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List of abbreviations and acronyms

ASEAN	Association of Southeast Asian Nations
BRICS	Brazil, Russia, India, China, and South Africa
CD	Cross-sectional Dependence
CO2	Carbon Dioxide
FDI	Foreign Direct Investment
FGLS	Feasible Generalized Least Squares
GCP	Global Carbon Project
GDP	Gross Domestic Product
ICTs	Information and Communication Technologies
GVCP	Global Value Chains Participation
MRIO	Multi-Regional Input-Output
PCA	Principal Component Analysis
PCSE	Panel Corrected Standard Error
R&D	Research and Development
SSA	Sub-Saharan Africa
STRIPAT	Stochastic Impacts by Regression on Population, Affluence, and Technology
UNCTAD	United Nations Conference on Trade and Development
WDI	World Development Indicators
WIOD	World Input-Output Database

Abstract

This study analyses the effect of Global Value Chains participation (GVCPs) on environmental pollution. It also assesses whether the use of digitalization can mitigate the effect of GVCPs on environmental pollution. We employed the second-generation panel analysis on data from 112 developing countries over the period from 1990 to 2018. Using Driscoll and Kraay estimation technique, we find that the GVCPs increases environmental pollution while digitalization reduces CO2 emissions in developing countries. However, the results show that the U-inverted hypothesis between GVCPs and environmental pollution is not verified in the study areas. Furthermore, the study shows that, unlike renewable energy consumption, the FDI inflows, industrial value-added, and electricity consumption are positively correlated to environmental pollution in developing countries. We find that, reducing CO2 emissions from digitalization is more pronounced in other developing countries than in sub-Saharan Africa. Moreover, the findings show that digitalization can be used as an effective channel in reducing the effects of GVCPs on environmental pollution and helping developing countries to go green. These findings have important policy implications in exploring the GVCPs development dynamics in terms of upgrading opportunities in using digital technologies to reduce environmental pollution and promote green technologies' adoption for structural transformation of developing countries.

Key words: *Global value chains; Digitalization; CO2 emissions; Developing countries.*

JEL classification codes: *F64; O57; Q56.*

1. Introduction

The CO_2 emissions as the main component of climate change have become a major concern since the fossil energy demand has been continuously increased in the Global Value Chains participation (GVCPs), which is widely recognized as a fuel of economic diversification and structural transformation. The sustainable development policies to face climate change are, therefore, needed in the process of production and distribution of goods and services across countries to meet the international standards (Pah & Timmer, 2020; Wang et al., 2020; Constantinescu et al., 2019; Kee & Tang, 2016; Gereffi & Lee, 2012). The CO2 emissions are strongly associated with international transport along the GVCPs. Heterogeneous effects of GVCPs on environmental pollution are reported in the literature (Jin et al., 2022; Wang et al., 2021; Zhang et al., 2021; Duan et al., 2021; Hu et al., 2021; Fei et al., 2020; Ji et al., 2020). For example, using multi-region structural decomposition analysis, Zhang et al. (2021) found that GVCPs reduces the global CO2 emissions in the case study of emerging economies as reported by Hoekstra et al. (2016) for high-wage countries. The negative relationship between GVCPs and environmental pollution was empirically tested by Jin et al. (2022) and Duan et al. (2021) in a case study of developed countries.

However, Fei et al. (2020) found that the GVCs development has increased the carbon dioxide emissions in China. Similarly, Jin et al. (2022) pinpoint that deepening the GVCPs in developing countries characterized by the low-tech industries has increased CO2 emissions. These findings are supported by the theory which postulates that the developing countries with less coercive environmental regulation tend to adopt polluting environmental industries. Using firm-level data in China, Zheng et al. (2022) found a non-linear relationship between GVCPs and environmental pollution. Wang et al. (2019) used panel data on 62 countries and found a U-shaped relationship between GVCPs and CO2 emissions. Hu et al. (2021) found that the development of GVCs might lead to the adoption of green technologies innovation and increase firms' efficiency, but such empirical investigation is rare in the case of developing countries. Looking at high value-added in the GVCPs at the cost of domestic environmental pollution needs policy design and implementation (environmental governance) for sustainable production as suggested by Ji et al. (2020).

Digitalization, which refers to the use of digital technologies to transform a business model for more value-addition, can be a useful channel of environmental governance and, therefore, the sustainable value chains (Ren et al., 2022; Wang et al., 2020; Gereffi & Lee, 2012). Digitalization can be used to mobilize industries for a clean and circular economy with less environmental impact. For example, Ma et al. (2022) and Mondejar et al. (2021) found that digitalization fosters green growth by reducing significantly the CO2 emissions. Digitalization can benefit the sustainable production and distribution of goods and services, in green energy generation and usage and this could be a way of transition towards sustainable manufacturing practices (Mondejar et al., 2021). The development of digitalization technologies such as Information and Communication Technologies (ICTs) can, not only be a profitable channel in reducing the geographical distance between producers and consumers, but also the dissemination of environmental information and knowledge for better implementation of environmental policies (Aker et al., 2016). Based on consumers' behaviour with an experiment on real products, Hoffmann et al. (2022) and Joerß et al. (2021) concluded that digitalization is an efficient solution to an environmental problem in Germany.

The participation of developing countries in GVCs is becoming considerable over the years. For example, the GVCPs in developing countries reached, on average, about 45% of gross export since 1990. However, the contribution from the GVCPs in sub-Saharan Africa (SSA) reached, on average, about 50% of gross export compared to 42.8% for the other developing countries for the period 1990–2018 (authors calculation based on the UNCTAD-Eora database). The use of digitalization technologies follows a similar trend in these two sub-regions. For example, the proportion of the population using mobile phones from 1990 to 2018 was about 30.67% in SSA compared to 46.85% for the other developing countries. Even though the Internet penetration in SSA countries is still very low compared to the other developing regions, it is important to note that it is in its booming era. On average, about 6.11% of the population have access to the Internet in SSA compared to 17.30% in other developing countries. . At the same time, environmental pollution remains high in other developing countries (4.86 million tons of CO2 emissions per capita) compared to SSA (0.89 million tons of CO2 emissions per capita).

Understanding the impact of GVCPs on environmental quality needs more investigation by considering the countries' specific context since countries with less environmental regulation may join the GVCs to earn more from the global market at the cost of environmental pollution (Duan et al., 2021; Duan & Yan, 2019; Clarke & Boersma, 2017). When focusing on developing countries, it is rare to find empirical work examining the links between digitalization, the GVCPs, and environmental pollution. This empirical evidence can lead to new policy implications for the economic development of the region. A supplementary investigation on the topic is, therefore, needed. Moreover, it is reported that the sub-Saharan African countries (SSA) are not deeply integrated into global production networks (Balié et al., 2019). Therefore, comparing the SSA to other developing countries could be another added value in redesigning policies that promote the participation of developing countries in GVCs in the era of digitalization. This paper analyses the effect of GVCPs on environmental pollution, and assesses whether digitalization can mitigate the effect of GVCPs on environmental pollution in the study areas. To the best of our knowledge, this is the first study linking digitalization, GVCPs, and environmental pollution with a focus on international comparisons of SSA countries to other developing countries. We used second-generation panel data spanning the period 1990–2018 over 112 developing countries and Driscoll and Kraay (1998) estimation technique and found that GVCPs increases CO2 emissions in developing countries. We also found that the moderating effect of digitalization in GVCPs on CO2 emissions is negative, indicating that digitalization is a channel of mitigation of the effect of GVCPs on environmental pollution in developing countries.

