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Technological Catch-Up, Innovation, and Productivity Analysis of National Innovation Systems in Developing Countries in Africa 2010–2018

Simon Ndicu[1] · Dianah Ngui[2] · Laura Barasa[3]

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Abstract
This study investigates the levels and determinants of regional innovation catch-up, frontier shift, and productivity growth of African national innovation systems from 2010 to 2018. The study relied on the World Development Indicators data for 28 African countries. Non-radial non-oriented Data Envelopment Analysis (DEA) and bootstrapped truncated regression were the central estimation methodologies. The results revealed that 18% of Africa's national innovation systems had experienced progress in the catch-up and frontier shift indexes. Further results showed that 21% had experienced total factor productivity growth. Nigeria and South Africa were on the region's efficient frontier and had achieved the most technological advancement. In addition, Ghana and Senegal had the most productive national innovation systems. The results suggested that national innovation systems in Africa had experienced marginal progress. Further results indicate that the population growth rate and GDP per capita are the critical determinants of African national innovation systems, efficiency, technical efficiency, and productivity performance. Consequently, the implications of the results to policy are twofold. First, African countries should use benchmarking practices with the region's best-performing national innovation systems. Lastly, African countries have the potential to grow their economies through regional collaborative Science, Technology, and Innovation practices.

Keywords National innovation system · Regional innovation system · Innovation efficiency · Malmquist productivity index (MPI)

✉ Simon Ndicu
ndungu.simon@mnu.ac.ke; simonndicu8@gmail.com

1 Department of Economics and Finance, Mama Ngina University College (Constituent College of Kenyatta University), P. O. Box 444-01030, Gatundu, Kenya

2 Department of Econometrics and Statistics, Kenyatta University, P. O. Box 43844-00100, Nairobi, Kenya

3 Department of Economics and Development Studies, University of Nairobi, P. O. Box 30197-00100, Nairobi, Kenya

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Introduction

In Africa, well-functioning national innovation systems (NIS) can accelerate African economies' transition to fully knowledge-based ones (Quartey & Oguntoye, 2021; Tchamyou, 2017). For the past few decades, Africa has embraced the role of Science, Technology, and Innovation (ST&I) and the importance of well-functioning NIS as a driver of economic growth. Consequently, fundamental regional innovation policies have been developed to realize a knowledge-based region and catch up with the global ST&I frontier, for instance, policies such as the African Science, Technology, and Innovation Indicators (ASTII) initiative established in 2007, the Science, Technology, and Innovation Strategy for Africa 2014–2024 (STISA 2014–2024) established in 2014, and the Africa we want 2063 agenda launched in 2013 (African Union–New Partnership for Africa's Development, 2014, 2019).

The distribution of innovation-related activities is not randomized but tends to be concentrated in particular regions within a regional innovation system (RIS) (Cocciaa, 2015; Grillitsch et al., 2013). Therefore, asymmetries are expected among the African NIS. For instance, different countries have integrated regional policies into their NIS to varying degrees and have varying Domestic Expenditures on Research and Experimental Development (GERD/GDP ratio). Additionally, according to African Union-New Partnership for Africa's Development (2019), 23 countries had conducted their national Research and Development (R&D) surveys, and only 19 countries had data on public sector R&D activities as of 2019. However, some member states are still strengthening their national ST&I frameworks by creating ST&I institutions, conducting national innovation surveys, and publishing reports. The interventions provided by regional innovation policies can be attributed to the high number of Africa Union (AU) member countries with ST&I statistics as a foundation for policy development (African Union-New Partnership for Africa's Development, 2019).

In light of the heterogeneous nature of innovation-related activities and the regional efforts by Africa to catch up with the ST&I frontier, this study investigates the distribution of innovation activities and the progress of NIS in Africa from 2010 to 2018. Further, using a Data Envelopment Analysis (DEA) model and bootstrapped truncated regression, the study investigates the levels and the determinants of the African NIS catch-up, frontier shift, and productivity. The productivity analysis of NIS in Africa has not yet been adequately analyzed scientifically. Being a developing region, the study of the NIS framework and ST&I indicators is still in their early development stages and gaining momentum (Egbetokun et al., 2017). The few available empirical works discuss the nature of NIS in Africa and policies to enable catch with knowledge-based economics (Asongu, 2017; Asongu & Odhiambo, 2020; Egbetokun et al., 2017). Further, Asongu et al. (2018) attempted to investigate the knowledge economy performance in Africa from 1996 to 2010 using the sigma convergence approach.

This study extends the discourse on NIS and knowledge-based economics in Africa in three unique ways. First, the paper attempts to find suitable innovation inputs and outputs for the African NIS during the study period based on theoretical literature focusing on developing economies. Secondly, there is no published study empirically evaluating the productivity of NIS in Africa during the study period based on an economic model. Therefore, this becomes the first study to empirically analyze the African RIS, estimate the African ST&I frontier, and compare Africa's NIS using DEA estimation approaches. Thirdly, this study assesses the levels and determinants of technological progress, efficiency change, and productivity change of NIS in Africa from 2010 to 2018, a period when regional policies such as ASTII and STISA 2014–2024 vision were being implemented.

These robust innovation policies, among other innovation efforts, are geared toward accelerating Africa's transition to an innovation-led knowledge-based region. Determining the levels and determinants of productivity and technical progress of NIS in Africa over time is crucial to realizing this Africa innovation vision in two ways. First, evaluating whether there has been productivity progress or regress indicates the innovation efficiency stance of NIS in Africa. It can also be a good indicator of the effectiveness of current innovation policies and strategies. Secondly, it is possible to know the best-performing NIS in Africa that other NIS can use as a benchmark to enhance regional growth. Lastly, determining the significant factors driving the productivity of NIS in Africa is critical to the policy implications of this study and the realization of a knowledge-based region.

Theoretical Framework and Hypothesis

Innovation is defined as introducing novel ideas and methods to the firm, country, or workplace and includes imitations (Griffith et al., 2006; Hall et al., 2014). In line with this definition, most innovation initiatives and activities in developing countries have been described as catching up with developed economies (Liu et al., 2017). The NIS underlies successful innovation, especially in developing countries (Lundvall, 2016). A NIS refers to interconnected economic agents collaborating in the generation, utilization, and diffusion of knowledge and innovations. It shows how smooth interconnections and regular interactions of all national innovation actors can enhance firms' and countries' innovation and productivity (Fagerberg et al., 2018; Rong et al., 2021; Watkins et al., 2015).

The national innovation actors include society, academia, government, and industry. Meuer et al. (2015) generally categorize the NIS actors into two broad categories: institutions and organizations. Organizations encompass research institutes, universities, government policy organs, and private firms (Yuzhuo Cai & Liu, 2015; Fagerberg, 2018). On the other hand, institutions are rules and laws that encourage fair play in innovation, for example, patent laws. Institutions also include social norms that shape industry and academia's linkages (Yuzhuo Cai & Liu, 2015; Li, 2015) and other national traditions and social norms (Khan & Cox, 2017).

According to Carayannis & Campbell (2012), a NIS comprises five helices. They include the education system, the political system, the economic system, the natural environment, and the media and culture-based public and political system

(Carayannis & Rakhmatullin, 2014). These five “sub-systems” are represented by four agents in the innovation system: firms, government, academia, and society (Carayannis & Campbell, 2012). Knowledge flows from one “sub-system” into another in an interconnected manner, leading to new knowledge and innovation. The fifth helix of the natural environment acts as a driver of new knowledge rather than an agent in the innovation process (Grundel & Dahlström, 2016).

