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The interplay between technological innovation and human capital development in driving industrial productivity and competitiveness in Africa

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Abstract
Purpose – This study examines how technological innovation (TECIN) and human capital development (HCD) combine to impact industrial productivity (INPR) and competitiveness in Africa.
Design/methodology/approach – The study used secondary data covering the period from 1996 to 2021 on 36 African countries, in a panel data framework of fixed effect and generalized method of moments techniques.
Findings – The study found that while TECIN negatively affected INPR in Africa, HCD exerted a strong positive influence. The interaction of TECIN and HCD showed a joint positive impact on INPR, emphasizing the role of human capital in mitigating transitional productivity loss tied to new technology assimilation. The results also showed positive individual and combined effects of TECIN and HCD on industrial competitiveness in Africa.
Practical implications – The findings therefore compel the need for implementation of policies that can simultaneously advance TECIN and strengthen HCD for sustainable industrial development in Africa. Governments in African countries need to allocate more resources to research and development to foster home-grown technologies, revamp educational curricula to align with industry needs and emphasize practical skills training, and facilitate technology transfer partnerships to enhance technological capabilities and INPR.
Originality/value – Although previous studies acknowledge the importance of TECIN and HCD for enhancing INPR and competitiveness in Africa, there is a noticeable lack of comprehensive studies that investigated the interplay between TECIN and HCD for industrialization gains.

Keywords Technological innovation, Human capital development, Industrial productivity, Industrial competitiveness, Africa
Paper type Research paper

1. Introduction
The convergence of technological innovation (TECIN) and human capital development (HCD) is reshaping global economies and revolutionizing the approaches used by firms to produce and market their goods and services. Both factors offer significant potential in driving innovation, enhancing operational efficiencies and improving economic prospects (Dahlman *et al.*, 2016). However, the dynamics of TECIN and HCD have not been uniformly distributed across regions (Gaglio *et al.*, 2022).

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The economic growth strategies of many developed countries have revolved mainly around the Industrial Revolution, powered through deliberate but thoughtful processes of developing and usage of indigenous innovation across productive sectors coupled with significant investment in HCD, which led to a substantial increase in total factor productivity, and ultimately increased economic growth and development (Fu *et al.*, 2018). As noted by Fagerberg *et al.* (2010), the growth trajectory of low-income countries is not entirely different. It involves a combination of capital, skills and ideas as well as their organization in generating localized knowledge, which helps in improving firms' capabilities.

Africa's economic development has witnessed significant growth in recent years, yet industrial productivity (INPR) and competitiveness remain key challenges for the region. The continent's potential for growth and development largely depends on its ability to leverage TECIN and develop a skilled workforce to stay competitive in the global market. Despite abundant natural resources and a growing population, Africa faces considerable hurdles in achieving sustainable industrialization. Many countries on the continent are trapped in low-productivity economies characterized by low value-added activities, poor technology adoption and underdeveloped human capital. Furthermore, many African countries struggle to achieve sustainable industrial growth, resulting in low productivity and a narrow range of competitive products in the global market. This low level of INPR and competitiveness hampers the continent's potential to attract investments, increase exports and create sustainable economic growth.

The "Digital Transformation Strategy for Africa 2020–2030" by the African Union (AU) emphasizes the pivotal role of digital transformation in driving innovative, inclusive and sustainable growth towards achieving Agenda 2063 and the Sustainable Development Goals. This strategic vision recognizes the present moment as a crucial opportunity for leapfrogging advancement across the continent. It highlights that African countries with fewer legacy challenges have the potential to embrace digitized solutions at an accelerated pace, enabling them to capitalize on the benefits of digitalization and achieve faster progress in their socio-economic development. Although some countries on the continent have identified the crucial role of TECIN in driving productivity and competitiveness to power economic growth and have made it a crucial component of their developmental initiatives, the rate of TECIN on the continent remains low, leaving a huge technological gap.

The Global Innovation Index (GII) (2022) [1] highlights the overall inadequacy of the TECIN ecosystem in Africa. Within the African continent, Mauritius emerged as the highest-ranking economy in terms of innovation, securing the 45th position out of 132 countries ranked globally. With an innovation score of 34.4, Mauritius is the only African nation to feature among the top 50 most innovative economies in the world. Following closely behind, South Africa attains a score of 29.8, earning it the 61st rank, while Morocco achieves a score of 28.8, placing it at the 67th position. Tunisia secures a score of 27.9 and holds the 73rd spot among the innovative economies worldwide. Of greater concern is the fact that 17 out of the lowest-ranking 20 nations are African countries.