The rest of the paper is structured as follows. Section 2 presents a brief literature review, while Section 3 discusses the materials and methods used. Section 4 presents the descriptive results and empirical results, while discussion is presented in Section 5. Section 6 concludes this paper with policy implications.

2. Brief literature review

GVCPs and environmental pollution: What does the literature say?

The correlation between GVCs and environmental degradation has been a subject to various scholars and continues to be within the topmost debate around the world in the era of globalization (Duan et al., 2021; Wang et al., 2021; Fei et al., 2020; Yasmeen et al., 2019; Song & Wang, 2017). Positive and negative relationships were found (Hua et al., 2021; Fei et al., 2020; Song & Wang, 2017). Hua et al. (2021) reported that GVCPs decreases SO2 emissions. Probably this result depends on the proxy of the environmental pollutant (SO2) chosen in their study. Fei et al. (2020), using Multi-Regional Input Output (MRIO) and World Input-Output Database (WIOD) model, revealed that intermediate products trade and deepening of the GVCPs are positive and highly correlated with carbon emissions in China. Song and Wang (2017), using big data from Chinese enterprises, found that green technology levels can improve from GVCPs and, therefore, enhance the environmental quality.

However, empirical works have shown the threshold effect beyond which GVCPs will increase environmental pollution. For example, using data on four developing countries from 1995 to 2009, Wang et al. (2021) reported that there is a threshold in value chain development that influences environmental quality. Yasmeen et al. (2019) found also a nonlinear relationship between the value-added trade and eight air pollution indicators for a sample of 39 countries. Indeed, the international trade activities in the context of globalization, including GVCPs, is subject to environmental pollution (Ali & Giniguè, 2022; Ali, 2021; Bataka, 2021; Wang et al., 2020; Fei et al., 2020), but depend on countries' development (Duan et al., 2021; Wang et al., 2020). Wang et al. (2020) and Ali (2021) found that trade openness is associated with significant carbon emissions in developing countries. Environmental governance, investing in Research and Development (R&D), and policy supporting the use of digitalization technologies could help businesses increase, not only the efficiency of production and services (Cariolle, 2021; Chen et al., 2021), but also lead countries to go green by participating in global value chains, especially in developing countries that are seeking for rapid industrialization.

GVCPs and environmental pollution: Can digitalization foster a clean environment?

In the context of climate change and globalization, what could be the best way for developing countries to go green in the GVCPs which is highly correlated with environmental pollution? Digitalization can play dual effects (Asongu et al., 2017; Higón et al., 2017; Zhang & Liu, 2015; Hamdi et al., 2014). The production and distribution of goods along the GVCs in the era of globalization is the subject of environmental pollution (Haseeb et al., 2019) which can depend on countries' development and technological progress (Higón et al., 2017). Wang et al. (2020) found that technological progress is positively correlated with environmental pollution in developing countries while being negatively related to emissions in developed countries. Zhang and Liu (2015) revealed that digitalization has reduced environmental damage at the regional level in China from 2000 to 2010. Similarly, Wen et al. (2021) reported that ICT positively contributed to environmental quality in Chinese enterprises. However, Wang et al. (2021) found a threshold in the case study of four developing countries. Digitalization can foster the GVCP process while reducing environmental pollution from GVCs development. Haseeb et al. (2019) found that the information and communication technologies, measured by the Internet usage and mobile cellular subscription, enhance the environmental quality in BRICS case studies.

While increasing GVCPs, digitalization could hamper the environmental quality. Hamdi et al. (2014) found that the use of ICT can increase environmental pollution through an increase in electricity consumption. Avom et al. (2020), by considering a direct and indirect effect, found similar results in 21 sub-Saharan African countries. The study by Belkhir and Elmeligi (2018) reported that the greenhouse gas emission from the ICT could increase by 14% by 2040, and the carbon footprint from smartphone use is estimated to be more important than other ICT infrastructure. This is possible through the production and consumption of ICT machinery. In that case, the joint use of renewable energy, ICT, and tax policies was suggested for sustainable environmental protection (Belkhir & Elmeligi, 2018). Using panel data on ASEAN countries and a composite index of four indicators as a proxy of digitalization, Lee and Brahmasrene (2014) found that digitalization has increased CO2 emissions from 1991 to 2009. Asongu et al. (2017) found a positive effect on CO2 emissions of an increase in Internet penetration from interactive regression in sub-Saharan African countries for the period spanning from 2000 to 2012. However, using mobile phones alone as a proxy of digitalization, Asongu et al. (2017) came out with negative effects on environmental pollution, suggesting an existence of a threshold beyond which digitalization technology will have a positive effect on environmental damage. Either positive or negative effect found in the literature depends on the digitalization proxy used; the internet penetration on the one hand and mobile phone subscription on the other hand; while the use of both is highly correlated. These empirical results may lead to a bias of environmental policies toward green growth in the global value chain development. This paper stands out from the previous studies by using a new digitalization index that takes into account both internet penetration and mobile phone subscription. The article assesses the effect of GVCPs on environmental pollution by testing the U-inverted hypothesis and analyses the direct and indirect effect of digitalization on environmental pollution in GVCPs of developing countries with a focus on an international comparison between SSA and other developing countries.

3. Methodology

Model

To achieve the objectives of this study, we specify two separate empirical models on a sample of 112 developing countries (see the countries list in Table A1 in the appendix) for the period 1990–2018. To analyse the effects of GVCPs on environmental pollution, we used the theoretical model based on the Stochastic Impacts by Regression on Population, Affluence, and Technology (STRIPAT) model used by Li et al. (2019) and Bataka (2021). The basic formulation of the STRIPAT model is as follows in Equation 1:

$$I_{it} = \rho P_{it}^{\sigma_1} A_{it}^{\sigma_2} T_{it}^{\sigma_3} \varepsilon_{it} \quad (1)$$

Model (1) shows that the environmental quality (***I***) is a function of the population size (***P***), economic prosperity (***A***), and technology (***T***). ρ is a constant; σ_i (i= 1, 2, 3) are parameters of the determinants of the environmental quality; ε is the composite error term assumed to be spatially correlated; *i* and *t* are the individual and time dimensions, respectively. Model (1) is estimated in its linear form taking the natural logarithm. The STRIPAT model also offers the flexibility to add economic policy variables to analyse their effects on environmental pollution. The empirical model is obtained using the natural logarithm. Thus, considering the vector of control variables, the empirical model assessing the effect of GVCPs on environmental pollution is presented as Equation 2.