Strengthening inter-relations among NIS helices and investment in ST&I by African countries may play a crucial role in industrialization, sustainable development, and growth (OECD, 1999). Investment and incorporation of ST&I into economic, social, and governance policies increase productivity, global competitiveness, and employment opportunities in African countries (Lema et al., 2018). Intensified application of ST&I by developing nations in Africa is essential for improving living standards, enhancing financial growth, and enabling their contribution to the world economy’s growth (OECD, 1999). Appropriate investment in ST&I will likely allow efficient and well-functioning NIS in Africa.

There are four types of information or knowledge diffusion among the helices experienced in any efficient NIS: (1) collaboration among enterprises, mainly multidisciplinary research, and technical activities; (2) formal and informal linkages among industries, academia, and public research institute through joint research, co-publishing, and co-patenting; (3) new technology adoption by establishments leading to products and services innovation; and (4) R&D workforce exchanges within the public and private sectors (OECD, 1999). Linking the four different information flows among the helices in Africa’s NIS to a firm performance may increase technology diffusion and technical collaboration levels. Further, exchanging R&D personnel can help a firm achieve enhanced innovative capacity (Ockwell et al., 2015). Consequently, this will improve Africa’s NIS efficiency, transforming African countries into knowledge-based economies.

Most African countries are classified as developing or less developed nations trying to catch up with the global ST&I frontier (Cirera et al., 2016). While the NIS concept is in its initial stages globally, most African countries are still lagging (Egbetokun et al., 2017). In most developing countries in Africa, national innovation systems still suffer from numerous micro and macro-level challenges, hampering an effective innovation environment (Watkins et al., 2015). Research institutions do not function at their full potential. Additionally, the commercialization of R&D is poor, and most public R&D policies are ineffective. Moreover, most developing countries have limited collaboration between institutions and organizations (Sağ et al., 2016). Many institutions have inadequate organizational capacity, and the social and political systems hamper the development of sound NIS (United Nations Conference on Trade and Development, 2021).

Compared to the OECD, EU, Latin America, and Asia, Africa still lags in NIS policy frameworks and investment in ST&I. For instance, according to the Africa innovation outlook III report of 2019, only 23 countries in the region have conducted independent national R&D surveys, 11 countries have data on GERD/GDP ratio, and 19 countries have data on public R&D expenditures. Besides, 43 countries have embraced the ASTII initiative. Most African countries are still setting up NIS institutional frameworks, while others are still conducting national ST&I and R&D surveys and publishing their reports (African Union-New Partnership for Africa's Development, 2019). Regional policy goals such as STISA 2014–2024 provide solutions to these challenges by highlighting the policy priority areas and strategic policy to enhance Africa's NIS competitiveness. For instance, the vision priority areas include improving ST&I infrastructure, human capital, and research capability. The vision also encourages AU member countries to spend at least 1% of their GDP on R&D activities to enhance the productivity of NIS (African Union Commission, 2014).

Productivity growth of national and regional innovation systems is measured by composite innovation indexes showing aggregated innovation activities by all innovation actors within a NIS (Lee & Lee, 2020). Various hybrid innovation indexes have been developed in the innovation literature. For instance, indexes such as the Technology Achievement Index (TAI) and a new technology capability index were created in the classical innovation literature. Cornell University, INSEAD, and the World Intellectual Property Organization (WIPO) have recently developed the Global Innovation Index (GII) (Lee & Lee, 2020).

In the same vein as the GII and empirical literature, this study constructed an African region innovation index using 28 African countries. The African region innovation index benchmarked African countries' innovation efficiency based on Africa's best-performing NIS. The African countries' common regional innovation policy goals informed benchmarking of NIS in the African region. Hence, NIS outside Africa were omitted from the study sample. Regional benchmarking of NIS from other world areas has been widely conducted. For instance, Halaskova et al. (2020), using a non-radial non-oriented Malmquist productivity index (MPI) DEA, found that out of the EU28 countries, Italy and Germany were the most efficient from 2010 to 2015.

Dobrzanski (2020) evaluated the efficiency of spending on R&D in the Latin American region between 2000 and 2017 using 15 countries. Constant Returns to Scale (CRS) and Variable Returns to Scale (VRS) input-oriented MPI-DEA models revealed that Chile, Guatemala, Honduras, and Panama were on the efficient CRS frontier. Notwithstanding, Brazil, Costa Rica, Mexico, Chile, Guatemala, Honduras, and Panama were on the efficient VRS frontier. Klevenhusen et al. (2020) investigated innovation efficiency in OECD countries using non-parametric approaches. The results indicated that 11 countries were on the efficient frontier.

A survey of the empirical literature suggests that the selection of inputs and outputs of NIS varies from region to region. The GII, for instance, classifies NIS outputs into creative outputs and scientific outputs such as patents, exports of high technology goods, and the publication of technical journals. The expected inputs into the NIS include indicators of the quality of institutions, market sophistication, infrastructure quality, human capital, and research (Cornell University INSEAD & WIPO, 2018; Lee & Lee, 2020). Other factors that enable catch-up and innovation diffusions across NIS, such as internet access, international trade, and credit access, also determine the productivity of NIS in developing regions (Cornell University INSEAD & WIPO, 2020; United Nations Conference on Trade and Development, 2021). Recent literature appreciates that innovation indicators in developing countries' NIS cannot be the same as those in developed economies. Social, economic, and political impediments still hinder the development of efficient, well-functioning NIS in developing countries (Casadella & Tahi, 2022).

In an efficient and highly ranked NIS, it is expected that knowledge flows freely among the innovation actors (government, industry, academia, and society) in an interconnected manner. Consequently, there are improved chances of ST&I collaborations among the innovation actors (Carayannis & Campbell, 2012). As a result, the firms have increased R&D expenditures and innovations within that NIS, improving firm productivity and increasing national output (Carayannis & Rakhmatullin, 2014). The national high production can be seen through increased high-technology exports, patent applications, scientific and technical journals, and intellectual property leasing gains. The realized knowledge within the RIS may also vary by sociodemographic factors of NIS, such as income per capita, population growth rates, education attainment, fertility, and life expectancy, among other factors (Casadella & Uzunidis, 2017). The empirical literature has confirmed the importance of the NIS and composite innovation index on economic growth (Lee & Lee, 2020).

Empirical literature indicates that most studies on regional innovation systems are based on the EU member countries and OECD countries. A few studies are from Latin America, Asia, and Oceania countries. There are virtually no studies examining cross-country innovation efficiency in Africa based on an economic model during the study period, and this study sought to bridge this gap in the empirical literature. Taking note of the varied implementation of the regional policies, efforts to catch up with the ST&I frontier, and the challenges facing NIS in Africa as a developing region, this study's overarching research question is "what has been the productivity of NIS in Africa over the past decade". In line with this, the study's central hypothesis is that the productivity, efficiency change, and technical progress of NIS in Africa have improved over time.