While existing literature acknowledges the importance of TECIN and HCD for enhancing INPR and competitiveness in Africa, there is a noticeable gap in comprehensive studies that simultaneously investigate the interplay between these two factors. Most research studies in this domain tend to focus on either TECIN (Fu *et al.*, 2018; Edeh and Acedo, 2021; Gaglio *et al.*, 2022) or HCD (Abubakar *et al.*, 2015; Eigbiremolen and Anaduaka, 2014; Okunade, 2018; Babasanya *et al.*, 2018; Okunade *et al.*, 2022) separately, rather than examining their combined influence on industrial growth in the African context. Although Oyinlola *et al.* (2021) studied the indirect effect of human capital through innovation, however, the study centered on inclusive growth and not INPR, and was limited to just 17 sub-Saharan Africa countries. Consequently, a crucial gap exists in understanding how the convergence of TECIN and HCD can synergistically drive INPR and competitiveness in Africa.

This gap in the literature is significant because TECIN and HCD are intrinsically linked and mutually reinforcing elements in the growth of industrial sectors. TECIN, such as the adoption of advanced manufacturing processes and digital technologies, can lead to increased productivity, efficiency and product quality. However, without a skilled and adaptable workforce capable of effectively utilizing these technologies, the full potential of innovation cannot be realized. Conversely, investing in HCD, including education, vocational training and talent retention strategies, fosters a skilled workforce capable of embracing technological advancements and driving innovation within industries. However, the absence of TECIN may limit the range of opportunities available to the skilled workforce, potentially leading to underutilization of human capital.

By examining the interplay between TECIN and HCD, this study provides insights into how African countries can effectively align these two critical components to boost INPR and enhance competitiveness in the global market. It addresses the need for a comprehensive approach that considers both factors in policy formulation and strategic planning to foster sustainable and inclusive industrial growth in Africa.

Thus, the outcomes of this study will have significant implications for policy formulation and strategic planning at both the national and regional levels. Policymakers can leverage the findings to design comprehensive industrial development strategies that prioritize both TECIN and HCD. Emphasizing this synergy can lead to the creation of conducive environments that attract investments, foster innovation and strengthen the industrial base in Africa. Furthermore, businesses can use the insights to optimize their recruitment, training and technology adoption strategies to remain competitive in rapidly evolving markets.

2. Literature review

The relationship among INPR, competitiveness, TECIN and HCD has roots in economic growth theories. The endogenous growth theory, as advanced by economists such as Romer (1990), Grossman and Helpman (1991), and Uzawa (1965), identifies research and development (R&D) and human capital as the primary drivers of long-term productivity growth. R&D is fundamental to endogenous growth theory because it leads to TECIN, which is essential for increasing productivity. By investing in R&D, firms and economies can innovatively create new products, enhance production processes and improve efficiencies. The continuous cycle of innovation spurred by R&D efforts drives economic growth by enabling industries to produce more with the same or fewer resources (Ghosh and Parab, 2021). On the other hand, human capital, which is defined as the skills, knowledge and experience possessed by individuals, is another critical driver of productivity growth. Investments in education and training enhance the capabilities of the workforce, making it more skilled at developing and utilizing new technologies. A well-educated and skilled workforce can better engage in innovative activities, adapt to technological changes and improve industrial processes, thereby boosting productivity. However, the interaction between R&D and human capital is synergistic. R&D activities often require a highly skilled and educated workforce to conduct advanced research and implement new technologies for production. Conversely, advancements in technology can enhance the effectiveness of education and training programs by providing new tools and methods for production (Tetteh, 2024).

The review of empirical literature has been undertaken through the lens of four distinct thematic areas, aiming to gain a deeper understanding of the interplay between the variables of interest. The first and second strands of the review focused on exploring existing literature that shed light on the connections between TECIN and INPR, as well as TECIN and industrial competitiveness. Subsequently, in the third and fourth strands, previous studies that specifically investigated the relationship between HCD and INPR, and in parallel, the relationship between HCD and industrial competitiveness were reviewed.

Romer (1986) introduced the idea of TECIN spillovers into the production function, sparking extensive research into the impact of TECIN on productivity. Numerous studies have explored the relationship between TECIN and INPR, consistently finding a strong connection.