$$ln(CO_{2it}) = \sigma_{0i} + \sigma_{1i}\, ln(pop\_urban_{it}) + \sigma_{2i}\, ln(gdp\_pc_{it}) + \sigma_{3i}(ln(gdp\_pc_{it}))^2 + \sigma_{4i}\, ln(DIG_{it}) + \sigma_{5i}\, ln(GVCP_{it}) + \sigma_{6i}(ln(GVCP_{it}))^2 + \beta_i Z_{it} + \varphi_i + \gamma_t + \vartheta_{it} \quad (2)$$

Where: pop_urban_{it} is the urban population used to capture population size. gdp_pc_{it} is the GDP per capita used to capture the economic development. Technology is often captured by the level of industrialization. The digitalization (***DIG***) variable is identified in the literature as an important determinant GVCPs and could affect environmental pollution (Ali & Gniniguè, 2022; Avom et al., 2020; Asongu et al., 2017; Khan et al., 2018). Based on data availability, digitalization is captured in this study by mobile phone subscription (number of mobile phone subscriptions per 100 people) and the Internet penetration (Internet users as a percentage of the total population), on the one hand, and a digitalization index constructed using principal component analysis (PCA), on the other hand. Indeed, the digitalization index obtained from the PCA takes into account the Internet and mobile phone uses which are highly correlated. This index allows overcoming the problem of multicollinearity that can arise from Internet use and mobile phone subscription. The information provided by the PCA proves the viability of the calculated index. The test of good fitness of the digitalization index constructed provides a very high statistic (3940.139) with a p-value less than 1%, rejecting the hypothesis that the correlation matrix is an identity matrix, thus a possibility to initiate a PCA (see Table A2 in the appendix).

In Equation 2, $\boldsymbol{GVCP_{it}}$ is the global value chain participation of country *i* in year *t*. $\boldsymbol{DIG_{it}}$ is the level of digitalization of country *i* in year *t*. The introduction of $(\ln(\boldsymbol{GVCP_{it}}))^2$ and $(\boldsymbol{ln(gdp\_pc_{it})})^2$ allows us to assess the threshold effect of the impact of GVCPs and economic propensity on environmental pollution. Z_{it} is a vector of controls that may influence environmental pollution (access to electricity, renewable energy consumption, foreign direct investment, and industry value-added). β_i is a vector of parameters of control variables. φ_i refers to the country fixed effect, and γ_t capture the year fixed effect. ϑ_{it} is the error term, assumed to be spatially and temporally correlated. To examine the extent to which digitalization mitigates the effect of GVCPs on environmental pollution, we introduce an interaction variable into the model (2) as follows:

$$\boldsymbol{ln(CO_{2it}) = \sigma_{0i} + \sigma_{1i}\, ln(pop\_urban_{it}) + \sigma_{2i}\, ln(gdp\_pc_{it}) + \sigma_{3i}(ln(gdp\_pc_{it}))^2 + \sigma_{4i}\, ln(DIG_{it}) + \sigma_{5i}\, ln(GVCP_{it}) + \sigma_{6i}(ln(GVCP_{it}))^2 + \beta_i Z_{it} + \rho_i[ln(GVCP)_{it} * ln(DIG)_{it}] + \varphi_i + \gamma_t + \vartheta_{it}} \quad (3)$$

Where: ρ_i allows us to measure whether digitalization mitigates the effect of GVCPs on environmental pollution. Thus, when $\rho_i>0$ the effect of GVCPs on environmental pollution increases even as digitalization increases. Alternatively, when $\rho_i<0$ then the environmental pollution decreases with an increase in digitalization in GVCs development.

Preliminary tests and estimation strategy

Several panel tests are performed to provide details on the estimation techniques of the empirical models. We first performed the cross-sectional dependence (CD) test between the units under study. This test guides on the appropriate panel tests.

Indeed, two generations of unit root and cointegration tests are used in panel data (Nirola & Sahu, 2020). The choice of a test will depend on the cross-sectional dependence between the units. Contemporary research in panel data reveals that some commonly observed or unobserved factors between units (countries) can explain their interdependence relationships (Belotti et al., 2017). Note that the GVCPs is a spatial phenomenon through imitation between firms and interactions between countries through trade and foreign direct investment (FDI) resulting in cross-sectional dependence. The CD between geographically located units also stems from spillover effects and neighbourhood effects (Amidi & Majidi, 2020). Recent modelling shows that the presence of this dependence in the individual and temporal dimensions of panel data leads to biased and inconsistent estimators (Munir et al., 2020).

To diagnose the CD, we use the post-estimation test (Pesaran, 2004) since our study deals with unbalanced panel data. This test considers that the cross-sectional dependence under the null hypothesis of the error terms between individuals is independent of the alternative hypothesis of cross-sectional between individuals. The implementation of the CD test shows that statistics associated with each regression are significant at 1% (see Table A3 in the appendix). These results lead to the rejection of the null hypothesis of spatial independence between the individuals studied and over time.

The cross-sectional dependence being confirmed in the structure of the data, the unit root tests of the second-generation notably that of Pesaran (2007), are the most appropriate to overcome the CD issues. However, the unbalanced nature of our panel does not allow the implementation of these tests. Knowing that the first-generation unit root tests (Maddala & Wu, 1999) are ineffective in the presence of cross-sectional dependence, they will be used as an indication to assess the unit root of variables. Thus, the Maddala and Wu (1999) test which is the most suitable for unbalanced panel data is used for this purpose. The test postulates a unit root panel under the null hypothesis against an alternative stationary panel hypothesis. The statistics of the test (Inverse Chi-square) associated with each variable are significant at 1%, 5%, and 10% levels. This result invalidates the null hypothesis of the existence of the unit root of the variables. The confirmation of the absence of the unit root for all variables allows us to decide on the appropriate estimation strategy for the empirical models (2) and (3).

Indeed, because estimation techniques that do not consider cross-sectional dependence lead to biased and inconsistent results (Hoechle, 2007; Pesaran, 2021), several alternative estimation approaches are proposed in the literature. Elhorst et al. (2012) propose regressions incorporating spatial weighting matrices to address the problem of cross-sectional dependence. This technique is inefficient due to controversial interpretations of the estimation results because of the multiplicity of weighting matrices constructed and that the cross-sectional dependence is not only caused by geographical factors alone (Corrado & Fingleton, 2012; Bataka, 2020). Other estimation approaches from classical econometrics are proposed. For example, the Feasible Generalized Least Squares (FGLS) by Parks (1967), the Panel

Corrected Standard Error (PCSE) by Beck and Katz (1995), the Common Correlated Effects Estimator by Pesaran (2006), and the estimation approach of Hoechle (2007). The latter is based on the non-parametric estimation technique of Driscoll and Kraay (1998). The FGLS and PCSE estimation approaches achieve the same objectives and overcome the problem of cross-sectional dependence. The estimation method of Hoechle (2007) which is based on the non-parametric technique of Driscoll and Kraay (1998) has advantages that surpass the abovementioned approaches. Indeed, the latter allows tackling all forms of dependencies (cross-sectional and temporal). It also overcomes the problems of heteroscedasticity and error autocorrelation (common in panel data). While considering the forms of dependence for treating treatment of the variance-covariance matrix, this technique also provides robust standard errors. The above estimation approaches also require the panel to be balanced, which is not the case in our study. Because of the proven advantages of this estimation method, we use it to regress the empirical models.