Methodology, Data, and Variables of Interest

Empirical Strategy

Productivity analysis of NIS hypothesizes a knowledge production function with inputs and outputs (Sagiyeva et al., 2018). A technology set, S, may be defined as

$$S = \{(x, y) : x \text{ can produce } y\} \tag{1}$$

where x denotes an n-dimensional vector of non-negative innovation inputs and y represents an n-dimensional vector of non-negative innovation outputs. The technology set S consists of all input-output vectors (x, y) such that x can produce y. The production technology defined by the set S may be equivalently defined using the output set, $p(x)$, which represents the set of all output vectors y that can be produced using the input vector x; the output vector is defined by

$$p(x) = \{y : x \text{ can produce } y\} = \{y : (x, y) \in S\} \tag{2}$$

The output set is referred to as production possibilities. Directional distance functions such as the non-parametric DEA are very useful in describing the production technology to make it possible to measure other things like productivity. Directional distance DEA models evaluate the productivity of Decision-Making Units (DMUs) along the given direction. DEA models can be classified into four categories: (1) radial, (2) non-radial and oriented, (3) non-radial and non-oriented, and (4) radial and non-radial (Tone & Tsutsui, 2014). The radial approach focuses on a proportionate change in input/output values, while a non-radial approach deals with slacks and does not assume a proportional change in outputs/inputs. Oriented models focus on either input reduction or output expansion, while non-oriented models simultaneously focus on input reduction and output expansion (Cooper et al., 2007; Tone & Tsutsui, 2010).

This study employed a non-radial, non-oriented MPI to correctly estimate African NIS productivity and technical progress over time. A non-radial measure-slacks-based model (SBM) was used to account for asymmetries between African NIS, making it possible to obtain non-uniform input/output factor efficiencies. A non-radial model that deals with input/output slacks directly estimates an efficiency score between 0 and 1. Additionally, the non-radial SBM gives an efficiency score of 1 when a DMU is on the efficient frontier with no input/output slacks. In that respect, the non-radial SBM differs from traditional radial measures of efficiency that do not take slacks into account and do not account for asymmetries of DMUs (Tone, 2002). DMUs in this study were assumed to have control over inputs and outputs. A non-oriented model that deals with input reduction and output expansion was considered to account for interactions of inputs and outputs. A non-oriented SBM model accounts for all inputs and output slacks. Moreover, a non-oriented model helps uncover the asymmetries of DMUs and the responsiveness of innovation outputs to innovation inputs, an analysis that is not possible under oriented models (Cantor & Poh, 2020; Tone, 2002).

When estimating DEA models, the returns to scale can either be constant (CRS) or variable (VRS) (Mattsson et al., 2020). As opposed to the VRS, the CRS was considered to assume that most DMUs were not operating at their optimal scales. The CRS non-radial non-oriented SBM Malmquist index's algebraic expression is presented in Tone (2002). The MPI represents the total factor productivity (TFP) of the DMU. It reflects progress or regress in the DMU's efficiency and progress or regress of the frontier technology. Therefore,

$$\mathrm{MPI} = (\mathrm{catch-up}) \times (\mathrm{frontier\ shift}) \tag{3}$$

The MPI is the geometric mean of the two efficiency ratios: the efficiency change measured by the period one technology and the efficiency change measured by the period two technology. Therefore,

$$\mathrm{MPI} = \left[\frac{\delta^1\left(\left(x_0, y_0\right)^2\right)}{\delta^1\left(\left(x_0,\ y_0\right)^1\right)} \times \frac{\delta^2\left(\left(x_0,\ y_0\right)^2\right)}{\delta^2\left(\left(x_0,\ y_0\right)^1\right)} \right]^{1/2} \tag{4}$$

The MPI consist of four terms: $\delta^1((x_0,y_0)^1)$, $\delta^2((x_0,\ y_0)^2)$, $\delta^1((x_0,\ y_0)^2)$, and $\delta^2((x_0,\ y_0)^1)$. The first two are related to measurement within the same period, while the last two are for intertemporal comparison. In the non-radial non-oriented MPI, the within and intertemporal scores are measured by the linear program given as

$$\delta^t\left(\left(x_0,\ y_0\right)^s\right) = \min_{\lambda,\ \ s^-,\ s^+} \left(1 - \frac{1}{m}\sum\nolimits_{i=1}^{m} {}^{s_i^-}/_{x_{io}^s}\right)/\left(1 + \frac{1}{q}\sum\nolimits_{i=1}^{q} {}^{s_i^+}/_{y_{io}^s}\right) \quad (5)$$

Subject to

$$x_o^s = X^t\lambda + s^- \quad (6)$$

$$y_o^s = Y^t\lambda - s^+ \quad (7)$$

$$L \leq e\lambda \leq U \quad (8)$$

$$\lambda \geq 0,\ \ s^- \geq 0,\ \ \ s^+ \geq 0 \quad (9)$$

The non-radial non-oriented SBM model measure of efficiency assumes that there are n DMUs with the input and output matrices $X=(x_{ij})\in R^{m\times n}$ and $Y=(y_{ij})\in R^{s\times n}$, respectively. $\lambda\geq 0$ is the positive intensity vector. The vectors $s^-\in R^m$ and $s^+\in R^s$ represent input excess and output shortfall, respectively. Equation (5) is the objective function that generates MPI and its components by simultaneously minimizing output shortfalls and input excess. Equations (6) and (7) are the optimization constraints. Equations (8) and (9) are the non-negativity constraints of the linear program (LP). These functional programs can be transformed into linear programming models that evaluate the non-radial non-oriented MPI and its components involving efficiency and technical changes (see Tone, 2002).

A set of second-stage regressions was conducted to investigate the determinants of the achieved level of technical progress, efficiency change, and productivity growth. In the second stage regression, the non-radial, non-oriented MPI efficiency scores were regressed on some social-demographic factors relating to African NIS, thereby identifying significant factors explaining variation in the African NIS efficiency levels. Simar & Wilson (2007) posit that the efficiency scores obtained in the first stage may be serially correlated. To overcome the statistical limitations of the DEA approach and enable the evaluation of statically significant factors determining the efficiency scores, Simar & Wilson (2007) suggested bootstrapped truncated regression procedures expressed as

$$\hat{\delta}_i = z_i\beta + \varepsilon_i \quad (10)$$

where $\hat{\delta}_i$ is the efficiency score (MPI, catch-up index and frontier shift index) of the i^{th} NIS at a given time t. z_i is a vector of socio-demographic factors influencing NIS efficiency scores. β is a vector of parameters to be estimated based on Maximum Likelihood Estimation (MLE). See Simar & Wilson (2007) for a detailed bootstrapping procedure and truncated regression.

Data Type, Source, and Challenges

One of the significant impediments to conducting NIS research in Africa is incomplete data. Data unavailability can be attributed to most AU member countries' weak NIS frameworks (AUDA-NEPAD, 2019). The AU and the ASTII initiative collect data on ST&I indicators from at least 20 AU member countries. However, the information is generally incomplete. Hence, this study used the World Bank's World Development Indicators. The period 2010–2018 was selected based on the availability of regional data and the implementation period of the ASTII initiative, the STISA 2014–2024 vision. The ASTII initiative has been implemented since 2007, while the STISA 2014–2024 has been in place since 2013. These two regional policies show the medium-term efforts towards investment in ST&I catch-up in Africa. Therefore, the period they have been in existence was ample to evaluate the African NIS productivity, efficiency change, and technical progress.