Following Mohnen and Hall (2013) and Crespi and Zuniga (2012), this review examines both product/process innovations and their links to productivity. Aboal and Garda (2016) found that both technological and non-technological innovations boost productivity in services, with non-technological innovations playing a larger role. Álvarez *et al.* (2015) extended these findings to the manufacturing sector in Chile. Jung *et al.* (2017) confirmed that TECIN drives productivity and economic growth, while Crowley and McCann (2018) highlighted sectoral differences in productivity enhancements due to TECIN. Wu and Du (2018) demonstrated that independent innovation significantly boosts economic growth and INPR, while Yu and Dong (2018) showed that technological progress improves industrial structure by fostering new industries and optimizing existing ones. Masso and Vahter (2008) specifically noted that product innovation enhanced productivity in Estonian manufacturing firms from 1998 to 2000. Zheng *et al.* (2023) noted that it is TECIN that directly determines INPR growth. However, the authors also considered that as technology advances within an industry, there comes a point where productivity growth starts to slow down due to natural or economic constraints. Eventually, it reaches a standstill, and this is when the INPR dilemma arises. Wadho and Chaudhry (2022) confirmed thus productivity dilemma in a study on manufacturing firms in Pakistan, showing that product innovation initially negatively impacts productivity due to disruptions and challenges in adopting new processes and equipment. This productivity loss is notable during the early stages of new technology implementation. Other studies (Chudnovsky *et al.*, 2006; Goedhuys, 2007; Raffo *et al.*, 2008) reported no significant effect of innovation on firm productivity. While Romer's seminal work and other subsequent studies confirm the critical role of TECIN in driving productivity and economic growth, their findings highlight the need for innovation-friendly environments while acknowledging the potential initial negative impacts of TECIN on productivity.

While the previous review focused on the link between TECIN and productivity, the following studies examined the relationship between TECIN and industrial competitiveness. Scholars highlight the role of TECIN in driving competitive advantage by expediting the introduction of new products and advanced processes, essential for sustaining competitiveness (Freeman, 1994; Sen and Egelhoff, 2000; Simmie, 2004). Chatterjee *et al.* (2022) found that firms' innovation capability positively influences competitiveness, while Guan *et al.* (2006) reported mixed results. Mulkay (2019) suggests that increased competition may hinder innovation for many firms, especially those with smaller market shares. Conversely, Kiveu *et al.* (2019) found positive effects of process, marketing and organizational innovations on competitiveness for Kenyan manufacturing SMEs. Similarly, Efendi *et al.* (2020) observed similar trends for Indonesian manufacturing SMEs, supported by the findings of Khyareh and Rostami (2022) of a positive impact of innovative activities on competitiveness. Thus, there are some differing views on the role of TECIN on industrial competitiveness. Some studies reported positive associations, noting that TECIN capability is crucial for achieving long-term competitive advantage, enabling firms to quickly introduce new products and adopt advanced processes (Freeman, 1994; Simmie, 2004; Chatterjee *et al.*, 2022). However, Guan *et al.* (2006) found no significant link at the firm level, while Mulkay (2019) noted that intense competition can hinder innovation, especially in product development.

In the third strand of this review, the study reviewed the related studies on the link between HCD and productivity. Miller and Upadhyay (2000) found a positive impact on total factor productivity across various specifications, except for low-income countries where an initial negative effect was observed, which turned positive with increased trade openness (TRO). Abrigo *et al.* (2018) noted a positive effect of human capital investments on labor productivity and overall economic output. Ramírez *et al.* (2020) found that human capital affects R&D investment decisions, innovation behavior and labor productivity in Colombian manufacturing. Similarly, Escosura and Rosés (2010) observed a modest positive contribution of human capital to labor productivity growth in Spain by facilitating TECIN. Li (2014) highlighted the direct productivity-enhancing role of human capital in the Canadian tourism/hospitality industry, consistent with Samargandi's (2018) findings for the MENA region. Mason *et al.* (2012) and Huang *et al.* (2019) also support the importance of human capital for total factor productivity growth in various contexts. Similar findings are observable for Greece in Benos and Karagiannis (2016) and for Europe in Azorín and Sánchez de la Vega (2015), Corvers (1997), Fischer *et al.* (2009) and Mačiulytė-Šniukienė and Matuzevičiūtė (2018). Studies in Africa on the link between human capital and productivity have reported mixed findings. For instance, Okunade *et al.* (2022) reported positive but insignificant effects of human capital on productivity in a sample of 17 African countries, and that human capital needs to reach a threshold level before it can meaningfully contribute to productivity growth. Whereas, Osei (2024) found that human capital plays a complementary role in promoting the positive effect of digital infrastructure on innovation in a sample of 28 African countries, suggesting that digital infrastructure can indirectly boost innovation through the accumulation of human capital in Africa. However, their study focused on innovation as an outcome variable, rather than as a critical determinant of INPR and competitiveness, as done in this study.