4. Data and descriptive results

The data used in this paper come from three sources: the UNCTAD-Eora database for GVCPs, the Global Carbon Project (GCP) for CO2 emissions, and the World Development Indicators (WDI) for digitalization, and other control variables (Table 1). The GVCPs is measured as a percentage of gross export. The country participates in GVCs either by forging backward or forward linkages. The GVCPs is then determined as the sum of backward participation (*FVA*) and forward participation (*DVX*). The data show that, on average, the GVCPs of developing countries is about 45.2% of their gross exports between 1990 and 2018.

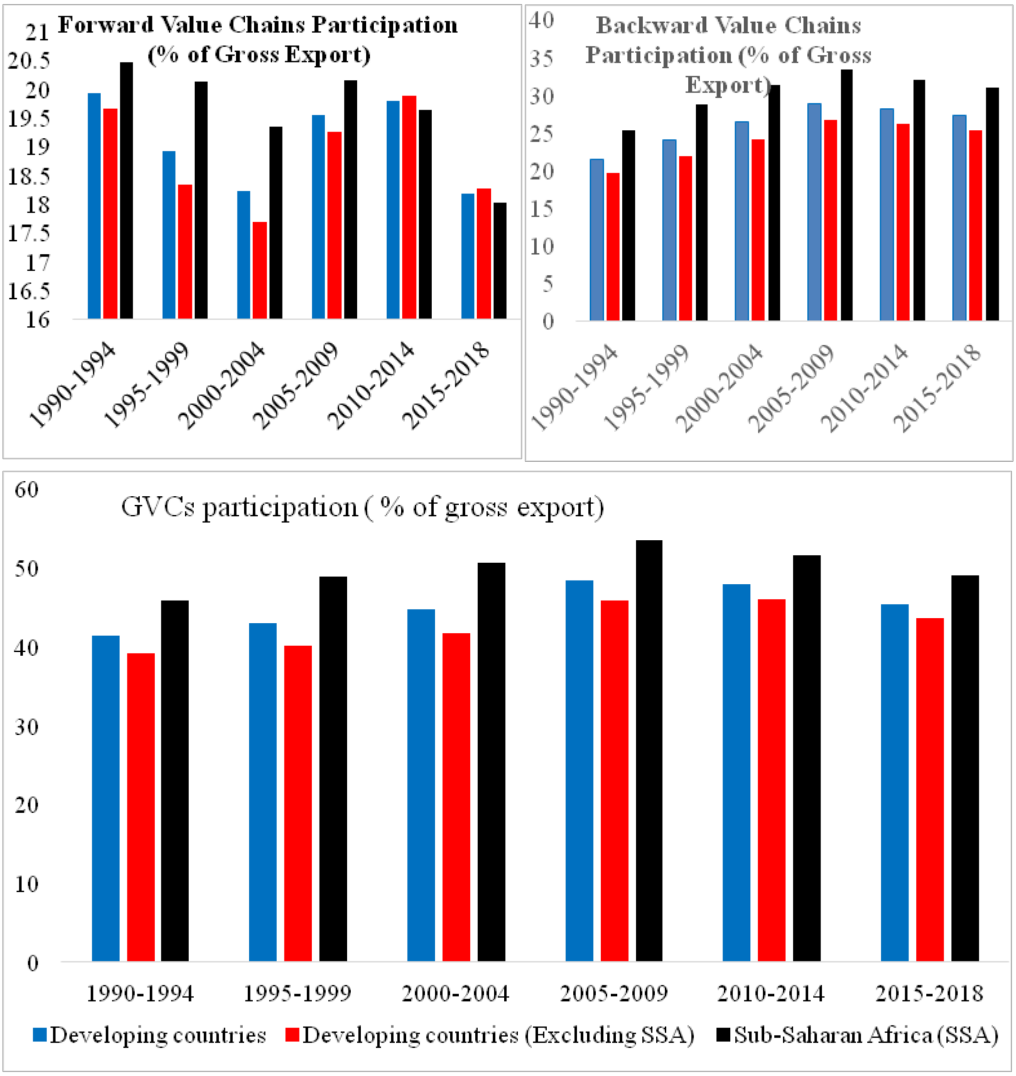
Table 1: Description and sources of variables

Variables	Description	Sources
FVA	Upstream participation	UNCTAD-Eora
DVX	Downstream participation	UNCTAD-Eora
GVCPs	GVC participation	UNCTAD-Eora
CO2_per_capita	CO2 per capita emission (million tons)	GCP
Internet	Internet users (% of the population)	WDI
mobile_phone	Mobile phone subscription (per 100 people)	WDI
Digital index	Digitalization index	Computed
pop_urban	Urban population	WDI
gdp_per_capita	GDP per capita	WDI
FDI_inflow	FDI inflow (% GDP)	WDI
renewable_energy	Renewable energy consumption (% of total)	WDI
industry_added	Industrial value-added (% GDP)	WDI

Notes: GCP means Global Carbon Project; WDI means World Development Indicators.

Moreover, the SSA participates more in GVCs up to 53.6% of gross export (Figure 1). The data show that forward participation is declining over time while the backward value chain participation is increasing. The downward trend of forward value chain participation is more pronounced in other developing countries (developing countries excluding SSA) compared to SSA. The five years average of the forward value chain participation in SSA is ranging from 20.47% to 18% of gross export. The upward trend of backward value chain participation can be explained by the importance of raw materials in export and import, mostly manufacturing goods. We expect that GVCPs in developing countries increases environmental pollution since carbon taxation is almost non-existent.