The selection of DMUs was based on the regional datasets available on ST&I indicators of 55 countries in Africa; 28 had extensive data, even though some gaps existed in some years. This study constructed a balanced panel covering nine years (i.e., 2010 to 2018). 27 African countries were dropped from the sample because of the high degree of missing information on ST&I indicators. The final sample considered for analysis included 4 North African countries (Morocco, Egypt, Tunisia, and Algeria), 7 South African countries (Zambia, Angola, South Africa, Botswana, Namibia, Mozambique, and Malawi), 9 Western African countries (Ghana, Cote d'Ivoire, Nigeria, Togo, Guinea, Senegal, Burkina-Faso, Niger, and Gambia), 6 Eastern Africa countries (Uganda, Mauritius, Tanzania, Kenya, Rwanda, and Madagascar), and 2 Central African countries (Cameroon and Burundi). According to the principle of DMUs and variable selection Banker et al. (1989) provided a sample of 28 DMUs was representative and sufficient for a non-parametric DEA analysis. The DMUs were selected from the African region since the authors intended to have a sample subjected to standard regional innovation strategies and targets.

Variables of Interest

Availability of regional dataset, ST&I catch-up, and empirical literature were the main factors considered in the choice of innovation input and output indicators. Since the concepts of the NIS and ST&I indicators in Africa are still in their initial development stages compared to other regions, data on most ST&I indicators from this region is incomplete. Following empirical literature, this study settled on two innovation outputs and three innovation inputs in African NIS. The innovation inputs include domestic credit provided by the financial sector as a percentage of GDP, imports of goods and services as a percentage of GDP, and fixed broadband subscriptions. The two innovation outputs included high-technology exports as a percentage of manufactured products and the number of scientific and technological journal articles. These variables are discussed in the subsequent section.

Most countries in Africa can be described as least developed or developing countries, and innovation in these countries has been described as a catch-up (United Nations Conference on Trade and Development, 2021). In developed areas like the EU and the OECD, the key input in the NIS analysis is R&D expenditure and R&D researchers. In contrast, Africa's innovation is predominantly a catch-up with unavailable R&D expenditure and researchers' data. Consequently, the author's selection of input variables also considered variables that can enable innovation catch-up and ST&I adoption or diffusion across the NIS. Therefore, access to domestic credit, Information Communication and Technology (ICT), and importation of goods and services were among the variables of interest in this study (United Nations Conference on Trade and Development, 2021).

Domestic Credit

This variable is measured as the total domestic credit provided by the financial sector annually within a country expressed as a GDP percentage. The financial sector, especially in developing regions, is considered a key player in the innovation process (Cornell University INSEAD & WIPO, 2020). In the empirical literature, access to credit has been associated with innovation because a cost is involved in ST&I adoption, and funding is required from financial institutions (Hirsch-kreinsen, 2011; Hsu, 2011).

Imports of Goods and Services

Importation of goods and services is measured as the annual total value of all goods and other market services as a percentage of GDP a country receives from the rest of the world. The GII uses it to compute business and market sophistication innovation input sub-index. International trade and importing influences innovation, especially in developing countries that import the much-needed R&D-intensive capital goods and services (Blind & Jungmittag, 2004; Lu & Ng, 2012; Nasierowski & Arcelus, 2003; Ramírez-Alesón & Fernández-Olmos, 2019).

Fixed Broadband Subscriptions

This variable is measured as the subscriptions to high-speed access to the public internet (a TCP/IP connection) at downstream speeds equal to or greater than 256 kbit/s. ICT infrastructure is critical in ST&I catch-up in developing economies (United Nations Conference on Trade and Development, 2021). ICT infrastructure access and usage have been associated with innovation in the empirical literature (Abdulqadir & Asongu, 2022; Kurniawati, 2020). In the empirical literature, the GII and Hollanders & Celikel-Esser (2007) have used internet access as indicated by fixed broadband subscriptions as an indicator of infrastructure quality innovation inputs in estimating NIS efficiency.

High-Technology Exports

High-technology exports are an innovation output indicator measured as a country's percentage of annual domestically manufactured exports of products with high R&D intensity, like machinery, pharmaceuticals, and computers (Matei & Aldea, 2012). High-technology exports have been widely used to analyze NIS's efficiency in developing and developed economies.

Scientific and Technological Journal Articles

This variable is measured annually by the number of scientific and technical journal articles published in Science, Technology, Engineering, and Mathematics (STEM). Scientific and technical journal articles are a significant innovation output in developed and developing economies NIS (Dobrzanski, 2020).

Socio-Demographic Variables

The study identified five social-demographic variables likely to influence the efficiency, technical efficiency, and productivity levels of the NIS in Africa. Table 1 summarizes the socio-demographic variables, their definition, and measurements, while Table 2 summarizes the innovation inputs and outputs of the African NIS.

Table 2 summarizes innovation input and output variables, their measurement units, sources, and the percentage of missing data points.

Data Cleaning and Descriptive Statistics

Completeness of data is required in efficiency calculations. The 5% average missing data points of the study variables were assumed to be missing at random and

Table 1 Definition and measurement of socio-demographic variables

Socio-demographic variables	Definition and measurement
Government expenditure on education	A Countries' total expenditure on education expressed as a percentage of GDP
Total fertility rate	Number of children that would be born to a woman if she were to live to the end of her childbearing years and bear children under age-specific fertility rates of the specified year
GDP per capita	Gross domestic product divided by midyear population measured in current U.S. dollars
Population growth	The annual population growth rate for year t is the exponential growth rate of the midyear population from year $t-1$ to t, expressed as a percentage
Life expectancy at birth	The number of years a newborn baby would survive if prevailing trends of mortality at the time of its delivery were to stay the same throughout its life

Source: *World Development Indicators data*

Table 2 Innovation input and output variables of the Africa regional innovation system

	Variable	Unit of measurement	Source	% missing data
Outputs	High-technology exports	% of manufactured products	United Nations	15%
	Scientific and technological journal articles	Number of journal articles	National Science Foundation, Science and Engineering Indicators	0%
Inputs	Fixed broadband subscriptions	Number of subscriptions	International Telecommunication Union	1%
	Imports of goods & services	% of GDP	World Bank Group	5%
	Domestic credit	% of GDP	World Bank Group	5%

Source: *World Development Indicators data*

all the variables included in the study were continuous. Multiple imputation criteria were used to fill in the missing data points (Kwadwo, 2018). Multivariate Normal Mode (MVN) and Multiple Imputation by Chain Equations (MICE) are the two main methods of multiple imputations. MVN assumes that partially complete data under consideration has a multivariate normal distribution. MICE assumes that data points are missing at random and uses regression to estimate the missing data points (White et al., 2011). MICE has been widely applied and has produced better estimates of missing data than MVN (Groothuis-oudshoorn, 2011). It was therefore used to address the missing data problem. Table 3 shows the descriptive statistics. Regional averages of the study variables were compared to the global average from the World Development Indicators.

Table 3 indicates that the standard deviation exceeded the mean for fixed broadband subscriptions input and the two output variables. When the standard deviation exceeds the mean, it implies high spread and high-scale heterogeneity in these three variables in the sample. On average, high-technology exports during the study period in Africa were 5% of the region's total manufactured goods, while the world average was 20%.

