 2015 U.S. dollars to control for inflation, and physical units are consistent across the dataset. No normalization was performed, as the DEA and Malmquist-Luenberger index models are units-invariant, with results based on input–output ratios rather than absolute scales, thus preserving the validity of cross-country comparisons.

Results and discussions

Economic efficiency evaluation of G20 countries

The results in Section 5.1, Table 2, provide an overview of the economic efficiency of G20 countries from 1997 to 2022, using three key indicators: Meta-frontier, Group-frontier, and Meta-Technology Ratio (MTR). When the study evaluates the efficiency of all G20 countries in one group without distinguishing between developed and developing the Meta-frontier scores, which predominantly approximate 1, indicate that G20 economies typically operate near their maximum capacity. It indicates the optimum utilization of resources by G20 economies to produce GDP. The average *meta*-frontier efficiency score is 0.9556, which indicates a 4.44 % potential for growth in economic efficiency. The Group-frontier ranking regularly exceeds 1, suggesting that certain countries within particular economic groups (developed or developing) surpass their counterparts. Nevertheless, this does not necessarily indicate that they are leading worldwide; it only demonstrates that they are performing comparatively well within their group.

The MTR values convey a significant narrative. With averages below 1, there is a constant disparity in performance between developed and developing G20 economies. Despite a country's success within its group, it often has a considerable distance to cover to achieve the highest levels of global economic efficiency. Over time, these values vary, indicating the degree of similarity or disparity between group and meta frontier, which may be driven by economic difficulties or divergent country agendas. The average MTR value is 0.8965 which is less than 1 and indicates the technological gap in developed and developing economies.

Table 1
Inputs and outputs.

Inputs	Outputs
Labor force, total	GDP (constant 2015 US$)
Gross fixed capital formation (constant 2015)	CO_2 Emissions million tonnes
Primary energy consumption (TWh)	
Research and development expenditure (% of GDP)	

Table 2
Average meta, group frontier economic efficiency, and MTR in G20 countries.

Year	Meta-frontier	Group-frontier	MTR
1997	0.9363	1.0592	0.884
1998	0.9881	1.0631	0.9295
1999	0.9942	1.063	0.9353
2000	0.9881	1.071	0.9226
2001	0.9523	1.0463	0.9102
2002	0.9404	1.0707	0.8783
2003	0.9394	1.0274	0.9143
2004	0.9476	1.0599	0.894
2005	0.9535	1.0255	0.9298
2006	0.9538	1.0189	0.9361
2007	0.9356	1.0193	0.9179
2008	0.9577	1.0241	0.9352
2009	0.922	1.0434	0.8836
2010	0.934	1.041	0.8972
2011	0.9239	1.0287	0.8981
2012	0.9736	1.0341	0.9415
2013	0.9666	1.0723	0.9014
2014	0.9163	1.0915	0.8395
2015	0.9829	1.1107	0.8849
2016	0.9598	1.108	0.8662
2017	0.9592	1.0955	0.8756
2018	0.9425	1.1037	0.8539
2019	0.9194	1.0551	0.8714
2020	0.9598	1.1233	0.8544
2021	0.9865	1.1378	0.867
2022	1.0129	1.1401	0.8884
Average	**0.9556**	**1.0667**	**0.8965**

Fig. 2 further explains the average efficiency scores of G20 countries from 1997 to 2022. These efficiency scores indicate the performance of these economies in converting their input resources like labor, capital, technology, and energy to produce the GDP with strong disposability of undesirable output carbon emissions. It illustrates that maybe some countries efficiently utilize their resources and produce more GDP growth but, in the process, they emit more emissions which ultimately lower their efficiency scores in global evaluation through DEA. The Figure illustrates the diverse degrees of economic efficiency among G20 countries from 1997 to 2022, emphasizing significant disparities in resource utilization among these economies. Argentina and South Africa are the Top performers, continually maximizing their labor, capital, technology, and energy inputs to achieve enhanced GDP, demonstrating their exceptional resource optimization. The United States, Saudi Arabia, and Australia are also positioned at the top, showing their impressive utilization of resources to maintain robust economic growth.

In contrast, countries such as Germany, Brazil, Japan, and Canada have a more moderate level of economic efficiency. They have successfully expanded their economies, while there are significant inefficiencies that indicate the need for improvement in resource utilization. Meanwhile, Russia, Indonesia, China, and India have faced significant challenges in terms of efficiency. Their lower ratings may be attributed to persistent difficulties in optimizing their utilization of labor, capital, and technology, or slower integration of novel technologies that have the potential to enhance their productivity. Another crucial consideration is the influence of carbon emissions. In certain nations, increased emissions may have adversely affected their efficiency ratings, as pollution can be perceived as an undesirable consequence of economic operations. This implies that although certain countries have achieved success in

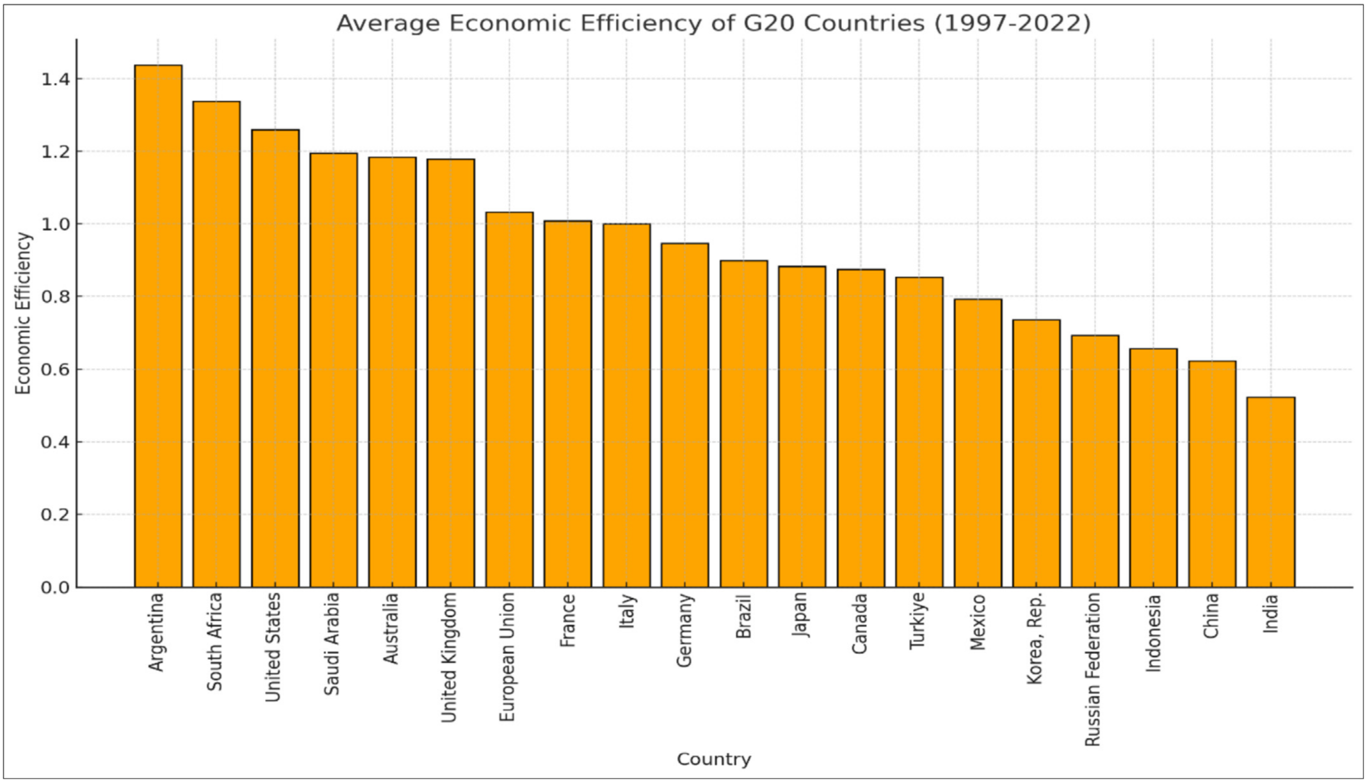

Fig. 2. Average Economic efficiency level in G20 countries.

increasing their Gross Domestic Product (GDP), the negative impact on the environment has hindered their economic efficiency [81,82]. Fig. 2 not only illustrates variations in countries' economic efficiency but also indicates the difficulties of achieving sustainable development. These countries face the ongoing challenge of achieving a balance between economic expansion and environmental protection.