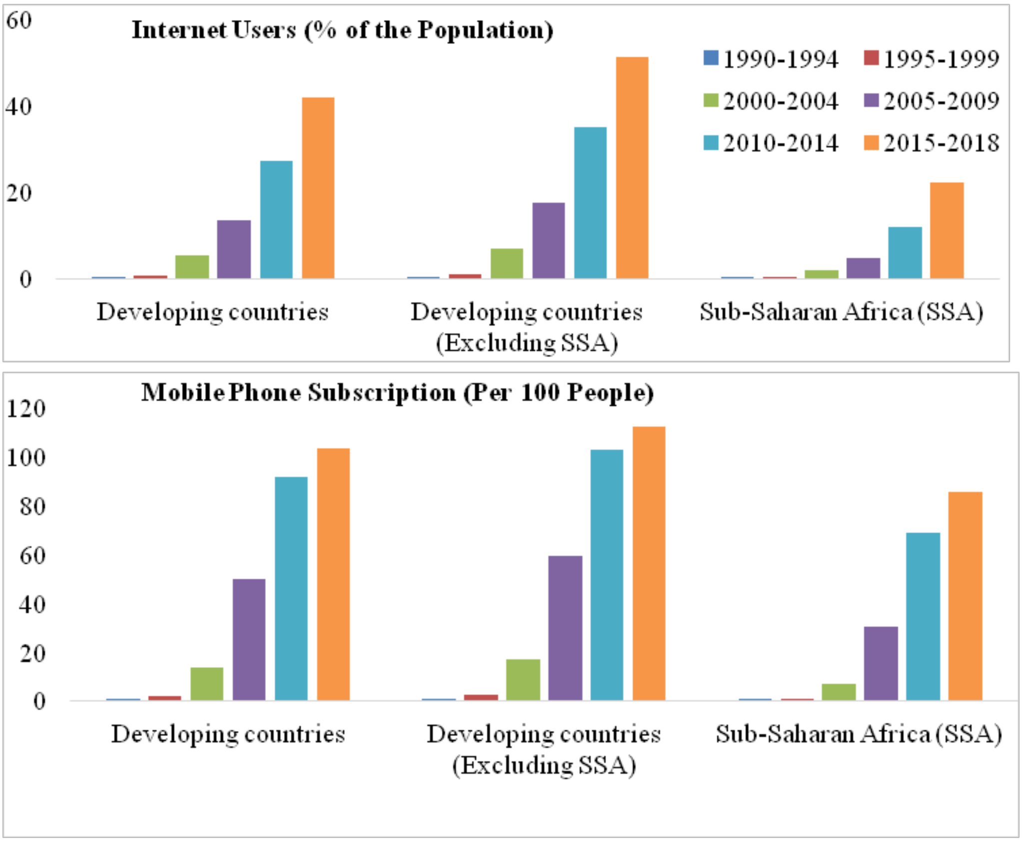
Figure 1: GVCPs in developing countries



Source: Authors' own construction.

Indeed, several indexes of digitalization are developed but all of them are based on the information and communication technology (ICT) infrastructure (Internet and mobile phones) and the level of access to them by individuals, government, and businesses (Xu et al., 2022) Based on data available in the study areas, digitalization is captured by mobile phone subscriptions (number of mobile phone subscriptions per 100 people) and the Internet penetration as a percentage of the total population (Figure 2).

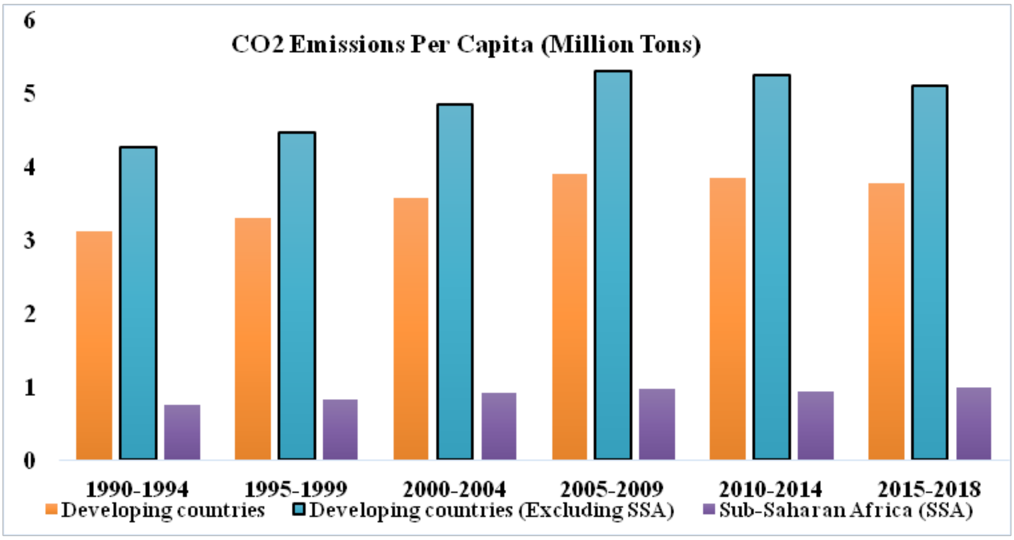
Figure 2: Internet penetration and mobile phones subscription in developing countries



Source: Authors' own construction.

The data show that the Internet and mobile phones penetrations have continuously increased in developing countries. The same trend is observed in the SSA sub-sample or not. The data show that Internet penetration measured by the number of Internet users is about 13.62% of the total population compared to 41.55% of the mobile phone subscriptions. The average Internet penetration is about 6.017% of the total population in SSA, while this average value is about 17.30% of the total population for other developing countries. For mobile phones, the average value of subscribers was about 30.67% and 46.85% for SSA and other developing countries, respectively. The Internet and mobile phones penetrations and the digitalization index are expected to have positive effects on GVCPs since it reduces transaction costs (World Bank, 2019). The environmental pollution in this study is approximated by the CO_2 emissions per capita since it is the main source of climate change. The data show that the average carbon dioxide (CO_2) emissions were about 3.58 million tons per capita per year, with a maximum of 68.9 million tons per capita (Figure 3).

Figure 3: CO2 emissions in developing countries



Source: Authors' own construction.

Figure 3 shows that SSA pollutes less than other developing countries throughout the study. The five years average CO2 emissions in other developing countries, excluding SSA, are shown to be above developing countries' average. This difference can be explained by the emergence of industrialization in Asia and Northern Africa compared to SSA. The control variables are selected according to the theoretical and empirical literature and data availability (Ali & Gniniguè; 2022; Bayale et al., 2021; Hamdi et al., 2014; Kersan-Škabić, 2019; Avom et al., 2020). These variables comprise the level of industrialization, foreign direct investment, the urban population , and renewable energy consumption. . Table 2 provides the descriptive statistics, and tests whether there is any heterogeneity between SSA and other developing countries.

Note that a perfect heterogeneity between SSA and other developing countries can be found when looking at most of the key variables. Indeed, the difference between the means of the two groups of countries is significant for almost all variables. For example, the average GVCPs of SSA is about 50% of their gross exports against about 43% for other developing countries. For environmental pollution, the average CO2 emission for SSA countries is about 0.891 million tons per capita per year compared to 4.862 million tons per capita for other developing countries. At the same time, the GDP per capita in other developing countries (6,160 current dollars) is much higher than that in SSA (1,729 current dollars). Nevertheless, the SSA seems to use more renewable energy than other developing countries throughout the study (68.58% compared to 27.96% of total energy consumption). These differences justify the need for international comparison, to capture the potential regional effect of GVCPs and digitalization technologies on environmental pollution. This is an integral part of this study.