The mean number of scientific and technological journal articles published in the STEM area during the African region's study period was 1452. The African journal articles were 0.06% of the world's mean scientific journal articles published in this area. The fixed broadband subscriptions for the region were less than 0.01% of the world's average fixed-broadband subscriptions, which was an indicator of low internet access during the study period. The mean imports of goods and services as a percentage of GDP during the study period was about 38% against a world average mean of 29%. The mean imports of goods and services indicated an unbalanced balance of payments where more regional countries were importers. The mean domestic credit provided by the financial sector as a percentage of GDP was 38%. The domestic credit provided by the financial industry was considerably low compared to the world

Table 3 Descriptive statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max	World average
High-technology exports	252	4.82	6.73	0.03	60.3	19.34
Scientific and technological journal articles	252	1452	2777	9	13,326	2,246,545
Fixed broadband subscriptions	252	339,592	832,945	350	6,579,762	782,336,176
Imports of goods & services	252	38.72	13.53	10.79	84.22	29.08
Domestic credit	252	38	29.19	0.1	125.67	129.33
Government expenditure on education	224	4.55	1.729	1.777	10.639	4.5
Fertility rate	224	4.377	1.289	1.36	7.429	2.4
GDP per capita	224	2442.025	2450.629	238.034	11208.34	10,825
Population growth rate	224	2.458	0.792	0.055	3.907	1.2
Life expectancy	224	63.346	6.285	51.346	76.693	72

Source: *World Development Indicators data*

average of about 129% of GDP. This result points to limited financial access in the African region. The limited credit access also implies that the region's business and market sophistication was below the world average during the study period.

The summary statistics of the social demographic variables indicate that regional average government expenditure on education was at par with the world average. The mean fertility rate for the region was 4.4 for the region, compared to 2.4 world average. The mean GDP per capita in Africa was $2442 with a standard deviation of 2451. In summary, the descriptive statistics revealed that Africa's mean innovation outputs and inputs and the mean of the socio-demographic indicators considered were strikingly below the world average.

Empirical Results and Discussion

Summary of Annual Efficiency and Productivity Growths

This study used the CRS, non-radial, non-oriented MPI to estimate NIS productivity and the technical progress in Africa 2018–2010. Table 4 shows an annual average efficiency change (catch up—CU), technological progress (frontier shift—FS), and MPI from 2010 to 2018.

The non-radial non-oriented model's efficiency indices differ from the usual economic interpretation. For example, an efficiency score of 1.350 does not indicate a 35% growth but is interpreted as progress (Halaskova et al., 2020). Values of the indices larger than one show progress, and indices values less than one indicate a regress. However, the non-radial non-oriented model allows us to compare the degree of relative progress or regress between periods or between DMUs. For instance, Table 4 shows that the MPI of NIS in 2016/17 was better

Table 4 Average efficiency index measures, 2010–2018

Year	Efficiency change	Technical progress	Malmquist productivity index
2010/11	0.5100	0.8171	0.7201
2011/12	0.7968	0.8934	0.9696
2012/13	0.6349	0.8237	0.7843
2013/14	0.8913	0.8154	0.7932
2014/15	0.7469	0.5897	0.9510
2015/16	0.8391	0.9908	0.9086
2016/17	0.8242	0.9188	1.0159
2017/18	0.6501	1.3550	0.8541
Mean	0.7366	0.9005	0.8746
No. of years with progress	CU > 1 = 0	FS > 1 = 1	MI > 1 = 1
No. of years with regress	CU < 1 = 8	FS < 1 = 7	MI < 1 = 7

an index = 1 indicates efficient frontier, an index > 1 indicates progress, an index < 1 indicates regress than in 2017/18. Changes in the MPI can be attributed to technological progress (frontier shift) and efficiency change (the catch-up index). Adopting the best practice frontier and the movement of DMUs towards the efficient frontier are shown by technological change and efficiency change, respectively.

Table 4 shows that the African region experienced no change in average regional efficiency between 2010 and 2018. Average regional technical progress was experienced in the year 2017/18. Average regional productivity progress was experienced in 2016/17. The overall mean of annual average indices revealed an average of 0.7366, 0.9005, and 0.8746 for efficiency change, technological progress, and the Malmquist, respectively. Figure 1 shows a marginally increasing trend in the average regional efficiency change, average technological advancement, and average regional Malmquist productivity growth.

These results from Fig. 1 show that there has been marginal growth over the years in Africa's innovation efficiency of NIS. The marginal increase points to a successful foundation in catching up with the ST&I frontier, and an upward trend is expected even in the future.

The non-radial non-oriented model results revealed that six NIS in Africa recorded progress in the average productivity growth during the study period. Ghana recorded the highest average productivity growth, followed by Senegal, South Africa, Morocco, Nigeria, and Namibia. Furthermore, the results revealed that NIS in Ghana, South Africa, Nigeria, Kenya, and Tanzania experienced average efficiency change progress. Additionally, results showed that Senegal, South Africa, Nigeria, Tunisia, and Egypt's NIS experienced average technological progress during the study period. Furthermore, South Africa's and Nigeria's NIS improved in all three average efficiency measures, as shown in Table 5.

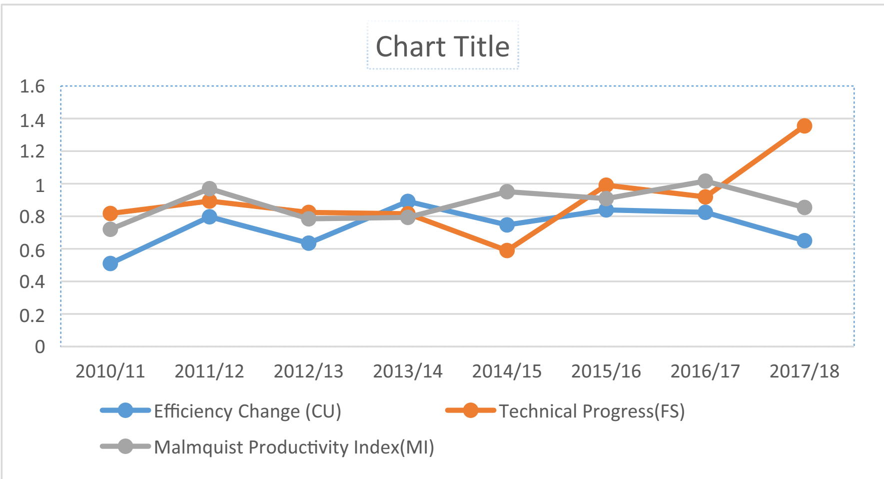

Fig. 1 The trend of efficiency change (CU), technical progress (FS), and productivity growth (MI) of Africa's regional innovation system 2010–2018

Table 5 Malmquist productivity index efficiency analysis of Africa's regional innovation systems, 2010–2018

Rank	DMUs	Efficiency change	Frontier shift	Malmquist productivity index
1	Ghana	1.03314	0.89178	1.205730
2	Senegal	0.89191	1.00143	1.113235
3	South Africa	1.00286	1.10552	1.103949
4	Morocco	0.78053	0.83967	1.054370
5	Nigeria	1.00000	1.05123	1.051235
6	Namibia	0.71716	0.88477	1.000956
7	Mozambique	0.63650	0.74013	0.993410
8	Tunisia	0.73071	1.19225	0.992092
9	Angola	0.67771	0.96842	0.961545
10	Kenya	1.05153	0.77012	0.958397
11	Botswana	0.60940	0.85473	0.957254
12	Cameroon	0.70006	0.76807	0.945159
13	Tanzania	1.03546	0.83229	0.899501
14	Egypt	0.68213	1.22941	0.889747
15	Guinea	0.44645	0.73918	0.845573
16	Togo	0.67511	0.84935	0.815395
17	Uganda	0.88316	0.99185	0.795296
18	Cote d'Ivoire	0.91259	0.88324	0.769299
19	Zambia	0.70033	0.90826	0.740995
20	Mauritius	0.48744	0.99356	0.686782
21	Rwanda	0.52014	0.66704	0.674517
22	Algeria	0.84752	0.80209	0.671266
23	Madagascar	0.83322	0.62959	0.665720
24	Burundi	0.49810	0.80464	0.644995
25	Burkina Faso	0.69225	0.66772	0.636865
26	Niger	0.72384	0.78076	0.607837
27	Malawi	0.69600	0.84058	0.603660
28	Gambia	0.27683	0.77950	0.478527

an index = 1 indicates efficient frontier, an index > 1 indicates progress, an index < 1 indicates regress. The ranking is based on descending order of the average Malmquist productivity index