Further elaborating on the economic efficiency scores study found significant heterogeneity between developed and developing G20 countries. Fig. 3 indicates that the developed G20 countries have continually demonstrated effective management of their economic resources over the study period, consistently maintaining a position ahead of those developing with higher economic efficiency scores. Simultaneously, developing G20 countries in the process of development have encountered several fluctuations, which mirror the difficulties they encounter in sustaining consistent economic growth enhancement. Developed economies have successfully implemented strategies to continuously maximize their resources, but emerging countries are still grappling with the challenges of economic growth, often demonstrating resilience but experiencing inefficiencies more frequently.

Developing G20 can enhance their economic efficiency by emulating the resource management strategies employed by developed countries. By allocating resources towards education and vocational training, these nations can enhance the expertise and efficiency of their workforce. Consequently, this results in improved employment opportunities and increased economic productivity. By facilitating finance accessibility and promoting investment, they can effectively channel financial resources into the sectors that require it the most, so stimulating growth in crucial areas. Energy efficiency is vital as developing countries may increase their production while simultaneously reducing their carbon footprint by transitioning to renewable energy sources and using more efficient technologies. Adopting established technologies from industrialized nations can provide a significant advantage to emerging economies, enabling them to achieve rapid and sustainable growth. Ultimately, by prioritizing sustainability, they can guarantee that their economic expansion does not harm the environment, discovering methods to boost GDP while minimizing carbon emissions. Developing countries can enhance their economy and promote resilience by adhering to these sequential instructions, resulting in widespread benefits globally [8,83].

Technological heterogeneity among developing and developed G20 countries

Technological progress is a strong ingredient in economic growth. It enables economies to achieve more productivity with fewer resources, stimulates the emergence of novel concepts and sectors, and generates employment opportunities. Countries can enhance their global competitiveness, expand into untapped areas, and achieve sustainable growth by embracing innovative technologies. The Meta-Technology Ratio (MTR) shows how well a country or business is using its technology compared to the best technology available worldwide. Table 3 illustrates the technological gaps among developed and developing G20 countries. It examines the extent to which G20 countries are leveraging their technology to enhance economic efficiency, comparing their performance both on a global scale and within their respective subgroups. Countries such as the United States, United Kingdom, and Germany are effectively utilizing their technology to maintain a competitive edge on a global level. However, countries such as China and India, although performing satisfactorily within their respective categories, still have the potential for enhancement in terms of adopting state-of-the-art global technology. By embracing more sophisticated technologies, these countries have the potential to greatly enhance their economic performance.

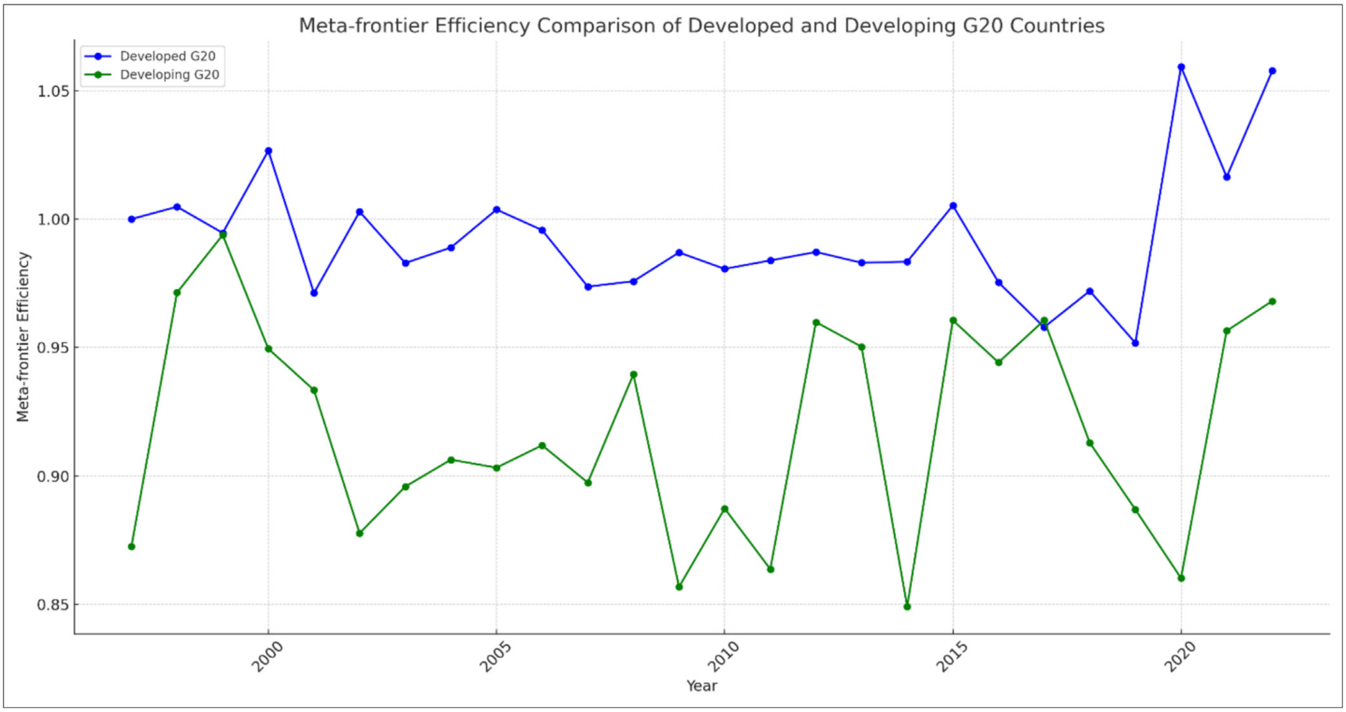

Fig. 3. Economic efficiency of developed and developing G20 economies (1997–2022).

To enhance the Meta-Technology Ratio (MTR), economies should adopt cutting-edge technology, allocate resources towards education to cultivate a proficient labor force, and enhance infrastructure to facilitate the implementation of such advancements. Governments can facilitate the adoption of innovative technology by implementing laws that incentivize businesses and by promoting collaboration between research institutions and enterprises. Facilitating enterprises' access to and utilization of emerging technology can enable governments to narrow the disparity with global frontrunners and bolster their economies [84–86].

Fig. 4 illustrates the utilization of technology by both developed and developing countries in the G20 group from 1997 to 2022. Developed economies have constantly maximized their utilization of existing technology, ensuring their efficiency levels remain consistently high. In contrast, emerging countries have experienced a more inconsistent trajectory, with their efficiency levels shifting significantly and largely remaining lower. This implies that developed nations have continuously utilized technology to boost their economies, whereas emerging countries have encountered greater obstacles in this mission, resulting in fluctuations in their technology attainment and utilization.

Table 3
Meta, group frontier economic efficiency, and MTR In G20 countries.

Country	Meta-frontier	Group-frontier	MTR
Argentina	1.4374	1.4709	0.9772
Australia	1.1836	1.3923	0.8501
Brazil	0.8995	1.0896	0.8255
Canada	0.8748	0.9556	0.9154
China	0.6227	1.2422	0.5013
European Union	1.0325	1.0325	1
France	1.0086	1.0186	0.9902
Germany	0.9457	0.9457	1
India	0.5221	0.6957	0.7505
Indonesia	0.6565	0.7019	0.9353
Italy	1.0005	1.1066	0.9041
Japan	0.883	0.8832	0.9998
Korea, Rep.	0.7355	0.8473	0.8681
Mexico	0.7929	1.0682	0.7423
Russian Federation	0.6929	0.8881	0.7802
Saudi Arabia	1.1948	1.2306	0.9709
South Africa	1.3378	1.3378	1
Türkiye	0.8535	0.9885	0.8634
United Kingdom	1.1785	1.1785	1
United States	1.2599	1.2599	1

The MTR for developed countries, as indicated by the solid yellow line, has remained stable and constantly near 1.0. This demonstrates their consistent utilization of modern technology to maintain efficient economies. In contrast, developing countries, as indicated by the orange line, have encountered a less consistent trajectory. Their MTR exhibits greater variability, usually ranging from 0.80 to 0.90, suggesting that they have encountered more difficulties in embracing and utilizing the most optimal technology. The variety in technology usage has resulted in developed countries consistently maintaining a solid level of technology adoption, whereas developing countries have witnessed more fluctuations, including significant declines in efficiency in 2001, 2009, and 2014. Nevertheless, there have been instances of economic recuperation, particularly in the early 2000s and post-2020, demonstrating their endeavors to narrow the disparity and enhance their technical efficiency. Numerous research studies emphasize the technological adoption and investment in research and development in developing economies to enhance their resource utilization efficiency [87,88].