Table 2: Descriptive statistics

Variables	Developing Countries (112 Countries)				Sub-Saharan Africa (37 Countries)		Other Developing Countries (75 Countries)		Difference (2)–(1)
	N	Mean	Min	Max	N	Mean (1)	N	Mean (2)	
CO_2_per_capita	3,218	3.575	0.00500	69.89	1,043	0.891	2,175	4.862	3.971***
Urban Population	3,245	1.383e+07	6,613	4.603e+08	1,073	5.949e+06	2,172	1.772e+07	1.18e+07***
GDP_per_capita	3,071	4,714	95.19	85,076	1,002	1,729	2,069	6,160	4430.991***
Internet	3,078	13.62	0	99.65	1,003	6.017	2,075	17.30	11.283***
Mobile_phone	3,190	41.55	0	210.0	1,044	30.67	2,146	46.85	16.180***
Electricity_access	2,636	70.03	0.01000	100	839	34.09	1,797	86.80	52.707***
FDI_inflow	3,008	3.736	-37.15	103.3	998	3.881	2,010	3.664	-0.217
Renewable_energy	2,864	41.14	0	98.34	929	68.58	1,935	27.96	-40.618***
Industry_added	2,883	28.44	3.243	84.80	967	24.56	1,916	30.39	5.826***
Digitalization index	3,057	0.0331	-0.763	4.060	996	-0.290	2,061	0.189	0.479***
FVA	3,248	0.191	0	1.000	1,073	0.197	2,175	0.189	-0.008**
DVX	3,248	0.260	1.51e-05	0.817	1,073	0.303	2,175	0.239	-0.064***
GVCPs	3,248	0.452	0.217	1.000	1,073	0.500	2,175	0.428	-0.160***

Note: *** p<0.01, ** p<0.05, * p<0.1

5. Empirical results and discussion

Here we analyse the effects of GVCPs on environmental pollution (Table 3), and assess whether digitalization through GVCPs can mitigate the CO2 emissions (Table 4) by considering three proxies of digitalization (Internet penetration, mobile phone subscription, and digitalization index constructed from the principal component analysis). In most cases (Table 3), the coefficients of the GVCPs variable are positive and significant at 1%, 5%, or 10%, whatever the proxy of digitalization. These results inform that the increase in GVCPs contributes positively to environmental pollution by increasing CO2 emissions. For example, deepening GVCPs in developing countries by 1% will increase the CO2 emissions by, on average, about 0.41% when considering the digitalization index as a proxy of digitalization. Similarly, the GVCPs will positively contribute to environmental pollution by releasing about 0.986% and 0.617% of CO2 emissions in SSA and other developing countries, respectively. There is a need to control the CO2 emissions to respond to climate change that has adverse effects on the countries' economies. All the coefficients associated with the GVCPs square term, except the SSA countries case, are positive and significant at 1% and 5%. These results show that the relationship between GVCPs and environmental pollution is linear. Ali and Gninigué (2022) found similar results using the same estimation technique on data covering 41 African countries from 1990 – 2018. However, this finding is in contradiction to those found by Duan et al. (2021) and Jin et al. (2022) for the developed countries and by Zheng et al. (2022) on the country-specific effect of China. The disaggregated data at sectoral levels or country case study could let deep understanding of this relationship for policy design taking into account countries’ specific context or economic sector characteristics. The findings show that the digitalization variables introduced in the regressions have negative coefficients, but are significant only for the other developing countries, excluding SSA, at the 1% level (Table 3).

Table 3: Effect of GVCPs on environmental pollution (CO2 emissions) in developing countries

Variables	Developing Countries			Sub-Saharan Africa			Other Developing Countries		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
GVCs (log)	0.3955**	0.3878**	0.4068**	0.9759	0.9326	0.9860*	0.6389***	0.6107***	0.6174***
	(0.166)	(0.149)	(0.166)	(0.584)	(0.608)	(0.573)	(0.112)	(0.127)	(0.121)
GVC_Square (log)	0.2182**	0.2049**	0.2170**	0.6421	0.5885	0.6485	0.3145***	0.2865***	0.2921***
	(0.088)	(0.085)	(0.088)	(0.458)	(0.487)	(0.447)	(0.064)	(0.072)	(0.068)
Internet (log)	-0.0061			0.0183			-0.1133***		
	(0.013)			(0.045)			(0.015)		
Mobile phone(log)		-0.0146			-0.0317			-0.0930***	
		(0.009)			(0.029)			(0.013)	
Digital index (Log)			-0.0296			-0.0309			-0.1854***
			(0.018)			(0.073)			(0.022)
Urban pop (log)	-0.0239	0.0055	0.0007	0.2015	0.3109**	0.2591*	-0.0222***	-0.0245***	-0.0220***
	(0.074)	(0.069)	(0.069)	(0.132)	(0.149)	(0.133)	(0.004)	(0.004)	(0.004)
GDP/capita (log)	0.0953	0.1114	0.0591	0.2137	0.1838	0.1207	-0.2211**	-0.0710	-0.2000*
	(0.089)	(0.083)	(0.085)	(0.194)	(0.245)	(0.225)	(0.103)	(0.119)	(0.113)
GDP/capita_SQ (log)	0.0034	0.0035	0.0070	-0.0133	-0.0077	-0.0043	0.0392***	0.0292***	0.0383***
	(0.005)	(0.004)	(0.005)	(0.011)	(0.018)	(0.015)	(0.005)	(0.006)	(0.006)
FDI_inflow	0.0014***	0.0020***	0.0015***	0.0016*	0.0019**	0.0018**	0.0061*	0.0059	0.0067*
	(0.001)	(0.001)	(0.000)	(0.001)	(0.001)	(0.001)	(0.004)	(0.004)	(0.004)
Renewable_energy	-0.0182***	-0.0184***	-0.0183***	-0.0246***	-0.0249***	-0.0246***	-0.0225***	-0.0223***	-0.0221***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)	(0.001)	(0.001)

continued next page

Table 3 Continued

Variables	Developing Countries			Sub-Saharan Africa			Other Developing Countries		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Electricity_access	0.0059***	0.0061***	0.0061***	-0.0034	-0.0015	-0.0021	0.0108***	0.0108***	0.0108***
	(0.001)	(0.001)	(0.001)	(0.004)	(0.004)	(0.005)	(0.001)	(0.001)	(0.001)
Industry_added	0.0069***	0.0066***	0.0068***	0.0079***	0.0073***	0.0079***	0.0202***	0.0212***	0.0208***
	(0.002)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)	(0.001)	(0.001)
Constant	-0.1435	-0.6852	-0.4740	-3.0658*	-4.6724**	-3.7469**	-0.1279	-0.6266	-0.5426
	(0.884)	(0.926)	(0.852)	(1.691)	(2.213)	(1.724)	(0.547)	(0.559)	(0.608)
Observations	2,023	2,036	2,016	665	667	662	1,358	1,369	1,354
F-Stat	4422***	3185***	4276***	229.7***	161.4***	183.2***	29824***	25199***	24331***
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