Regional Efficiency Change (Catch-Up)

Efficiency analysis of DMUs identifies the best-performing DMUs on the efficient frontier. All other DMUs are benchmarked against the best-performing DMUs (Cooper & Lovell, 2000). This study's findings revealed that Nigeria and South Africa had the most efficient NIS in Africa since they were on the efficient frontier, as shown in Table 6. This study also sought to compare the distribution of efficiency change across Africa's five regions. The regions include East Africa, West Africa,

Table 6 Regional efficiency change of national innovation systems in Africa, 2010–2018

Region	DMU	2010–11	2011–12	2012–13	2013–14	2014–15	2015–16	2016–17	2017–18	Average	Progress years
Central Africa	Cameroon	0.300	0.860	0.379	0.403	1.565	1.153	0.293	0.648	0.700	2
	Burundi	1.000	0.045	0.448	1.631	0.033	0.092	0.674	0.062	0.498	2
Eastern Africa	Kenya	0.118	1.350	0.516	1.016	1.808	1.915	0.803	0.887	1.052	4
	Mauritius	0.300	1.435	0.494	0.060	0.068	0.822	0.179	0.542	0.487	1
	Tanzania	0.244	1.297	0.555	0.678	1.118	1.980	0.972	1.439	1.035	4
	Rwanda	1.000	0.066	0.374	0.176	1.000	0.272	0.272	1.000	0.520	3
	Uganda	1.824	1.090	0.064	1.369	0.475	1.050	0.194	1.000	0.883	5
	Madagascar	0.696	0.194	0.295	1.891	1.611	0.392	0.738	0.849	0.833	2
Southern Africa	Angola	0.218	0.931	0.708	1.196	0.875	0.415	1.059	0.021	0.678	2
	Zambia	0.174	0.078	0.748	0.871	0.494	1.825	0.969	0.445	0.700	1
	South Africa	1.000	1.000	1.000	0.860	1.163	1.000	1.000	1.000	1.003	7
	Botswana	0.728	1.173	0.281	1.052	0.158	0.535	0.293	0.655	0.609	2
	Namibia	0.225	1.198	1.028	0.926	0.789	0.308	0.940	0.323	0.717	2
	Mozambique	0.037	0.347	0.219	0.840	1.151	0.404	1.675	0.420	0.637	2
	Malawi	1.000	0.422	0.235	1.182	0.490	0.239	1.000	1.000	0.696	4
Western Africa	Burkina Faso	0.205	1.481	0.640	0.236	0.990	0.883	1.074	0.028	0.692	2
	Cote d'Ivoire	0.831	0.608	0.649	1.020	1.472	0.908	1.164	0.650	0.913	3
	Gambia	1.000	0.098	0.098	0.004	0.183	0.157	0.127	0.548	0.277	1
	Ghana	0.341	1.889	0.801	0.974	1.664	1.051	0.410	1.135	1.033	4
	Guinea	0.402	0.069	0.060	0.060	1.000	1.000	0.348	0.633	0.446	2
	Niger	0.083	0.083	1.000	1.000	1.000	0.168	1.328	1.128	0.724	5
	Nigeria	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	8
	Senegal	0.415	1.042	0.626	1.393	0.488	1.648	0.815	0.709	0.892	3
	Togo	0.366	0.717	0.575	1.133	0.450	0.378	0.374	1.408	0.675	2
Northern Africa	Algeria	1.000	1.000	1.000	1.000	0.017	1.877	0.455	0.431	0.848	5
	Egypt	0.235	1.000	1.000	1.000	1.000	1.000	0.111	0.111	0.682	5
	Morocco	0.409	1.018	0.541	1.076	0.266	0.957	1.309	0.668	0.781	3
	Tunisia	0.531	0.784	0.490	1.006	0.288	1.028	1.031	0.688	0.731	3

an index = 1 or index > 1 indicates years with progress in efficiency change, and an index < 1 shows the years with regress in efficiency change

North Africa, South Africa, and Central Africa. The study also sought to evaluate the number of periods with progress.

The distribution of efficiency change in East and Central Africa revealed that Rwanda and Uganda were on Africa's efficient frontier for three periods and one period, respectively, during the study period. Kenya, Uganda, and Tanzania had experienced the highest number of years with progress in efficiency change. In the southern region of Africa, South Africa was on the efficient frontier for seven years, while on average only South Africa had recorded progress in efficiency change. Malawi was catching up with the region's efficient frontier in the same area. In West Africa, Nigeria was on the efficient frontier throughout the study period, while Niger and Ghana recorded the highest number of years with efficiency progress. On average, only Nigeria and Ghana experienced a gain in efficiency change during the study period. In Northern Africa, Egypt and Algeria recorded the most progress in efficiency change, as shown in Table 6.

Regional Technical Progress (Frontier Shift)

Technological progress is adopting the best practice frontier or the production frontier's shift. Table 7 shows that no country improved in East and Central Africa's average technical change during the study period. Mauritius and Tanzania had more periods of technological advancement in this region.

Only South Africa had experienced progress in the mean technical change in Southern Africa, while Namibia experienced the highest number of periods with technological progress. Further, only Nigeria and Senegal gained technical progress, while Cote d'Ivoire and Nigeria had the highest periods of technical progress in Western Africa. Egypt, Morocco, and Tunisia experienced the highest number of years with technological advancement in Northern Africa. Additionally, Egypt and Tunisia had gained average technical progress over the study period.

Regional Total Factor Productivity Growth (Malmquist Productivity Index)

Total factor productivity growth of DMUs is usually indicated by technological progress and efficiency change of DMUs (Heshmati & Rashidghalam, 2019). This study's findings revealed that Kenya, Uganda, and Tanzania had the highest number of years of productivity growth in the East and Central Africa regions. The results indicated that Namibia, Angola, and South Africa had the highest number of years with productivity growth in the Southern Africa region. Further, Namibia's and South Africa's average productivity growth shows progress during the study period. Senegal, Ghana, and Nigeria in Western Africa had the highest number of periods with productivity progress during the study period. Moreover, Table 8 shows that Morocco and Egypt from Northern Africa experienced productivity growth with the highest number of years with progress.