Total factor economic productivity change in G20 economies (1997–2022)

In Section 5.3 study employed the Malmquist- Luenberger productivity index to gauge the dynamic change in total factor economic productivity in the G20 economies over the study period. Table 4 presents a comprehensive analysis of the economic productivity, efficiency, and technical change in G20 countries between 1997 and 2022. The results indicate that economic productivity change has modest average growth.

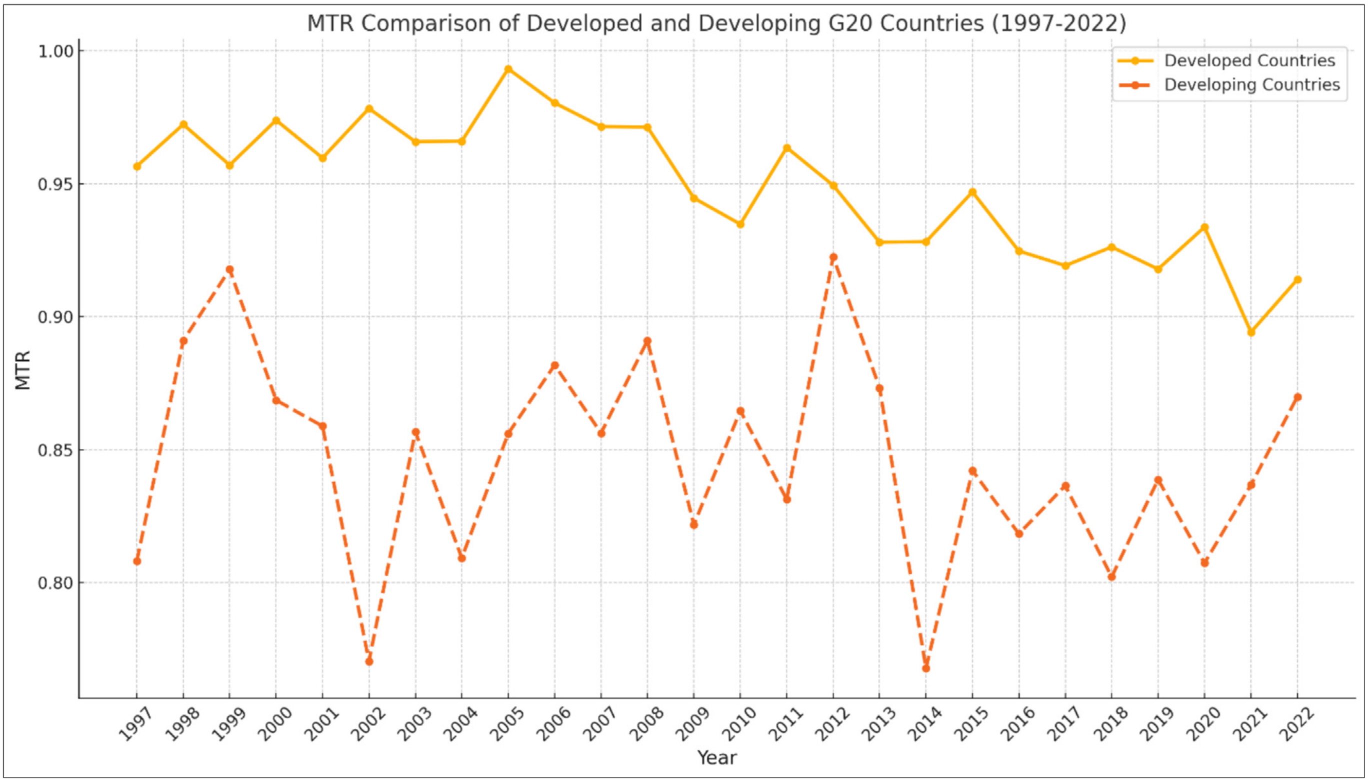

Fig. 4. Meta-technology ratio comparison in developed and developing G20 economies (1997–2022).

The average productivity growth in G20 countries was found to be 1.0114, which indicates a growth of 1.14 percent in TFPC. The efficiency change was found to be the main determinant in TFPC as EC (1.0198) is greater than TC (1.0057). During the late 1990s, the G20 countries faced a decline in productivity due to the slow pace of technological advancements, nevertheless some enhancements in efficiency. During the early 2000s, in the years 2000–2001 and 2002–2003, these countries had significant advancements in productivity due to advanced technological growth. The global financial crisis that occurred between 2008 and 2009 is of great relevance. Despite the financial insatiability, there was a notable gain in productivity during this period, primarily due to technological advancements, while efficiency change had slightly declined. However, the following years were not entirely favorable as there were occurrences when total factor productivity declined numerous times, primarily due to a decline in technology.

The data reveals a notable surge in productivity from 2021 to 2022, indicating a robust rebound from the effects of the pandemic. The resurgence can be attributed to substantial enhancements in both efficiency and technology, indicating that these countries are recovering from the pandemic crisis. Results indicate that the G20 countries have achieved certain advancements in productivity growth, however, their progress has not been consistent. The fluctuations, particularly in the realm of technology, emphasize the persistent obstacles and the necessity for continuous innovation and optimal utilization of resources to sustain growth. The recent upsurge in production provides optimism for the future, demonstrating that despite challenging circumstances, there is potential for robust recovery and expansion. Numerous research studies explain the importance of technological advancement and efficient management of resources to enhance the sustainable total factor productivity growth with less environmental effects [89–91].

Table 4
Total factor economic productivity change, Efficiency change, and technology change in G20 countries (1997–2022).

Year	MLI	EC	TC
1997–1998	0.9548	1.0789	0.8964
1998–1999	0.9436	1.0127	0.9368
1999–2000	1.0942	0.998	1.105
2000–2001	1.1139	0.9924	1.1484
2001–2002	0.8938	0.9927	0.9046
2002–2003	1.136	1.0053	1.1352
2003–2004	0.9042	1.0072	0.898
2004–2005	1.1156	1.0087	1.1114
2005–2006	0.9014	1.0032	0.9004
2006–2007	1.0983	0.98	1.1229
2007–2008	0.9065	1.0466	0.8844
2008–2009	1.1243	0.9672	1.1832
2009–2010	0.8839	1.0169	0.8754
2010–2011	0.8948	0.9885	0.9072
2011–2012	1.1878	1.0895	1.0969
2012–2013	1.1613	1.0403	1.163
2013–2014	0.8851	1.014	0.89
2014–2015	0.9364	1.1314	0.8665
2015–2016	1.1207	0.976	1.1822
2016–2017	0.9081	1.0039	0.9062
2017–2018	0.8952	0.9816	0.9157
2018–2019	0.9139	1.0349	0.8991
2019–2020	0.9319	1.0559	0.9024
2020–2021	0.858	1.0101	0.8674
2021–2022	1.521	1.0581	1.4437
Average	**1.0114**	**1.0198**	**1.0057**

Table 5 and Fig. 5 present a comprehensive analysis of the performance of various G20 countries in terms of productivity, efficiency, and technological innovation. The Malmquist-Luenberger Index (MLI), illustrates the overall change in productivity; Efficiency Change (EC), assesses the efficiency of resource utilization in a country; and Technology Change (TC), represents advancements in technology. Results illustrate that Countries such as China, India, the United Kingdom, and the United States are top performers for their substantial advancements in productivity

Table 5
Average MLI, efficiency change, and technology change in G20 countries.

Country	MLI	EC	TC
Argentina	1.0209	1.0611	0.9768
Australia	1.0058	1.0026	1.0034
Brazil	1.0201	1.0393	1.0025
Canada	0.9974	1.008	0.9945
China	1.0469	1.1	1.0268
European Union	1.0154	0.9991	1.0161
France	1.0159	0.9936	1.025
Germany	1.0035	1.0012	1.0067
India	1.0522	1.0389	1.0134
Indonesia	1.0154	1.0549	0.9915
Italy	1.0065	0.9951	1.0117
Japan	1.0082	1.0018	1.0051
Korea, Rep.	0.9915	1.0109	0.9962
Mexico	0.9986	1.0216	0.9902
Russian Federation	1.0065	1.0551	1.0262
Saudi Arabia	0.971	0.9882	0.9826
South Africa	0.9961	1.0026	0.9951
Türkiye	0.9822	0.9946	0.999
United Kingdom	1.0477	1.0038	1.044
United States	1.026	1.0228	1.0073

growth. China has achieved remarkable progress, fueled by improved efficiency and significant technology improvements. India and the United Kingdom have comparable growth patterns, as both countries are experiencing enhanced productivity due to enhanced resource utilization efficiency and technological advancements.