This result suggests the heterogeneity in terms of the effect of digitalization on environmental pollution in SSA compared to other developing countries. The results indicate that an increase in the use of digitalization reduces environmental pollution in other developing countries compared to the SSA, probably through its effects on the use of renewable energies. Indeed, digitalization can reduce significantly the intensity of fossil fuel energy consumption and therefore carbon footprints. In the value chain process, digitalization can be used to reduce emissions in transport by using smart cars and help consumers in the choice of products. Moreover, digitalization can be a channel by which decision makers, private sectors, and non-governmental organizations acting for a clean environment can enhance environmental governance. Digitalization reinforces the use of cleaner production technologies, and distribution of goods and services, and therefore improves the environmental performance of enterprises along the value chains. The results suggest that policies aiming to increase digitalization penetration will reduce environmental pollution. This finding is similar to the study by Wen et al. (2021) who report that industrial digitalization will significantly reduce the production scale of heavily polluting enterprises in China. Similar results were also found by Asongu et al. (2017) in the SSA; Haseeb et al. (2019) in BRICS and Wang et al. (2021) in developing countries. Combing the digitalization with other green growth policies such as an increase in renewable energy consumption will probably have an expected effect on environmental pollution in SSA. For Lu (2018), digitalization should be considered an important strategy in climate change mitigation since it shows a negative effect on CO2 emissions in the case study of 12 Asian countries. The other variables in Table 3 have in most cases their expected signs. The GDP per capita has positive and insignificant coefficients in most cases. The urban population has positive and significant coefficients for SSA countries but negative and significant for other developing countries. This means that environmental pollution increases with the urban population in SSA countries but decreases with the increase in the urban population in other developing countries. This result can be explained by the fact that the urban population would still depend on the use of fuel energy in SSA compared to other developing countries that would use more renewable energy at the household level. Industrial value-added and access to electricity have positive and significant coefficients in most cases. The more the countries urbanize or develop their industrialization, the higher they emit greenhouse gases contributing to environmental degradation.

The FDI variable has positive and significant coefficients in most cases. The positive and significant coefficients inform that it is the polluting multinational firms that relocate to developing countries (Ben-David et al., 2021; Christmann, 2004). This is clear that the developing countries with non-application of environmental laws in most cases will seek high economic growth by using industries that are more polluting, as found by Ali (2021) in the case study of ECOWAS. This calls for actions in the design and implementation of development policy toward environmental protection in developing countries. We find that the use of renewable energy reduces CO2 emissions. This result is consistent with findings from Ali (2021) in the case study of West African

States. When considering the upstream and downstream GVCPs (Table A4, Table A5, and Table A6 in the appendix), we found similar results to those in Table 3.

We now discuss the direct and indirect effect of the use of digitalization in GVCPs on environmental pollution (Table 4) by considering different proxies of digitization. The findings show that the digitalization variables and their interaction with GVCPs are negative and significant at the 1%, 5%, and 10% level. This result implies that although digitalization strengthens the GVCPs, it can be used as an important channel in enhancing the environmental quality in the study areas. These results show that the spread of digitalization in GVCPs in developing countries will reduce environmental pollution. Ekholm and Rockström (2019) reported that digitalization would be the most exponential climate solution by reducing about 15% of CO2 emissions by 2030. This can be achieved through the industry 4.0 revolution (speed of Internet of Things, artificial intelligence, accelerating the energy efficiency, transportation and traffic management). The disparities in the moderating effect of digitalization in GVCPs on environmental pollution by comparing SSA and other developing countries are shown in the data. The results show that the moderating effect of all digitalization proxies on the effect of GVCPs on CO2 emission is not significant for SSA countries compared to other developing countries. This situation would be due to the level of penetration of digitalization which is relatively low in SSA countries compared to other developing countries. In that sense, digitalization could be strengthened with other clean environment policies such as renewable energy consumption to have expected effects on environmental quality, especially in SSA as does in other developing countries.

This can be feasible with the lowest cost since Africa is identified as the next renewable powerhouse in the World in the coming century (Hafner et al., 2018; Odero, 2014; Dasappa, 2011). On the other hand, if digitalization helps GVCPs to reduce CO2 emissions, this would be since GVCPs is oriented in such a way that it reduces the consumption of fossil fuels and increases the consumption of renewable energies. We also estimated the moderating effect of digitalization in the upstream and downstream GVCPs on the CO2 emissions (Table A7, Table A8, and Table A10 in the appendix). The results are similar to those in Table 4, indicating the stability and the robustness of the results and the relevance of the study for policy process on environmental governance in developing countries in general and SSA in particular.

Table 4: Moderate effect of digitalization in GVCPs on environmental pollution in developing countries

Variables	Developing Countries			Sub-Saharan Africa			Other Developing Countries		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
GVCs (log)	0.8096***	1.0945***	0.7515***	1.0883*	0.9589*	0.8787*	1.1559***	1.4898***	1.1226***
	(0.249)	(0.243)	(0.198)	(0.566)	(0.518)	(0.506)	(0.314)	(0.318)	(0.275)
LogGVCs_SQ	0.4116***	0.5309***	0.4558***	0.7002	0.6027	0.5447	0.5622***	0.7021***	0.6216***
	(0.100)	(0.101)	(0.100)	(0.419)	(0.426)	(0.404)	(0.139)	(0.148)	(0.146)
Internet (log)	-0.0553*			0.0016			-0.0618**		
	(0.029)			(0.075)			(0.030)		
Mobile_phone (log)		-0.0695***			-0.0335			-0.0729***	
		(0.021)			(0.041)			(0.021)	
Digital index (log)			-0.1107***			0.0119			-0.1143***
			(0.040)			(0.103)			(0.041)
GVCs*internet (log)	-0.0585**			-0.0244			-0.0592*		
	(0.029)			(0.117)			(0.031)		
GVCs*mobile (log)		-0.0631***			-0.0027			-0.0694***	
		(0.020)			(0.049)			(0.021)	
GVCs*digital index (log)			-0.1000**			0.0632			-0.1044**
			(0.040)			(0.113)			(0.043)
Pop_urban (log)	-0.0228	0.0139	0.0013	0.1945	0.3099*	0.2718*	-0.0978**	-0.0943**	-0.0873**
	(0.075)	(0.070)	(0.070)	(0.148)	(0.154)	(0.142)	(0.041)	(0.042)	(0.040)
GDP/Capi (log)	0.0658	0.0815	0.0314	0.2065	0.1821	0.1343	0.0293	0.0540	0.0146
	(0.088)	(0.082)	(0.085)	(0.206)	(0.264)	(0.233)	(0.086)	(0.094)	(0.089)