Finally, we explore the relationship between HCD and industrial competitiveness, another crucial aspect of this study. Boone and van Witteloostuijn (1996) emphasize the significant impact of both objective (education and experience) and subjective (personality traits) human capital on organizational performance in competitive environments. Onyusheva (2017) establishes a direct connection between human capital and competitiveness in Kazakhstan, echoed by the findings of Chulanova (2017) on the importance of competitive human capital formation for economic development and innovation. Lin *et al.* (2017) highlight a positive link between HCD and employee value and uniqueness in Taiwan and Mainland China, emphasizing the role of training and job design. However, while talent acquisition methods varied between the two regions, neither effectively retained unique employees. Debrah *et al.* (2018) stress the strategic importance of education and on-the-job training in sustaining Sub-Saharan Africa's competitiveness in the global arena, emphasizing the need for skills acquisition relevant to today's evolving marketplace. Thus, the relationship between HCD and industrial competitiveness is well-documented, as HCD has been shown to significantly enhance industrial competitiveness. Studies show direct links between human capital in the form of education, experience personality traits that boost organizational performance and national competitiveness, highlighting the need for comprehensive approaches to education and skill development (Boone and van Witteloostuijn, 1996; Onyusheva, 2017; Chulanova, 2017; Lin *et al.*, 2017; Debrah *et al.*, 2018).

Overall, studies have linked TECIN or HCD to INPR or industrial competitiveness. However, the literature linking the interaction between TECIN and HCD with INPR and competitiveness can be best described as emerging, thus requiring more studies to be undertaken. Furthermore, the existing literature in this area has not fully explored the African context, a region primarily oriented towards the production of primary products rather than industrial products. This aspect bears significant importance, as it underscores the need for tailored policy directives to effectively address the INPR and competitiveness challenges that persist in the region.

3. Data and methodology

3.1 Model specification

In the literature, studies related to the innovation–productivity are often discussed within the purview of the Crépon *et al.* (1998) Crépon, Duguet and Mairesse (CDM) model. The CDM model presents a comprehensive framework that encompasses three distinct groups of relationships connecting innovation and productivity. The first group elucidates the determinants of enterprises' propensity to invest in innovation and the intensity of innovation expenditure. The second group establishes the connections between different types of innovation outputs, the intensity of innovation expenditure and various factors influencing innovation outcomes. The third group establishes the linkages between productivity, innovation outputs and other determinants that influence productivity. This study estimates the third stage of the CDM model because it allows us to augment the model with other variables, including HCD. The third stage equation is a Cobb–Douglas technology function with knowledge, capital and labor as inputs. This study adapts Khan *et al.* (2022) and augments it with the other variables that are vital to the present study. The basic form of the model is given as;

$$y_i = \alpha_0 + \alpha_1 k_i + \alpha_2 g_i + v \quad (1)$$

where the measure of productivity is denoted as y_i, measure of TECIN as g_i, tangible capital stock as k_i. Parameter estimates are represented by α_{0-2}, respectively. Augmenting Equation (1) with HCD, interaction of TECIN and HCD, and other control variables such that;

$$y_{it} = \alpha_0 + \alpha_1 g_{it} + \alpha_2 HCD_{it} + \alpha_3 g * HCD_{it} + \alpha_4 CTL_{it} + v_{it} \quad (2)$$

where α_{0-4} are parameter estimates; v is the error term; HCD is HCD; CTL is a vector of control variables encompassing trade openness (TRO), research and development (RD), and regulatory quality (RQ). The rationale behind the inclusion of trade openness lies in its dual benefits. On the one hand, countries embracing open trade policies gain access to larger markets, fostering increased competition and opportunities for specialization, ultimately boosting INPR. On the other hand, trade openness facilitates the exchange of knowledge, technologies and best practices between nations, as foreign firms bring novel expertise and innovations to domestic markets, thereby nurturing learning and driving innovation (Wong, 2009). Moreover, higher investments in research and development (R&D) can foster technological advancements and innovations, leading to enhanced INPR—an aspect also reinforced by the research of García-Pozo *et al.* (2021) and Serrano-Domingo and Cabrer-Borrás (2017). Regulatory quality further emerges as a key control variable, as a strong regulatory environment that nurtures entrepreneurship, streamlines bureaucratic processes and incentivizes innovation has a positive impact on INPR (OECD, 2010). By incorporating these dimensions into the discourse on trade and productivity, we gain a comprehensive understanding of the multifaceted factors that underpin economic growth and innovation. Renaming y_{it} as $INPR_{it}$ and g_i as $TECIN_{it}$ and incorporating explicitly our control variables, Equation (2) can be represented such that;

$$INPR_{it} = \alpha_0 + \alpha_1 TECIN_{it} + \alpha_2 HCD_{it} + \alpha_3 TECIN * HCD_{it} + \alpha_4 TRO_{it} + \alpha_5 RD_{it} + \alpha_6 RQ_{it} + v_{it} \quad (3)$$