On the other hand, Saudi Arabia, Türkiye, and South Africa have experienced a drop in total factor economic productivity. For instance, Saudi Arabia has had challenges in terms of both efficiency and technical innovation, resulting in a decline in average productivity. Countries such as Canada and Mexico exhibit minimal fluctuations, characterized by a combination of modest advancements and setbacks in several domains.

Further results show that China, Argentina, and the Russian Federation have been top scores in terms of efficiency change. It illustrated that these countries are more efficient in the transformation process of resources. Moreover, the United Kingdom, China, the Russian Federation, France, and the European Union ranked superior in terms of technological change (TC) over the study period. These Findings illustrate a diverse and heterogeneous MLI, EC, and TC level within the G20. Certain countries are actively advancing, enhancing their operational methods, and embracing innovative technologies, whereas others are encountering obstacles that impede their advancement. This comparison shows the strengths and improvement potential of different G20 countries, providing valuable insights into how they might mutually benefit and enhance their worldwide performance.

Fig. 6 and Table 6 compare productivity, efficiency, and technological changes over time between developed and developing nations. The Malmquist-Luenberger Productivity Index (MLI), which assesses total factor productivity, indicates that industrialized nations have generally steady productivity levels. The average MLI score of developed countries is 1.012; which indicates that developed countries enhanced 1.2 percent of their total factor productivity change over the study period. The index remained near 1.0 over the years, with minor fluctuations, such as an increase from 0.9655 in 1997–1998 to 0.9674 in 1998–1999. This indicates that their production remained rather stable over this era. Conversely, emerging nations have greater variability, with productivity occasionally exceeding 1.0, as shown by a figure of 1.1019 in 1999–2000. This indicates that certain years had notable enhancements in production, while other periods witnessed declines below 1.0, reflecting inconsistent growth. The average MLI score of developing G20 countries was found to be 1.0107. It shows that developing economies inclined their MLI by 1.07 percent over the study period. Regarding Efficiency Change (EC), which assesses the efficiency of resource use by countries to generate outputs, the data indicates that industrialized nations often sustain a consistent level of efficiency. In 1997–1998, developed nations

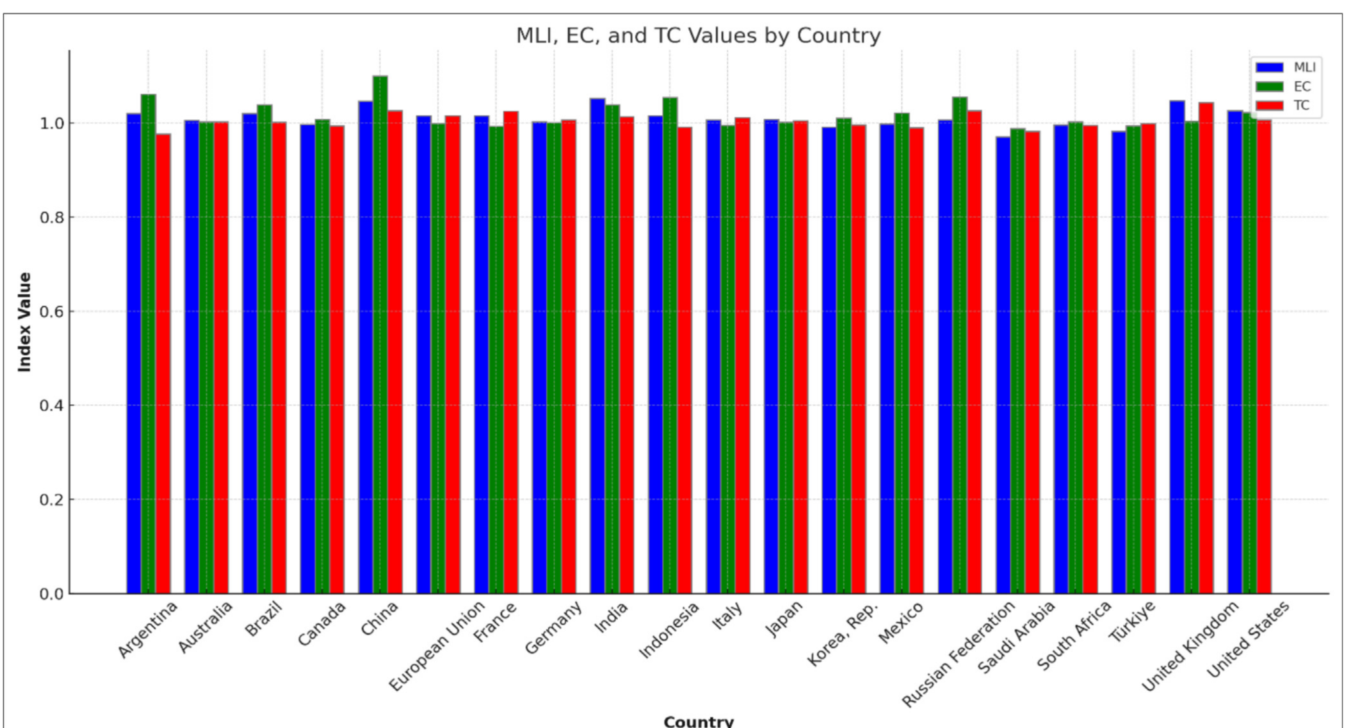

Fig. 5. Average MLI, EC, and TC in G20 economies.

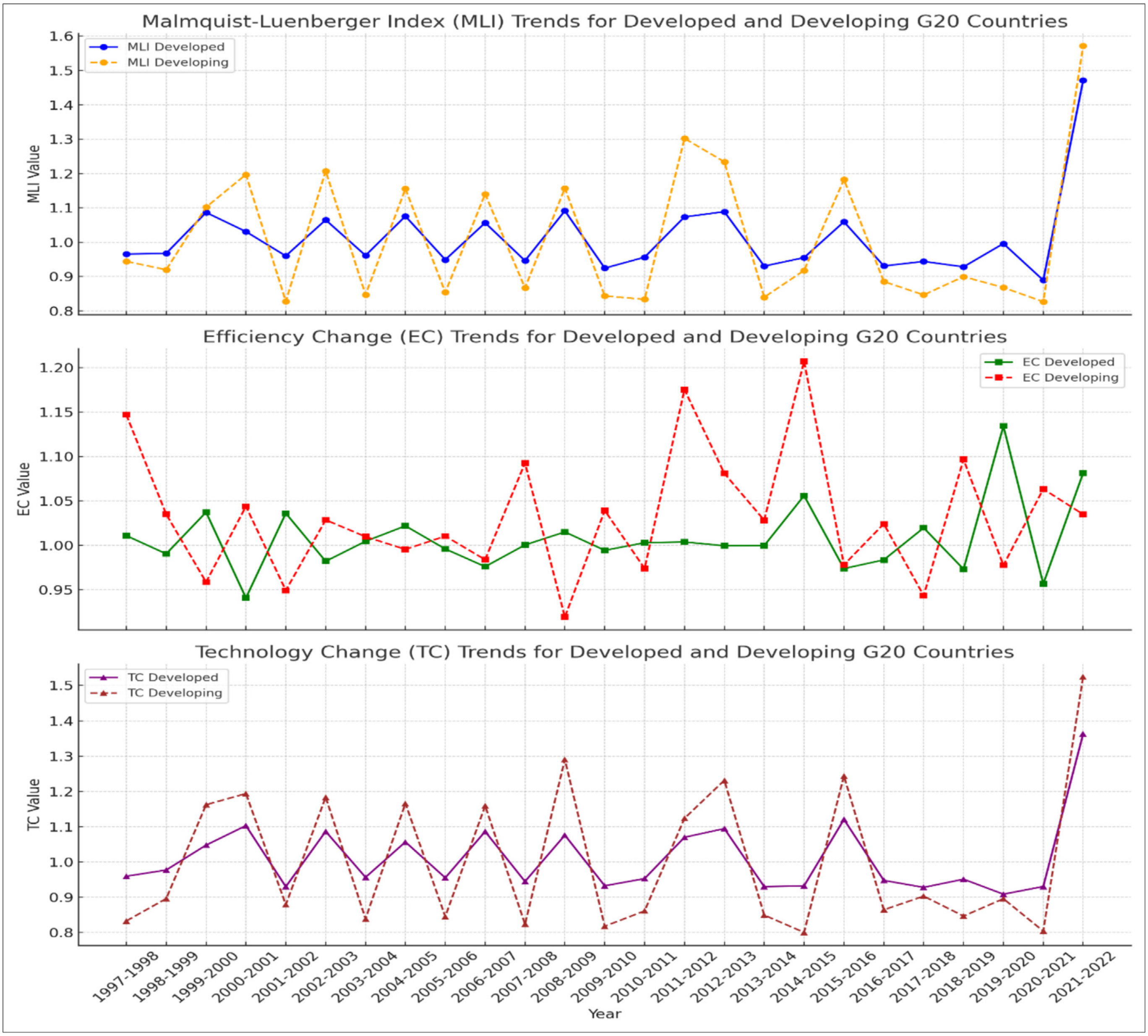

Fig. 6. Average MLI, TC, and EC trends in developed and developing G20 countries.