Table 7 Regional technical progress of national innovation systems in Africa, 2010–2018

Region	DMU	2010–11	2011–12	2012–13	2013–14	2014–15	2015–16	2016–17	2017–18	Average	Progress years
Central Africa	Cameroon	0.337	0.946	0.363	0.714	0.512	0.715	1.027	1.530	0.768	2
	Burundi	0.449	0.624	1.653	0.787	0.053	0.264	1.023	1.584	0.805	3
Eastern Africa	Kenya	0.405	0.932	0.481	0.915	0.510	0.674	1.050	1.195	0.770	2
	Mauritius	0.460	1.193	1.626	0.884	0.252	1.274	0.873	1.386	0.994	4
	Tanzania	0.360	0.979	1.370	1.003	0.394	1.008	1.075	0.469	0.832	4
	Rwanda	0.397	0.865	1.996	0.305	0.183	0.308	0.252	1.029	0.667	2
	Uganda	1.834	0.957	0.329	0.877	0.424	0.880	1.016	1.618	0.992	3
	Madagascar	0.231	0.728	0.323	0.766	0.355	0.825	0.836	0.972	0.630	0
Southern Africa	Angola	0.219	0.995	1.550	0.960	0.928	0.647	1.080	1.369	0.968	3
	Zambia	0.475	0.872	1.156	0.957	0.739	0.518	0.963	1.586	0.908	2
	South Africa	1.008	1.059	1.006	1.465	1.182	1.113	1.023	0.989	1.106	7
	Botswana	1.927	0.711	0.245	0.740	0.282	1.191	0.728	1.014	0.855	3
	Namibia	0.243	1.019	1.018	1.103	0.678	0.555	1.073	1.389	0.885	5
	Mozambique	0.099	0.680	0.391	1.052	0.871	0.355	1.004	1.469	0.740	3
	Malawi	0.434	0.586	1.839	0.776	0.504	1.045	0.712	0.828	0.841	2
Western Africa	Burkina Faso	0.209	0.866	0.252	0.587	0.290	0.830	0.910	1.398	0.668	1
	Cote d'Ivoire	0.189	1.034	1.146	1.096	0.459	0.720	1.041	1.381	0.883	5
	Gambia	0.847	0.467	0.484	0.455	0.298	1.124	0.670	1.891	0.780	2
	Ghana	0.461	0.932	1.334	0.882	0.510	0.944	0.789	1.283	0.892	2
	Guinea	0.431	0.119	0.147	0.292	0.243	1.742	1.243	1.697	0.739	3
	Niger	0.299	0.606	0.200	0.811	0.134	1.686	0.934	1.577	0.781	2
	Nigeria	1.256	1.070	1.025	1.139	1.000	0.762	1.029	1.128	1.051	7
	Senegal	1.983	0.877	0.407	0.906	0.745	0.567	1.082	1.444	1.001	3
	Togo	1.952	0.861	0.274	0.406	0.390	1.023	0.688	1.200	0.849	3
Northern Africa	Algeria	0.864	0.954	0.529	0.102	0.522	1.083	0.793	1.569	0.802	2
	Egypt	1.122	1.985	1.010	0.483	1.349	1.871	0.948	1.066	1.229	6
	Morocco	0.473	1.060	0.481	1.045	0.315	1.064	0.812	1.468	0.840	4
	Tunisia	1.850	1.114	1.980	1.054	0.355	0.980	0.854	1.352	1.192	5

an index = 1 or index > 1 indicates years with progress in technical progress, and an index < 1 shows the years with regress in technical progress

Table 8 Regional productivity growth of national innovation systems in Africa, 2010–2018

Region	DMU	2010–11	2011–12	2012–13	2013–14	2014–15	2015–16	2016–17	2017–18	Average	Progress years
Central Africa	Cameroon	0.890	0.814	1.044	1.771	0.802	0.824	0.426	0.991	0.945	2
	Burundi	0.449	0.028	0.740	1.284	1.584	0.346	0.689	0.039	0.645	2
Eastern Africa	Kenya	0.291	1.258	1.073	0.929	0.921	1.291	0.843	1.061	0.958	4
	Mauritius	0.652	1.712	0.803	0.053	0.271	1.048	0.205	0.751	0.687	2
	Tanzania	0.678	1.270	0.761	0.680	0.440	1.996	1.045	0.326	0.900	3
	Rwanda	0.397	0.057	0.188	1.734	0.183	0.884	0.924	1.029	0.675	2
	Uganda	0.299	1.044	0.195	1.200	0.893	0.924	0.191	1.618	0.795	3
	Madagascar	0.332	0.141	0.915	1.449	0.572	0.475	0.617	0.825	0.666	1
Southern Africa	Angola	0.993	0.926	1.097	1.148	0.811	1.558	1.144	0.015	0.962	4
	Zambia	0.083	0.068	0.865	0.833	1.496	0.945	0.933	0.706	0.741	1
	South Africa	1.008	1.059	1.006	1.259	1.375	1.113	1.023	0.989	1.104	7
	Botswana	1.402	0.834	1.150	0.779	1.789	0.637	0.403	0.664	0.957	3
	Namibia	0.927	1.221	1.046	1.021	0.535	1.800	1.009	0.448	1.001	5
	Mozambique	0.367	1.959	0.558	0.883	1.003	0.878	1.682	0.617	0.993	3
	Malawi	0.434	0.247	0.433	0.917	1.029	0.229	0.712	0.828	0.604	1
Western Africa	Burkina Faso	0.980	1.283	0.393	0.402	0.287	0.733	0.977	0.040	0.637	1
	Cote d'Ivoire	0.227	0.629	0.744	1.118	0.675	0.653	1.212	0.897	0.769	2
	Gambia	0.847	0.046	0.047	0.002	1.625	0.140	0.085	1.036	0.479	2
	Ghana	0.739	1.760	1.069	0.859	0.848	0.991	1.923	1.456	1.206	4
	Guinea	0.932	1.730	0.406	0.204	0.243	1.742	0.433	1.075	0.846	3
	Niger	0.278	0.138	0.200	0.811	0.134	0.284	1.240	1.778	0.608	2
	Nigeria	1.256	1.070	1.025	1.139	1.000	0.762	1.029	1.128	1.051	7
	Senegal	0.822	0.914	1.539	1.262	1.528	0.934	0.882	1.024	1.113	4
	Togo	0.188	0.617	0.477	0.460	0.867	0.387	1.839	1.689	0.815	2
Northern Africa	Algeria	0.864	0.954	0.529	0.102	0.009	0.492	1.744	0.676	0.671	1
	Egypt	0.209	1.985	1.010	0.483	1.349	1.871	0.105	0.104	0.890	4
	Morocco	0.865	1.079	1.124	1.124	1.182	1.018	1.062	0.981	1.054	6
	Tunisia	0.983	0.873	0.970	1.060	1.233	1.007	0.880	0.930	0.992	3

an index = 1 or index > 1 indicates years with progress in productivity growth, and an index < 1 shows the years with regress in productivity growth

Bootstrapped Truncated Regression

In RIS, the efficiency scores vary widely, as seen in the distribution of efficiency, technical efficiency, and MPI index. This study identified five social demographic indicators and regressed them on the various efficiency scores to investigate the determinants of NIS efficiency scores. Specifically, the study investigated whether NIS with specific social-demographic characteristics had more productive NIS. A bootstrapped truncated regression was conducted, and the results are indicated in Table 9.

The results in Table 9 indicate that public expenditure on education, life expectancy, and fertility rate had no significant effects on the three efficiency measures. Even though it can be noticed that government expenditure on education had a positive effect and the fertility rate and life expectancy had a negative effect, GDP per capita and population growth rate are the most significant determinants of the productivity performance of NIS in Africa. For instance, a NIS unit increase in GDP per capita leads to a 0.386 unit increase in efficiency change, 0.348 units increase in technical efficiency, and 0.371 units increase in MPI. On the other hand, one unit increase in NIS's population growth will lead to a 0.599-unit increase in efficiency change and a 0.266-unit increase in technical progress.