Thus, this study estimates Equation (3) to examine the effects of TECIN and human capital on INPR. However, to examine the effects of TECIN, HCD and their interactions on industrial competitiveness, the study estimates Equation (4) as adapted from Zhang (2014). Thus,

$$IC_{it} = \alpha_0 + \alpha_1 TECIN_{it} + \alpha_2 HCD_{it} + \alpha_3 TECIN * HCD_{it} + \alpha_4 TRO_{it} + \alpha_5 RD_{it} + \alpha_6 RQ_{it} + v_{it} \quad (4)$$

where IC represents industrial competitiveness. In measuring industrial competitiveness, this study employs a method similar to that of Zhang (2014) by calculating an industrial competitive index. The index is derived through principal component analysis (PCA) using four key indicators: manufacturing value added, manufactured exports (% of merchandise exports); Medium and high-tech exports (% manufactured exports); and medium and high-tech manufacturing value added (% manufacturing value added). Moreover, to gauge INPR, the study utilizes manufacturing value added. HCD is measured by tertiary school enrollment rates (following Osei, 2024). This is because higher education equips individuals with advanced skills and knowledge essential for economic productivity and innovation. Increased enrollment in tertiary education indicates a population's commitment to gaining specialized expertise, which directly contributes to a country's economic growth and development. Research and development is measured by research and development expenditure as a percentage of gross domestic product (GDP). For TECIN, patent applications by both residents and non-residents serve as proxies. This is because patent applications often involve new technologies or significant improvements to existing ones that can enhance production processes (Bashir *et al.*, 2023). These can include innovations in machinery, manufacturing techniques, materials and more. High numbers of patent applications in production-related fields suggest active innovation aimed at improving productivity and efficiency in manufacturing. The usage of patent applications as a proxy for TECIN aligns with other studies in the literature (Drucker and Feser, 2012; Bashir *et al.*, 2023). $TECIN * HCD$ refers to the interaction between TECIN and HCD. This is to capture the nature of complementarity that exists between TECIN and HCD in fostering INPR and competitiveness. A summary of the variables description is provided in Table 1.

3.2 Estimation technique

The study adopts the system of generalized method of moments (GMM) to estimate the links between our dependent variables (manufacturing value added and industrial competitiveness index), TECIN and HCD. The estimator was developed by Arellano and Bond (1991) and Blundell and Bond (1998). In line with the prevailing GMM literature like Oduola *et al.* (2022) and Alimi and Ajide (2021), the application of the system GMM estimation requires adherence to the following validations: First, this technique is well-suited for handling regressors and with high persistence, as evidenced by the correlation coefficients of the actual and its first lagged value, which exhibits a significant minimum values of 0.982 and 0.941 for manufacturing value added and industrial competitiveness respectively (see Appendixes 2 and 3), exceeding the threshold point of 0.800. Secondly, for panel studies with a smaller number of time periods (T) than countries (N), such as $T(26) < N(32)$, the estimator proves to be most appropriate. Thirdly, the GMM approach effectively addresses potential endogeneity bias in the independent variables. Fourth, it preserves cross-country variations in the estimation, a crucial aspect for accurate analysis. Lastly, based on these four reasons, Bond *et al.* (2001) advocate for the use of system GMM by Arellano and Bover (1995) and Blundell and Bond (1998) as a superior fit compared to the difference estimator.

3.3 Data

This research centres on an African context, incorporating data from 32 African countries [2] spanning the years 1996–2021. The decision to commence from 1996 is attributed to the absence of RQ data prior to this period. To ensure comprehensive data collection, we obtained

Table 1. Description of variables

Variables	Description	Measurement	Source
INPR	Industrial productivity	Manufacturing value added (% of GDP)	WDI
IC	Industrial competitiveness	PCA Index generated using for 4 components	WDI
TECIN	Technological innovation	Patent applications (residents and non-residents)	WDI
HCD	Human capital development	School enrollment, tertiary (% gross)	WDI
TRO	Trade openness	Trade (% of GDP)	WDI
RD	Research and development	Research and development expenditure (% of GDP)	WDI
RQ	Regulatory Quality	Regulatory Quality	WGI

Source(s): Authors' compilation

information from the World Bank database. Specifically, RQ data were sourced from the World Governance Indicator (WGI) for the year 2021, while data on other variables were acquired from the World Development Indicator (WDI) for the same year. Table 2 presents the descriptive statistics for the variables used in this study. In the table, INPR, with an average of 12.213 units and a moderately spread standard deviation of 7.370, unveils a range of productivity levels. Remarkably, TECIN showcases substantial spread, boasting an average of 330.227 units alongside an imposing standard deviation of 1223.682, a testament to wide-ranging innovation adoption. HCD maintains an average of 14.300 units, while a higher standard deviation of 14.967 accentuates pronounced technical skill diversity. TRO, indicating technological readiness and operational efficiency, bears an average score of 66.209 units, with a moderate standard deviation of 28.920, signifying diverse preparedness levels. Intriguingly, research and development expenditure (research and development) rests at an average of 0.388 units, accompanied by a relatively restrained standard deviation of 0.244, reflecting measured spending variability. Lastly, RQ manifests with an average of −0.529 units, showcasing a symmetrical distribution and a moderated kurtosis of 3.227, indicative of potential outlier values. Additionally, there were moderate correlations among the variables, as shown in Appendix 1.