achieved an efficiency score of 1.0109, somewhat above 1, signifying a small increase. Nonetheless, in certain years, such as 2003–2004, efficiency falls below 1.0 (0.9613), indicating a little decrease. While the average efficiency change in developed countries during the study period is 1.0076; it indicates that developed G20 economies enhanced their efficiency by 0.76 % in the resource utilization process. Conversely, developing nations undergo more pronounced transformations. During 1997–1998, their efficiency score was 1.1469, indicating substantial enhancements in resource use. Nonetheless, in subsequent years, efficiency diminished, seen by figures such as 0.8276 in 2001–2002 and 0.8539 in 2005–2006, signifying that efficiency increasingly posed a difficulty over time. On average the EC in developing economies was witnessed to be 1.0319. It indicates an average increase of 3.9 percent in EC over the study period. Finally, Technology Change (TC) has a comparable trend to efficiency. The average TC in developed countries was found to be 1.0097 compared to the developing countries with an average TC of 1.0016. It shows that developed countries enhanced their technological capabilities with an average of 0.97 while developing G20 economies enhanced their technology by 0.16 percent. Developed nations often sustain consistent technological advancement, although with small variations. In emerging nations, the tendency is more volatile, with certain years exhibiting significant technical progress, while others indicate regressions. This indicates that technological progress in underdeveloped nations may be more erratic, maybe attributable to disparate degrees of access to technology, infrastructure, and resources.

These results indicate that industrialized nations exhibit constant or somewhat decreasing trends in efficiency and productivity, whereas emerging nations encounter higher fluctuations, characterized by phases of substantial enhancement followed by regressions. This variety illustrates the obstacles encountered by emerging nations regarding economic development, resource distribution, and technical progress. Studies found that nations may enhance productivity, efficiency, and technological advancement

Table 6
MLI, EC, and TC in developed and developing G20 countries (1997–2022).

Year	MLI		EC		TC	
	Developed	Developing	Developed	Developing	Developed	Developing
1997–1998	0.9655	0.9441	1.0109	1.1469	0.9597	0.8331
1998–1999	0.9674	0.9198	0.9905	1.035	0.9773	0.8963
1999–2000	1.0865	1.1019	1.0373	0.9587	1.0478	1.1622
2000–2001	1.0308	1.1969	0.9409	1.0439	1.103	1.1938
2001–2002	0.96	0.8276	1.0361	0.9493	0.9301	0.8792
2002–2003	1.0649	1.2071	0.9821	1.0286	1.0867	1.1837
2003–2004	0.9613	0.8472	1.0046	1.0098	0.9567	0.8393
2004–2005	1.0757	1.1554	1.0219	0.9955	1.0568	1.166
2005–2006	0.9489	0.8539	0.996	1.0104	0.9553	0.8456
2006–2007	1.0564	1.1402	0.9761	0.9839	1.0864	1.1593
2007–2008	0.9461	0.8669	1.0005	1.0927	0.9448	0.8239
2008–2009	1.0913	1.1572	1.0151	0.9194	1.076	1.2903
2009–2010	0.9244	0.8434	0.9944	1.0393	0.9326	0.8181
2010–2011	0.9562	0.8335	1.003	0.974	0.953	0.8614
2011–2012	1.0735	1.3021	1.0038	1.1752	1.07	1.1237
2012–2013	1.0887	1.2339	0.9996	1.0809	1.0946	1.2314
2013–2014	0.9304	0.8398	0.9997	1.0283	0.9303	0.8496
2014–2015	0.955	0.9177	1.0559	1.2069	0.9324	0.8006
2015–2016	1.0593	1.1822	0.9739	0.9781	1.1207	1.2438
2016–2017	0.9308	0.8854	0.9837	1.0242	0.9479	0.8646
2017–2018	0.9439	0.8465	1.0197	0.9435	0.9281	0.9033
2018–2019	0.9282	0.8997	0.9733	1.0966	0.9513	0.8469
2019–2020	0.9959	0.8679	1.1341	0.9776	0.9089	0.896
2020–2021	0.8893	0.8267	0.9567	1.0634	0.9306	0.8043
2021–2022	1.4709	1.5711	1.0812	1.0349	1.3626	1.5248
Average	**1.012**	**1.0107**	**1.0076**	**1.0319**	**1.0097**	**1.0016**

Table 7
Mann-Whitney *U* test results.

Hypothesis Test Summary				
	Null Hypothesis Test Sig. Decision			
1	The distribution of economic efficiency is at the same level across developed and developing G20 countries.	Independent-Samples Mann-Whitney U Test	0<0.001	Reject
2	The distribution of MLI is at the same level across developed and developing G20 countries.		0.225	Retain
3	The distribution of MTR is at the same level across developed and developing G20 countries.		0<0.001	Reject

Asymptotic significances are displayed. The significance level is 0.050.

by concentrating on many critical domains. Investing in research and development (R&D) fosters innovation, while the adoption of new technology enhances industrial efficiency. Enhancing education and skills training enables governments to optimize resource use, resulting in increased production. Establishing robust infrastructure, such as improved transportation, electricity, and communication systems, mitigates inefficiencies and facilitates commercial prosperity. Moreover, establishing a robust framework of effective governance, equitable rules, and safeguards for businesses fosters a more stable environment for growth. Ultimately, enhancing efficiency entails the astute utilization of resources, minimizing waste, and endorsing methods that promote industrial sustainability [92,93].

The integration of the study's results reveals a cohesive narrative on the divergent growth trajectories within the G20. The decomposition of the Malmquist-Luenberger Index uncovers a fundamental structural dichotomy: for developing economies, productivity growth is primarily driven by Efficiency Change (EC), indicating a process of catching-up and learning to utilize existing resources and technologies more effectively. Conversely, developed economies rely more on Technological Change (TC), underscoring their role as the innovation frontier. This pattern is further contextualized by the persistent Meta-Technology Ratio (MTR) gap, which signifies that developing nations are still absorbing technologies from the global frontier. Consequently, the higher volatility in their EC and MLI scores reflects the challenges of this assimilation process, often disrupted by economic shocks and institutional instabilities. The statistically significant differences in economic efficiency and MTR, but not in MLI, confirm that while developing countries are managing to improve productivity through better management (efficiency catch-up), they have not yet consistently closed the fundamental innovation gap with their developed counterparts. This analytical synthesis moves beyond description to posit that the core challenge for global convergence is not just efficiency but the capacity for sustained technological creation and adoption.

Statistically significant test results

The results in Sections 5.1, 5.2, and 5.3 reveal that the average annual scores for economic efficiency, MLI, and MTR vary between developed and developing G20 economies. However, a key question that arises is whether these differences are statistically significant, as this is crucial to confirming the study's findings. To explore this, the Mann-Whitney *U* test was used to determine if there were significant differences in the average scores for economic efficiency, productivity change, and MTR between developed and developing economies. As shown in Table 7 and Fig. 7, the first hypothesis showed a significant difference (p-value < 0.0 01), so we reject it. This means we can conclude that economic efficiency levels are not the same across developed and developing G20 countries, highlighting a clear difference between the two.