Discussion

Collection of ST&I data, enhancement of NIS infrastructure and the institutional framework, evaluation of economic impacts of ST&I, and productivity analysis of NIS studies in Africa are still in their infancy. As a result, ST&I data in Africa is very scanty and incomplete. Nonetheless, based on theoretical literature central to developing regions, this study identified two innovation output indicators and three innovation input indicators helpful in analyzing the productivity and ST&I catch-up of NIS in Africa. In addition, data availability, empirical literature, and catch-up

Table 9 Results of the bootstrapped truncated regression

Social-demographic variables	Efficiency change (effch)		Technical change (techch)		Malmquist productivity index (MPI)	
	Coefficient	Bootstrapped Std. error	Coefficient	Bootstrapped Std. error	Coefficient	Bootstrapped Std. error
Government expenditure on education	0.036	0.047	0.013	0.028	0.033	0.038
Fertility rate	−0.303	0.201	−0.126	0.117	−0.197	0.150
GDP per capita	0.386*	0.222	0.348**	0.163	0.371**	0.188
Population growth rate	0.599**	0.299	0.266*	0.158	0.264	0.220
Life expectancy	−0.011	0.016	0.003	0.011	−0.018	0.014
Constant	−0.298	1.639	−0.658	1.209	0.752	1.508
Sigma	0.651***	0.887	0.584***	0.072	0.601***	0.074

$N=224$, bootstrap replications (1000); *, **, and *** indicate statistical significance at 10%, 5%, and 1% levels, respectively enabling factors also guided the NIS's choice of inputs and outputs (Casadella & Tahi, 2022; United Nations Conference on Trade and Development, 2021).

This study investigated the productivity of NIS in Africa from 2010 to 2018 using a non-radial, non-oriented MPI. The empirical results indicate that 18% of Africa's NIS had experienced efficiency change and technical progress, while 21% had experienced total factor productivity growth during the study period. Nigeria and South Africa were on the African regions' efficient frontier. Senegal and Ghana had the most productive NIS during the study period. The past studies' general results reveal asymmetries of NIS within regional innovation systems (Yuezhou Cai, 2012; Dobrzanski, 2020; Ekinci & Karadayi, 2017; Halaskova et al., 2020; Matei & Aldea, 2012). Similarly, this study's results indicate that Africa's NIS varies widely.

Regional efficiency measure results showed no progress in the average regional efficiency change over the study period. The results indicated that regional technical progress was experienced only in 2017/18, while regional productivity was only experienced in 2016/17. The findings suggest that Africa had achieved little productivity progress in regional innovation over the study period.

The distribution of innovation efficiency scores across Africa was not uniform but was concentrated in some areas within the region. For instance, the Kenyan NIS has achieved productivity progress in most years in East and Central Africa. Further, South Africa from the southern part of Africa, Nigeria from West Africa, and Morocco from North Africa had also achieved substantial productivity progress than their counterparts in the respective regions. Analyzing productivity in the five geographical areas indicates that some African countries have made considerable progress in investing and catching up with the ST&I frontier. The study further attempted to investigate the determinants of the achieved levels of NIS efficiency. The findings indicated that GDP per capita and population growth are the significant factors determining the efficiency performance of NIS in Africa.

In addition, the unevenness of the NIS in Africa can also be attributed to the varied implementation of the regional innovation policies, where different countries are at various implementation stages. For instance, some countries are still putting the ST&I institutional framework in place, while others are still conducting national R&D surveys and strengthening their NIS frameworks. Indeed, one-half of Africa's countries were excluded from this study's sample due to insufficient data. Despite the challenges encountered by NIS in developing regions like Africa for the past decade, the trend shows marginal growth in technical progress, efficiency change, and productivity change. The marginal increase of efficiency measures in Africa signifies that the past decade of laying the foundation of ST&I investment has been successful.

Conclusions, Policy Implications, and Areas of Further Research

This study sought to analyze the productivity of NIS in Africa from 2010 to 2018. This study established the African regional innovation systems' relevant innovation input/output indicators based on theoretical foundations of innovation in developing regions. Consequently, the NIS innovation output indicators in this study include high-technology exports of manufactured products and scientific and technological journal articles. On the other hand, innovation inputs are indicated by domestic credit provided by the financial sector as a percentage of GDP, imports of goods and services as a percentage of GDP, and fixed broadband subscriptions. ST&I catch-up enabling factors were a critical consideration in choosing study variables. We further support the fact that NIS indicators in developing economies cannot be viewed through the same lens as in the case of developed economies NIS. Most African countries continue to collect R&D data through their national R&D surveys and publishing reports. As more countries conduct R&D surveys, more innovation input/output indicators will be available for analysis.

This study investigated the productivity and asymmetries of NIS in Africa over the past decade. The findings suggest little progress had been realized over the past decade since only a quarter of Africa's sampled NIS had achieved productivity progress. The results further revealed that GDP per capita and population growth rate are the most significant factors influencing the efficiency performance of NIS in Africa. Determining the levels and determinants of productivity and technical advancement of NIS is crucial in evaluating Africa's innovation vision. Assessing whether there has been productivity progress or regress indicates the innovation efficiency stance of NIS in Africa. The findings suggest that marginal growth was experienced during the study period, and there is potential for further growth in the coming decades.

Evaluation of African NIS productivity over time can also indicate the effectiveness of regional innovation policies and strategies. As much as the authors did not conduct an impact evaluation of the regional policies, it is clear that it might be too early to investigate the effectiveness of ST&I policies since not all countries in Africa have fully adopted them. Furthermore, the ST&I policies have been implemented to varying degrees. Nonetheless, the results indicated marginal productivity growth in the region. The annual country-by-country analysis showed that each country had at least some progress in some of the years during the study period; then, it cannot be claimed that the ST&I policies and efforts are ineffective.

Analyzing NIS performance over time makes it possible to know the best-performing NIS in Africa that other NIS can use as a benchmark to enhance regional growth. The findings indicate that innovation activities in Africa are non-uniform. Further, in each of the five geographical regions in Africa, some NIS perform better than their counterparts in catching up with the regional ST&I frontier. However, the findings indicate that there is still room for productivity improvement. Consequently, the finding's implication to policy is that benchmarking with the best-performing DMUs and cross-country stakeholders' collaborative ST&I efforts are necessary to enable all DMUs to catch up with the efficient ST&I frontier in Africa. The benchmarking practices will encourage the free flow and diffusion of knowledge across Africa's five regional blocks. Further, regional collaborative ST&I efforts such as joint investment in ST&I projects, regional patenting or licensing of intellectual properties, knowledge infrastructure, and R&D personnel sharing may enhance regional innovation productivity. Lastly, population growth leading to the evolution of new generations and their economic well-being through the GDP per capita are some of the critical factors that can leverage the African innovation dream.

Lastly, just as in most scientific research, this study suffers from limitations that raise further research avenues. Compared to other regions of the world, the concept of a NIS is still in its infancy in Africa. Furthermore, Africa is a developing region still lagging in catching up with the ST&I frontier, and incomplete ST&I data is a fundamental limitation. Data on some innovation inputs like R&D personnel, business and government expenditure on R&D, and innovation outputs like patents are scanty, among other intellectual properties. Thus, a future research avenue arises to include these key innovation inputs and output indicators in Africa's regional innovation system efficiency analysis, as is the case for studies conducted in developed regions.

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Declarations

Conflict of Interest The authors declare no competing interests.

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