4. Empirical results and discussion

The empirical findings of this study rest upon two distinct methodological frameworks, specifically the baseline fixed effects estimation and the system GMM approach, as elucidated in Tables 3 and 4, respectively. The tables show the results of the main effect and the interactive effect of TECIN and HCD on INPR and competitiveness in Africa. Columns 1 and 2 present the effects of these regressors on INPR, while the 3rd and 4th columns present the effects of the regressors on industrial competitiveness. For the baseline estimation, the panel fixed effect is adopted over the random effect as informed by the result of the Hausman test that shows at significance level that does not exceed 5% all the models exhibit the rejection of the null hypothesis that the random effect is consistent. Furthermore, we allocated less emphasis to clarifying the baseline fixed effects result in Table 3. This decision stemmed from the recognized econometric shortcomings of baseline results in contrast to the system GMM approach. Consequently, the primary insights derived from this study are notably shaped by the outcomes presented in Table 4 using the system GMM estimation.

From Table 3, TECIN and HCD exhibit positive and significant relationships with manufacturing productivity and industrial competitiveness, with the interaction effect between them also playing a role. Conversely, TRO and research and development show mixed relationships with these outcomes, while RQ is negatively related to industrial competitiveness.

Table 4 presents the system GMM results of the TECIN and HCD role in INPR and competitiveness. First, the findings showed positive and statistically significant coefficients of prior INPR and competitiveness, which implies that the foundational framework in terms of

Table 2. Summary statistics

Variable	Mean	Std. dev	Min	Max	Skewness	Kurtosis
INPR	12.213	7.370	1.871	49.879	1.901	8.016
IC	−0.100	1.202	−1.875	3.862	1.310	4.102
TECIN	330.227	1223.682	0.000	8317.000	4.931	27.425
HCD	14.300	14.967	0.498	60.497	1.568	4.872
TRO	66.209	28.920	16.352	175.798	0.838	3.250
RD	0.388	0.244	0.005	0.962	0.188	1.785
RQ	−0.529	0.616	−2.282	1.197	0.001	3.227

Source(s): Authors' computation

Table 3. Baseline panel fixed effect result of the technological innovation and HCD role on INPR and competitiveness

Variables	Dependent variable: Manufacturing productivity Main effect	With interaction	Industrial competitiveness Main effect	With interaction
Constant	−0.226 (0.834)	3.474 (2.732)	1.066 (2.028)	0.979 (0.134)***
lnTECIN	0.092 (0.023)***	0.108 (0.064)	0.802 (0.206)***	0.109 (0.015)***
lnHCD	0.202 (0.046)***	0.134 (0.078)	0.188 (0.052)***	0.331 (0.045)***
TECIN X HCD	–	0.057 (0.020)**	–	0.037 (0.005)***
lnTRO	0.266 (0.240)	−0.029 (0.088)	−0.058 (0.443)	0.159 (0.439)
lnRD	−0.274 (0.027)**	0.097 (0.029)***	0.228 (0.108)	0.040 (0.200)
lnRQ	−0.096 (0.039)**	−0.003 (0.029)	−0.324 (0.256)	−0.220 (0.077)**
R-squared (within)	71.3	39.8	30.6	37.2
F-stat	44.83***	45.75***	7.35***	7.06***
Hausman test	14.36**	18.61***	13.10**	17.94***

Note(s): Standard errors are in parentheses; *, ** and *** denote significance level at 10, 5 and 1%, respectively
Source(s): Authors' estimation

INPR and competitiveness has a substantial influence on the present state of these factors in Africa. Furthermore, TECIN and HCD exhibit contrasting impacts on INPR and competitiveness, whereby TECIN negatively affects INPR. Conversely, HCD has a positive effect on INPR and industrial competitiveness in all the models except in the INPR model involving an interaction where it lacks significance. Although context dependent, the result of the negative effect of TECIN on INPR is explainable on many grounds, linkable to the disruptive effect of TECIN, which may cause productivity dip in the early stages as found by other studies (Chudnovsky *et al.*, 2006; Goedhuys, 2007; Raffo *et al.*, 2008; Wadho and Chaudhry, 2022). Firstly, during the initial technological implementation phase, getting accustomed to new technologies can be challenging for both employees and management. This adjustment period often leads to a decrease in productivity as everyone adapts to the new tools and processes. Additionally, introducing new technologies can disrupt established workflows and protocols, causing temporary decreases in productivity as employees navigate these adjustments. Furthermore, technical complications such as glitches and downtime are common when implementing emerging technologies, particularly in Africa where the level of technological diffusion is largely evolving. These issues can temporarily halt production and result in delays that negatively impact productivity until they are resolved. Simultaneously, adopting new technologies requires a significant investment, including costs for equipment, software, training and maintenance. These financial burdens may also have a short-term impact on productivity. For HCD, the results showed a positive effect of HCD on both INPR and competitiveness because as HCD increases, employees become more efficient, creative and adaptable, leading to enhanced productivity. This result also conforms with the large body of literature on the positive productivity effect of HCD (Li, 2014; Samargandi, 2018; Abrigo *et al.*, 2018; Ramírez *et al.*, 2020; Osei, 2024).