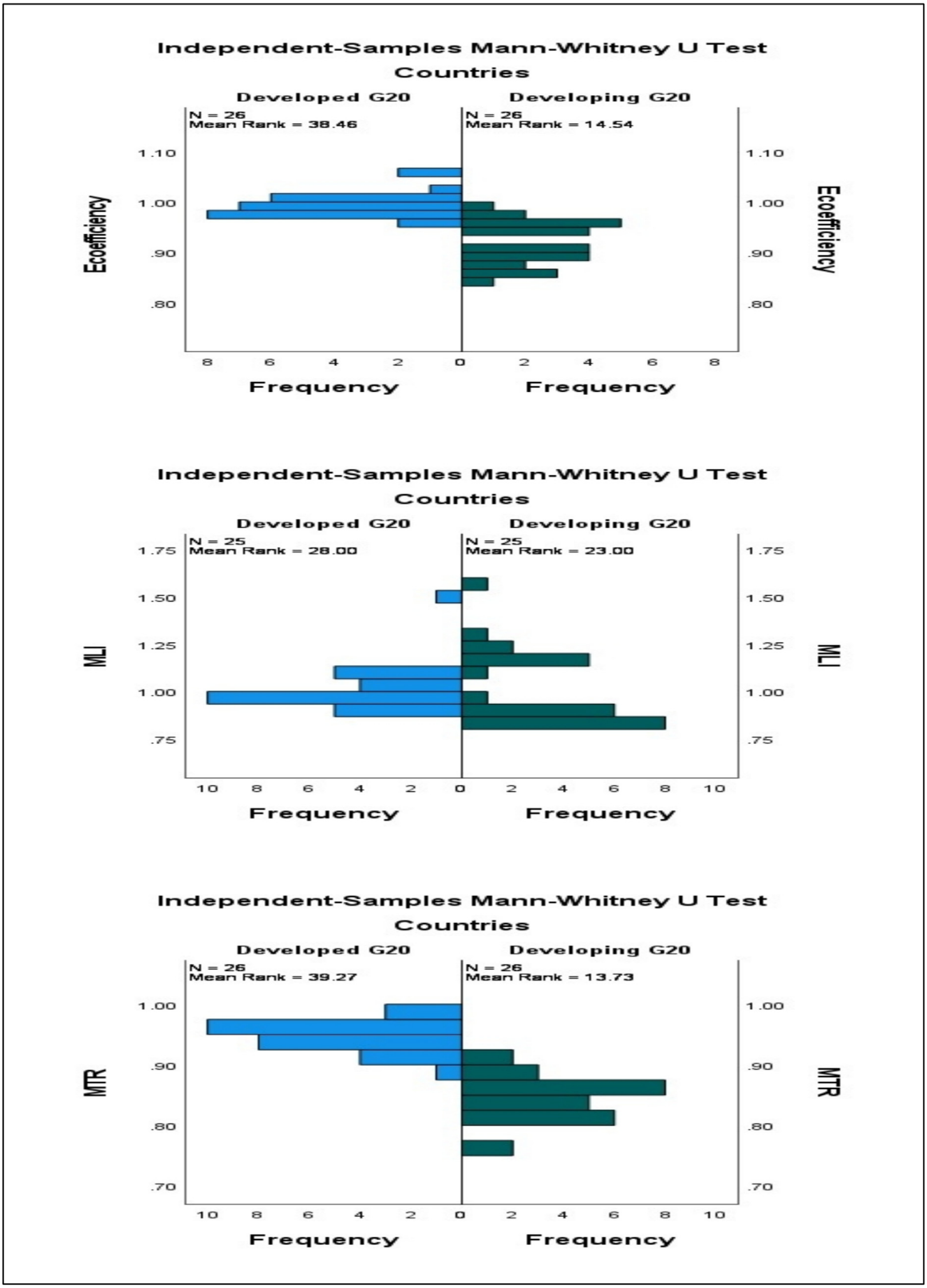

Fig. 7. The distribution of Economic efficiency, MLI, and MTR in developed and developing G20.

On the other hand, when we look at MLI, no significant difference was found between the two groups, since the p-value was above 0.05. Therefore, we keep the second hypothesis, which suggests that MLI levels are similar across both groups. Lastly, the analysis revealed that the MTR (technology gaps) between developed and developing G20 economies are also significantly different, with a

Table 8
Comparison of economic efficiency and MTR – full model vs. model excluding R&D.

Country	Main model meta-frontier	Robustness model meta-frontier	Main model MTR	Robustness model MTR
Argentina	1.4374	1.4302	0.9772	0.9751
Australia	1.1836	1.179	0.8501	0.8473
Brazil	0.8995	0.8948	0.8255	0.8221
Canada	0.8748	0.8695	0.9154	0.9128
China	0.6227	0.6189	0.5013	0.4982
European Union	1.0325	1.0287	1	0.9985
France	1.0086	1.0032	0.9902	0.9874
Germany	0.9457	0.9408	1	0.9989
India	0.5221	0.5189	0.7505	0.7473
Indonesia	0.6565	0.6521	0.9353	0.9327
Italy	1.0005	0.9958	0.9041	0.9012
Japan	0.883	0.8785	0.9998	0.9973
Korea, Rep.	0.7355	0.7312	0.8681	0.8654
Mexico	0.7929	0.7887	0.7423	0.7391
Russian Federation	0.6929	0.6885	0.7802	0.7774
Saudi Arabia	1.1948	1.1901	0.9709	0.9683
South Africa	1.3378	1.3329	1	0.9987
Türkiye	0.8535	0.8492	0.8634	0.8605
United Kingdom	1.1785	1.1738	1	0.9986
United States	1.2599	1.2547	1	0.9988
Developed G20 Average	1.034	1.029	0.963	0.96
Developing G20 Average	0.877	0.872	0.83	0.827

Table 9
Comparison of productivity indices – full model vs. model excluding R&D.

Country	Main model MLI	Robustness model MLI	Main model EC	Robustness model EC	Main model TC	Robustness model TC
Argentina	1.0209	1.0192	1.0611	1.0593	0.9768	0.9751
Australia	1.0058	1.0041	1.0026	1.0012	1.0034	1.0021
Brazil	1.0201	1.0183	1.0393	1.0378	1.0025	1.001
Canada	0.9974	0.9958	1.008	1.0065	0.9945	0.9931
China	1.0469	1.0448	1.1	1.0982	1.0268	1.025
European Union	1.0154	1.0137	0.9991	0.9976	1.0161	1.0145
France	1.0159	1.0142	0.9936	0.9921	1.025	1.0234
Germany	1.0035	1.0019	1.0012	0.9998	1.0067	1.0052
India	1.0522	1.0503	1.0389	1.0374	1.0134	1.0119
Indonesia	1.0154	1.0137	1.0549	1.0533	0.9915	0.9901
Italy	1.0065	1.0048	0.9951	0.9937	1.0117	1.0102
Japan	1.0082	1.0065	1.0018	1.0003	1.0051	1.0037
Korea, Rep.	0.9915	0.9899	1.0109	1.0094	0.9962	0.9948
Mexico	0.9986	0.997	1.0216	1.0201	0.9902	0.9888
Russian Federation	1.0065	1.0048	1.0551	1.0535	1.0262	1.0246
Saudi Arabia	0.971	0.9694	0.9882	0.9868	0.9826	0.9812
South Africa	0.9961	0.9945	1.0026	1.0011	0.9951	0.9937
Türkiye	0.9822	0.9806	0.9946	0.9932	0.999	0.9976
United Kingdom	1.0477	1.0458	1.0038	1.0023	1.044	1.0424
United States	1.026	1.0242	1.0228	1.0213	1.0073	1.0058
All G20 Average	1.0114	1.0097	1.0198	1.0183	1.0057	1.0042
Developed G20 Average	1.012	1.0103	1.0076	1.0061	1.0097	1.0082
Developing G20 Average	1.0107	1.009	1.0319	1.0304	1.0016	1.0001

Table 10
Robustness of statistical test results (Mann-Whitney U test) – model excluding R&D.

Hypothesis	Main model P-value	Robustness model P-value	Conclusion in both models
H1: The distribution of economic efficiency is the same across developed and developing G20 countries	<0.001	<0.001	Reject Null Hypothesis
H2: The distribution of MLI is the same across developed and developing G20 countries	0.225	0.238	Retain Null Hypothesis
H3: The distribution of MTR is the same across developed and developing G20 countries	<0.001	<0.001	Reject Null Hypothesis

p-value of less than 0.001. As a result, we reject the third hypothesis, which assumes that the MTR would be the same across both groups of countries.