Furthermore, when interaction effects of TECIN and HCD are considered, the negative association between TECIN and INPR becomes less pronounced, indicating that HCD mitigates the adverse influence of TECIN on productivity. The positive and significant coefficient of the interactive effect of TECIN and HCD on INPR implies that the skill levels, knowledge dissemination and workforce adaptability fostered by HCD could be instrumental in offsetting any potential drawbacks associated with rapid technological innovations. This finding is relatable to that of Osei (2024), who found that digital infrastructure and human capital play complementary roles in influencing innovation.

Table 4. System GMM results of the technological innovation and HCD role on INPR and competitiveness

Variables	Dependent variable: manufacturing productivity Main effect	With interaction	Industrial competitiveness Main effect	With interaction
Constant	0.922 (0.361)**	1.503 (0.147)***	−0.389 (0.024)***	0.162 (0.026)***
INPR (−1)	1.434 (0.126)***	1.103 (0.004)***	–	–
IC (−1)	–	–	0.822 (0.022)***	1.056 (0.018)
lnTECIN	−0.120 (0.048)**	−0.092 (0.021)***	0.060 (0.010)***	0.344 (0.162)**
lnHCD	0.205 (0.057)***	0.005 (0.003)	0.009 (0.001)***	0.004 (0.001)***
TECIN × HCD	–	0.011 (0.001)***	–	0.031 (0.006)***
lnTRO	−0.439 (0.118)***	−0.038 0.001)***	−0.142 (0.585)	−0.112 (0.031)***
lnRD	0.125 (0.054)**	0.682 (0.032)***	0.669 (0.109)***	0.221 (0.055)***
lnRQ	0.093 (0.049)	0.368 (0.146)***	−0.287 (0.037)***	−0.154 (0.032)***
AR (1)	0.045	0.022	0.002	0.012
AR (2)	0.747	0.437	0.241	0.202
Sargan OIR	0.872	0.531	0.133	0.131
Hansen OIR	0.757	0.946	0.975	0.942
DHT for exogeneity of instruments				
(a) Instruments for levels				
HT excluding group	0.587	0.583	0.650	0.473
Diff (null H = Exogenous)	0.690	0.970	0.989	0.986
(b) IV (yr, eq(diff)				
HT excluding group	0.704	0.927	0.965	0.903
Diff (null H = Exogenous)	0.529	1.000	1.000	1.000
Fisher	2868.13 ***	2,880***	7,160***	9,200***
Instruments	14	14	18	18

Note(s): Standard errors are in parentheses; *, ** and *** denote significance level at 10, 5 and 1%, respectively; DHT: Difference-in-Hansen test for exogeneity of instruments subsets; OIR: over-identifying restrictions test
Source(s): Authors' estimation

Moreover, it is striking that the positive coefficient witnessed in the impact of TECIN on industrial competitiveness stands in contrast to the adverse effect observed in its association with INPR. On the other hand, the development of human capital consistently demonstrates a positive connection with both INPR and competitiveness. The affirmative outcome derived from the influence of TECIN on industrial competitiveness is also plausible, as novel technologies have the capability to bolster cost reduction, thereby augmenting overall competitiveness. This conforms with the findings of Freeman (1994), Simmie (2004) and Chatterjee *et al.* (2022) that TECIN is essential for securing long-term competitive advantage, allowing firms to swiftly introduce new products and implement advanced processes. Furthermore, the augmenting effect of HCD on the interplay between TECIN and industrial competitiveness is apparent. The positive coefficient associated with the interaction term signifies that the development of human capital enriches the pool of technically skilled workers who are naturally inclined to embrace and proficiently deploy novel technologies. This subsequently translates into noteworthy contributions towards operational refinement, waste reduction and improved competitiveness. In the context of Africa with its large and youthful population, HCD plays a critical role in enhancing the link between TECIN and industrial competitiveness. This means that with significant investment in HCD geared towards developing a skilled workforce, African countries can more effectively complement the adoption and deployment of new technologies in production processes, leading to increased INPR and global competitiveness.

In terms of the control variables, the findings suggest that TRO has a detrimental effect on manufacturing productivity. This result is in agreement with the findings of Wong (2009), who found a positive effect of TRO on manufacturing productivity in Ecuador before 2000, but also found a negative effect after 2000 which outweigh the initial positive effects. It also agrees with the findings of Busse *et al.* (2024) deindustrialization effects of TRO in developing countries, which is more pronounced in sub-Saharan Africa and Latin America. The negative effect of TRO on INPR in Africa is plausible due to the continent's heavy reliance on exporting raw materials and importing mostly finished goods. This trade pattern undermines the competitiveness of local manufacturing industries, hindering their ability to invest in advanced technologies and processes. Additionally, reliance on imported intermediate goods creates supply chain vulnerabilities, while competition from more advanced foreign firms and job losses in the manufacturing sector further diminish productivity. Without strategic interventions to strengthen local industries and invest in technological and HCD, the negative impact of TRO on manufacturing productivity in Africa is likely to persist.

The results showed that research and development play a pivotal role in boosting both productivity and competitiveness. Thus, investing in R&D helps African nations to develop innovative solutions tailored to their specific challenges and needs. This can lead to improvements in productivity by introducing more efficient production processes, advanced technologies and high value-added products.

Furthermore, RQ, on the other hand, presents mixed outcomes, positively impacting INPR but potentially hindering industrial competitiveness. RQ encompasses the effectiveness of regulations and the ability to implement policies. The mixed result can be explained by the fact that effective regulations ensure that industries operate within a stable and predictable environment, reducing uncertainty and encouraging investment in productive activities. However, the same RQ can potentially hinder industrial competitiveness in certain contexts. In many African countries, there are stringent regulations, although aimed at maintaining standards and protecting the environment, but sometimes impose high compliance costs on businesses. These costs can be particularly burdensome for small- and medium-sized manufacturing firms that may lack the resources to comply with complex regulatory requirements. When the regulatory framework is overly rigid or poorly designed, it can stifle innovation, and this limits the ability of industries to adapt quickly to market changes and compete effectively on a global scale.

Lastly, to substantiate the statistical inferences drawn from the estimated coefficients presented in Table 4, a battery of validity tests was conducted. Notably, both the first (AR1) and second (AR2)-order auto-correlation tests based on the Arellano-Bond methodology revealed an absence of serial correlation within our model. Furthermore, through the application of the Hansen and Sargan tests, we established the lack of correlation between the instruments and the disturbance terms, underpinning the integrity of our over-identification restrictions. This conclusion is corroborated by the difference-in-Hansen test (DHT), which serves to validate the exogeneity of the instruments.

5. Conclusion

The quest for sustainable industrial development in Africa, especially in the era of Industry 4.0, requires a comprehensive strategy that synergistically integrates TECIN and HCD, underpinned by a framework of facilitative policies. By embracing these strategies, African nations can position themselves to harness the transformative potential of Industry 4.0 to engender sustainable economic progress. This study explored how TECIN and HCD jointly influence INPR and competitiveness in Africa. It utilized a comprehensive dataset from 36

African nations, employing a panel framework that combined fixed effect and GMM techniques. The results reveal interesting insights.

TECIN initially showed a negative link with INPR in Africa, while HCD had a strong positive effect. However, when combined, they yielded a complementary positive impact. This initial negative effect could be due to the transitional phase of adopting new technologies, which can disrupt workflows and cause temporary productivity dips. HCD helps moderate this effect by providing skilled manpower, knowledge sharing and adaptability.

Both TECIN and HCD also enhance industrial competitiveness by reducing costs and improving efficiency. Therefore, African governments should prioritize policies that simultaneously promote TECIN and also enhance HCD. This can include increased funding for research and development, aligning educational curricula with industry needs, facilitating technology transfer partnerships and investing in technical skills training. Additionally, policies to retain skilled professionals to reverse brain drain are essential.

6. Limitations and suggestions for further research

This study acknowledges certain limitations. Its most notable limitation is the omission of key variables such as infrastructure, which plays an undeniable role in influencing INPR and competitiveness. Infrastructure encompasses transport, energy and telecommunications, which are undeniably essential in supporting industrial activities by facilitating the movement of goods, access to markets and operational efficiency. However, its exclusion from this study was because of the need to narrow the focus to the specific interplay between TECIN and HCD for industrial growth and competitiveness in Africa. Future research would benefit from a multi-variable approach that integrates infrastructure and other important variables to provide a more holistic view of the factors driving INPR and competitiveness in Africa.

Notes

1. https://www.wipo.int/global_innovation_index/en/2022/
2. Algeria, Angola, Botswana, Burundi, Cabo Verde, Cameroon, Central African Republic, Congo Rep., Cote d'Ivoire, Egypt, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Kenya, Libya, Madagascar, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, South Africa, Tanzania, Tunisia, Uganda, Zambia, Zimbabwe.

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Supplementary material

The supplementary material for this article can be found online.

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