This study elucidates significant distinctions between developed and emerging G20 economies. Although economic efficiency and the technological gap ratio (MTR) exhibit prominent discrepancies between the two groups, no such distinction is shown in Total Factor Productivity change (MLI). The first hypothesis, which posited that economic efficiency would be comparable across the two groups, was refuted due to the large disparity discovered. The third hypothesis about the technology gap ratio (MTR) was likewise rejected, indicating a distinct disparity in technical advancement between the two categories of economies. Nevertheless, the second hypothesis, which posited that TFP change would be uniform between industrialized and developing nations, was validated, indicating that productivity changes do not differ considerably between the two. These findings highlight the distinct difficulties and possibilities confronting industrialized and developing countries, underscoring the requirement for customized policies that effectively address these disparities and promote more equal economic growth. Studies have investigated the policies to reduce the differences among economic efficiencies, total factor productivity, and technology for the developed and developing world [94–96].

The results and discussion presented in this section paint a comprehensive picture of the dynamics of economic efficiency, technological progress, and productivity growth within the G20. The analysis reveals several key findings: (1) There exists a significant and statistically confirmed gap in economic efficiency and technological levels (MTR) between developed and developing G20 nations, with the latter group facing persistent challenges in optimizing resources and accessing frontier technologies. (2) Despite this heterogeneity, the total factor productivity growth (MLI) for the entire G20 was positive, albeit modest, driven predominantly by efficiency improvements (EC) rather than technological shifts (TC). (3) A critical insight is the divergent paths of this growth; developed economies exhibited stability in both efficiency and technology, while developing economies, despite showing higher average efficiency gains, experienced greater volatility and struggled with consistent technological adoption. Collectively, these findings underscore that the path to sustainable economic development in the G20 is not uniform. The persistent technology gap and the primary role of efficiency catch-up highlight the need for tailored policies that address the specific challenges of developing economies, particularly in technology transfer and institutional strengthening, to ensure more balanced and sustainable growth across the bloc. These empirical conclusions provide a solid foundation for the policy implications discussed in the following section.

Robustness checks

To ensure the robustness of our findings, we conducted a comprehensive sensitivity analysis by re-estimating all models, excluding the Research and Development (R&D) expenditure variable. The results of this alternative specification, detailed in Tables 8-10, confirm that our core conclusions are not sensitive to this variable's inclusion. The comparative analysis reveals nearly identical country rankings and persistent, statistically significant gaps in economic efficiency and the Meta-Technology Ratio (MTR) between developed and developing G20 blocs. Furthermore, the results of the Mann-Whitney *U* test remain unchanged, continuing to show significant differences in efficiency and MTR but not in the Malmquist-Luenberger Index (MLI). The stability of these key findings across model specifications strongly reinforces the validity and reliability of our study's primary conclusions.

Synthesis and policy discussion

The integrated analysis reveals a core narrative of divergent development paths within the G20, characterized by a fundamental structural dichotomy between developed and developing economies. The empirical evidence consistently demonstrates a persistent "double gap" in both economic efficiency and technological levels (MTR), alongside a critical divergence in the drivers of productivity growth. While the Malmquist-Luenberger Index shows similar rates of productivity improvement across the bloc, its decomposition uncovers that developing economies rely primarily on Efficiency Change (EC)—a process of catching up and optimizing existing resources, whereas developed economies are propelled more by Technological Change (TC) at the innovation frontier. This explains the significant statistical difference in the level of technology (MTR) despite similar rates of productivity growth (MLI). This synthesis leads directly to distinct causal explanations and policy implications. For developing economies, the central challenge is the technology absorption gap, where volatility in efficiency scores points to difficulties in assimilating foreign technologies due to institutional weaknesses and skill mismatches. Their policy focus must therefore be on enhancing absorptive capacity through investments in education and vocational training, while simultaneously maximizing efficiency through improved governance and infrastructure. For developed economies, the imperative is to sustain their TC advantage by aggressively supporting R&D and frontier innovation. Furthermore, they have a role in facilitating global knowledge transfer through mechanisms that support green investment and technology diffusion in emerging markets. In conclusion, the path to convergence is not uniform; it demands a dual-track strategy where developing economies prioritize closing the absorption gap and developed economies focus on pushing the innovation frontier, ensuring a more balanced and sustainable growth trajectory for the entire G20.

Conclusion and policy implications

The effective utilization of resources, total factor productivity growth, and technological development are essential for the sustainable economic development of any country or region. G20 countries are the top 20 economies of the globe and have mutual agreements for sustainable economic development and environmental upgradation. However, the technological heterogeneity between the developed and developing G20 countries is a significant factor that could impact sustainable economic efficiency and productivity growth. Moreover, as a result of economic development, energy consumption has increased significantly, resulting in emissions of greenhouse gases and environmental degradation. To tackle these issues, G20 countries took serious actions and developed economic and environmental policies that could enhance economic efficiency and total factor productivity growth through technological advancement with the least environmental degradation. However, the success level of G20 countries in this mission of homogeneous technological availability for sustainable economic efficiency, and productivity growth with less ecological damage is still under investigation and worth examination.

To this end, firstly, this study employed DEA-Super SBM to gauge the economic efficiency in G20 countries over the study period of 1997–2022. It not only investigates the efficiency evaluation over the study period but also distinguishes the efficiency level of developed G20 countries from developing. Secondly, the study uses the Meta-frontier Analysis to gauge the production technology heterogeneity (technology gap ratio) in developed and developing G20 Economies. It evaluates the impact of research & development and technological advancement on economic efficiency and the technology gaps in both groups. Thirdly, research used MLI (Malmquist-Luenberger Productivity Index) to estimate the Total factor productivity change in G20 countries. TFPC estimation gauges the dynamic change in economic efficiency over the study period. Moreover, total factor productivity change is decomposed into efficiency change (EC) and technology change (TC) to gauge the main determinant (EC or TC) in the TFPC. Finally, to strengthen the study results, it applied the Mann-Whitney *U* test to gauge the statistically significant difference between developed and developing G20 countries for economic efficiency, TFPC, and MTR.

This study makes several key contributions to the literature on sustainable economic development in the G20. First, it provides a novel and comprehensive analysis of economic efficiency, revealing an average potential growth opportunity of 4.44 % for the G20 and highlighting a significant performance gap between developed and developing nations. Second, it offers critical empirical evidence of technological heterogeneity by quantifying the substantial technology gap (average MTR of 0.8965) that hinders developing economies. Third, by decomposing TFPC, the study identifies that efficiency change (EC), rather than technological change (TC), is the primary driver of productivity growth (EC = 1.0198 vs. TC = 1.0057) for the G20 as a whole, a finding with distinct implications for both groups of countries. The graphical evidence solidifies this study's conclusions. Fig. 3 confirms a persistent economic efficiency gap between developed and developing G20 nations, highlighting the need for better resource management. Simultaneously, Fig. 4 demonstrates a significant technology disparity, with developing economies showing volatile and lower MTR scores. Crucially, Fig. 6 reveals that efficiency change (EC), not technological change (TC), is the main driver of productivity growth. Therefore, bridging the technology gap (Fig. 4) and improving resource efficiency (Fig. 3) are the essential pillars for achieving sustainable and equitable economic growth across the G20. The study's conclusions illustrate a complex landscape of economic efficiency and technical progress across G20 countries. The G20 economies possess an average economic efficiency score of 0.9556, indicating a potential growth opportunity of 4.44 %. Argentina and South Africa have shown the highest efficiency by optimizing labor, capital, technology, and energy inputs to enhance GDP. These nations exemplify how resource efficiency may result in robust economic success. Developed countries such as the United States, Saudi Arabia, and Australia have shown proficiency in utilizing resources efficiently to achieve continuous economic growth. Nonetheless, other developed nations, like Germany, Japan, and Canada, although sustaining substantial economic efficiency, still exhibited inefficiencies in their resource utilization. Conversely, emerging economies such as Russia, China, India, and Indonesia encountered more significant obstacles to economic efficiency. These countries had challenges in maximizing their utilization of labor, capital, and technology, frequently attributable to a delayed integration of advanced technologies. Consequently, their efficiency scores have fallen short of that of developed nations, underscoring the requirement for enhanced expenditures in technology and improved resource management to bridge the disparity.

Moreover, research revealed a significant technology disparity between developed and underdeveloped nations. The average Meta-Technology Ratio (MTR) for the G20 was 0.8965, indicating a substantial technical disparity. Developed economies, including the United States, the United Kingdom, and Germany, successfully leveraged technology to sustain global competitiveness; conversely, nations such as China and India, despite their commendable performance domestically, exhibit significant potential for enhancement in the adoption of advanced global technologies. Developed nations often sustained MTR levels near 1.0, indicating consistent and efficient technological utilization. This tendency indicates their capacity to incorporate modern technical advancements into their economies, facilitating continuous economic growth. Conversely, emerging nations had greater variability in their MTR ratings, often oscillating between 0.80 and 0.90. The fluctuations indicate difficulties in the constant adoption and utilization of cutting-edge technologies. Several developing nations witnessed reductions in their MTR values throughout pivotal years, including 2001, 2009, and 2014, presumably attributable to the repercussions of global economic crises or internal challenges in adopting technology innovations. Nonetheless, indications of recovery emerged, especially post-2020, suggesting that with more investment in technological infrastructure and research and development, these nations might feasibly diminish the technological disparity and enhance their economic performance.

The research further examined Total Factor Productivity Change (TFPC), a crucial metric of economic efficiency throughout time. The mean TFPC for the G20 nations was 1.0114, indicating a little 1.14 % increase in productivity throughout the analyzed period. Upon analysis of this modification, it was determined that Efficiency change (EC) was the primary contributor to productivity enhancements, with a score of 1.0198, in contrast to Technology Change (TC), which attained a score of 1.0057. This indicates that enhancements in resource use were more important in fostering productivity increase than technology innovations. Countries such as China, India, the United Kingdom, and the United States demonstrated significant productivity gains, primarily attributable to enhancements in efficiency. China, notably, achieved substantial advancements in efficiency and technology, optimizing resources and embracing innovations to enhance output. Nevertheless, several nations, such as Saudi Arabia, Turkey, and South Africa, encountered obstacles in efficiency and technical advancement, resulting in reduced output. These setbacks underscore the requirement of attaining equilibrium in both efficiency and technology to sustain long-term productivity development. The study revealed that developed nations often exhibited stable and continuous advancements in Efficiency Change (EC) and Technological Change (TC) trends. The average EC for developed economies was 1.0076, signifying a modest 0.76 % enhancement in resource usage efficiency, but the average TC was 1.0097, denoting minor although consistent technical progress. Conversely, emerging nations encountered increased variability in both EC and TC. The mean EC for emerging nations was 1.0319, reflecting a notable 3.9 % increase in efficiency over the research duration. This indicates that although these economies achieved significant advancements in efficiency, maintaining these improvements has been more challenging. Simultaneously, the average TC for emerging countries was at 1.0016, indicating a little 0.16 % improvement in technical advancement. The inconsistent technical progress may be ascribed to several issues, such as restricted access to cutting-edge technology, insufficient infrastructure, and budgetary limitations, which have impeded developing nations from completely adopting contemporary technological solutions. Further study underscores the gaps in economic efficiency and technical progress between developed and developing G20 nations. Although developed nations have achieved consistent advancements in all domains, emerging economies still encounter considerable obstacles in effectively using their resources and integrating new technology. The findings indicate that bridging the technology divide, optimizing resource management, and promoting innovation are essential for emerging economies to improve productivity and maintain sustained economic growth. Moreover, for all G20 nations, reconciling efficiency improvements with technology advancements will be crucial for attaining more equitable and sustainable growth. Finally, Mann-Whitney test results validate the finding of heterogeneity of economic efficiency, MTR, and TFPC among developed and developing countries.

This study's findings underscore critical policy directions for G20 nations to promote more impartial and sustainable economic growth. The core of these findings is the requirement to narrow the technical and efficiency disparities between developed and developing nations, enabling all countries to fully leverage their potential for sustainable development. Primarily, fostering technology advancement and innovation in underdeveloped nations must be a paramount objective. The study indicates that developed economies such as the United States, Germany, and the United Kingdom have successfully used modern technology to maintain competitiveness, but several emerging nations, including China, India, and Indonesia, continue to have difficulties in this domain. To bridge this gap, developing nations must enhance investments in research and development (R&D), establish innovation ecosystems, and bolster their capacity to integrate new technology. This entails measures that enhance access to innovative technology, offer incentives for corporate innovation, and establish partnerships for knowledge exchange with more developed countries.

In combination with technology, enhancing resource efficiency is essential for both advanced and emerging economies. Although developed nations often exhibit resource efficiency, countries such as Germany, Japan, and Canada continue to encounter inefficiencies. Developing nations have more challenges in optimizing labor, capital, and technology. Policymakers have to prioritize enhancing resource use efficiency via improved management practices, investment in human capital, and the advancement of sustainable technology. This encompasses enhanced education and skills training to guarantee that the workforce can adapt to emerging technology and more sustainable industrial practices. Environmental sustainability is a crucial consideration that governments must confront. The research indicated that as countries or regions experience economic growth, their energy consumption and emissions often increase, leading to environmental degradation. Consequently, governments must advocate for regulations that facilitate the use of clean, energy-efficient technology and sustainable manufacturing methods. This entails incentives for renewable energy adoption, more stringent environmental legislation, and promoting the establishment of circular economies that reduce waste and enhance resource efficiency.

Ultimately, international collaboration will be essential in closing these disparities and guaranteeing that the advantages of economic expansion are distributed more evenly. Although developed nations have achieved consistent advancement, emerging economies require assistance to address the obstacles they encounter. Enhancing international collaborations, prioritizing technology transfer, and providing financial and technical support to underdeveloped countries will be essential for bridging technological and efficiency disparities. International cooperation can facilitate the equitable distribution of technological and innovative achievements across all G20 nations, fostering a more inclusive and sustainable global economy. This study highlights the requirement for a comprehensive strategy for development that prioritizes technical advancement, resource efficiency, and environmental stewardship. Policymakers should prioritize investments in innovation, optimize resource use, and promote global collaboration to assist emerging countries in bridging the gap with developed nations. By doing so, the G20 can guarantee that all nations progress collectively towards a more sustainable and affluent future.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

Data Sources

The data for GDP, labor force (total), gross fixed capital formation, and research & development expenditure were obtained from the World Development Indicators database, available at https://databank.worldbank.org/reports.aspx?source=2&country=ARE.

Data on primary energy consumption and annual CO_2 emissions were sourced from Our World in Data, accessible at https://ourworldindata.org.

CRediT authorship contribution statement

Wasi Ul Hassan Shah: Conceptualization, Formal analysis, Writing – original draft. **Gang Hao:** Conceptualization, Formal analysis, Writing – original draft. **Rizwana Yasmeen:** Conceptualization, Formal analysis, Writing – original draft. **Hong Yan:** Conceptualization, Formal analysis, Writing – original draft. **Heshan Sameera Kankanam Pathiranage:** Methodology, Supervision, Writing – review & editing. **Qian Yang:** Methodology, Supervision, Writing – review & editing.

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Appendix

Table A1
Parameters and variables.

Symbol	Description
General Indices and Counts	
i	Index for inputs
r	Index for outputs
j	Index for Decision-Making Units (DMUs)
0, k	The specific DMU under evaluation
m	Total number of inputs
$s1$	Total number of desirable outputs
$s2$	Total number of undesirable outputs
Variables in SBM & Super-SBM Models (Eq. 1–3)	
θ^*	Efficiency score of the DMU under evaluation
$xi0$	Observed amount of the i-th input for DMU00
$yr0g$	Observed amount of the r-th desirable output for DMU00
$yr0b$	Observed amount of the r-th undesirable output for DMU00
S_i^-	Slack variable for the i-th input
S_r^g	Slack variable for the r-th desirable output
S_r^b	Slack variable for the r-th undesirable output
λj	Intensity weight assigned to the j-th DMU
t	Scalar variable
ε	A very small non-Archimedean number
Variables in Meta-Frontier Model (Eq. (4)	
MTR	Meta-Technology Ratio
GTE_i	Group Technical Efficiency
MTE	Meta Technical Efficiency
Variables in Malmquist–Luenberger Index (Eqs. ((5)–(7))	
ML_t^{t+1}	Malmquist–Luenberger Productivity Index
x^t, y^t, b^t	Input, desirable output, and undesirable output vectors in period t
$\mathrm{MLEFFCH}_t^{t+1}$	Efficiency Change component
$\mathrm{MLTECH}\ _t^{t+1}$	Technical Change component

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