continued next page

Table 4: Continued

Variables	Developing Countries			Sub-Saharan Africa			Other Developing Countries		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
GDP/Cap.SQ (log)	0.0055	0.0059	0.0089*	-0.0127	-0.0076	-0.0054	0.0099**	0.0092*	0.0116**
	(0.005)	(0.005)	(0.005)	(0.013)	(0.020)	(0.016)	(0.005)	(0.005)	(0.005)
FDI_inflow	0.0015***	0.0023***	0.0017***	0.0016*	0.0019**	0.0017**	0.0007	0.0023	0.0010
	(0.000)	(0.001)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)
Renewable_en	-0.0180***	-0.0182***	-0.0183***	-0.0246***	-0.0249***	-0.0247***	-0.0158***	-0.0158***	-0.0160***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)
Electricity_ac	0.0059***	0.0060***	0.0061***	-0.0033	-0.0015	-0.0022	0.0087***	0.0086***	0.0087***
	(0.001)	(0.001)	(0.001)	(0.004)	(0.004)	(0.005)	(0.001)	(0.001)	(0.001)
Industry_add	0.0067***	0.0066***	0.0067***	0.0079***	0.0073***	0.0078***	0.0042***	0.0044**	0.0042**
	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	0.1396	-0.3731	-0.2646	-2.8975	-4.6432*	-3.9830*	1.4739	1.4638	1.2318
	(0.882)	(0.944)	(0.859)	(2.194)	(2.472)	(1.963)	(0.911)	(0.904)	(0.869)
Observations	2,023	2,036	2,016	665	667	662	1,358	1,369	1,354
F-Stat	3834***	2473***	5129***	255.3***	145.9***	184.5***	2697***	1215***	2827***
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0

6. Concluding remarks

This study analysed the effect of GVCPs on environmental pollution, and assesses whether digitalization can be a critical channel in reducing the effect of GVCPs on CO2 emissions in developing countries. The study covered 112 developing countries for the period 1990–2018. We employed the second-generation panel analysis to overcome the problems of cross-sectional dependence, heteroscedasticity, and errors' autocorrelation. We used Driscoll and Kraay (1998) estimation technique with the country and the year fixed effects for the robustness of the results. The findings are robust and consistent while considering the backward and forward linkages. The study reveals the positive relationship between CO2 emissions and GVCPs in developing countries, including SSA. However, the U-inverted hypothesis between GVCPs and environmental pollution is not verified. We also find that the use of digitalization reduces the effect of GVCPs on the CO2 emissions in developing countries, but heterogeneity can be found between SSA and other developing countries. Moreover, renewable energy consumption was revealed to be a key strategy in reducing CO2 emissions in all sub-groups of developing countries. The results of this study inform that, to promote sustainable GVCPs, governments of developing countries, irrespective of group, need to work towards the rooting of digitalization. Digitalization in this regard can be directed towards the areas of fossil fuel or hydrocarbon consumption, which are highly polluting areas of GVCPs. Digitalization, coupled with green growth policy such as the use of renewable energy in GVCPs, is suggested to gain from GVCPs while reducing environmental pollution for sustainable development of sub-Saharan African countries, as well as other developing countries.

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Appendix

Table A1: Countries list

Sub-Saharan Africa (37 Countries)	Other Developing Countries (75 Countries)	
Angola	Afghanistan	Kyrgyzstan
Botswana	Argentina	Lao PDR
Burundi	Armenia	Lebanon
Cameroon	Aruba	Malaysia
Cape Verde	Azerbaijan	Maldives
Central African Republic	Bahamas	Mexico
Chad	Bahrain	Mongolia
Congo (Kinshasa)	Bangladesh	Morocco
Côte d'Ivoire	Barbados	Myanmar
Gabon	Belize	Nepal
Gambia	Bhutan	Nicaragua
Ghana	Bolivia	Oman
Kenya	Brazil	Pakistan
Lesotho	The British Virgin Islands	Panama
Liberia	Brunei Darussalam	Papua New Guinea
Madagascar	Cambodia	Paraguay
Malawi	Chile	Peru
Mali	Colombia	Philippines
Mauritania	Costa Rica	Qatar
Mauritius	Cuba	Samoa
Mozambique	Djibouti	Saudi Arabia
Namibia	Dominican Republic	Singapore
Niger	Ecuador	Sri Lanka
Nigeria	Egypt	Suriname
Rwanda	El Salvador	Syrian Arab Republic (Syria)
Sao Tome and Principe	Fiji	Tajikistan
Senegal	French Polynesia	Thailand
Seychelles	Georgia	Trinidad and Tobago

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Table A1 Continued

Sub-Saharan Africa (37 Countries)	Other Developing Countries (75 Countries)	
Sierra Leone	Guatemala	Tunisia
Somalia	Haiti	Turkey
South Africa	Honduras	Turkmenistan
South Sudan	India	Uruguay
Swaziland	Indonesia	Uzbekistan
Tanzania	Iran, the Islamic Republic of	Vanuatu
Togo	Iraq	Venezuela (Bolivarian Republic)
Uganda	Jamaica	Viet Nam
Zambia	Jordan	Kuwait
	Kazakhstan	

Table A2: Details on the principal component analysis; Kaiser-Meyer-Olkin (KMO) and Bartlet's Sphericity tests

Variables	Observations	Min	Max.	Mean	Std. Dev.
Internet	3,078	0.00	99.65	13.6234	20.70315
mobile_phone	3,190	0.00	210.05	41.5516	49.55593

KMO Index and Bartlett Test	
Kaiser-Meyer-Olkin index for sampling quality Bartlett's Sphericity test	0.5
Chi-Square	3940.139
Chi-Square Probability	0.0000

Total Variance Explained						
Component	**Initial Eigen Values**			**Extraction Sums of Square Loadings**		
	Total	**% of variance**	**Cumulative (%)**	**Total**	**% of variance**	**Cumulative (%)**
1	1.832	91.594	91.594	1.832	91.594	91.594
2	0.168	8.406	100			

Source: Authors' own construction.

Table A3: Pesaran cross-sectional dependence test (CD test)

Variable	CD-statistics	*p*-value	Correlation
GVCPs	161.51***	0.000	0.502
FVA	44.19***	0.000	0.398
DVX	202.76***	0.000	0.555
CO2_per_capita	95.57***	0.000	0.510
Urban Population	362.12***	0.000	0.940
mobile phone	385.68***	0.000	0.925

Note: *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table A4: Effect of value chains (FVA, DVX) on environmental pollution in developing countries (access to Internet as digitalization proxy)

Variables	Developing Countries		Sub-Saharan Africa		Other Developing Countries	
	FVA	DVX	FVA	DVX	FVA	DVX
FVA (log)	-0.0021		0.3306*		0.0119	
	(0.031)		(0.186)		(0.042)	
FVA_Square (log)	-0.0036		0.0680		-0.0012	
	(0.006)		(0.058)		(0.008)	
DVX (log)		-0.1753		0.2032		-0.0453
		(0.224)		(0.517)		(0.174)
DVX_Square (log)		-0.0207		0.1693		-0.0405
		(0.066)		(0.173)		(0.057)
Internet (log)	-0.1343***	-0.0040	0.0100	0.0111	-0.1119***	-0.1209***
	(0.017)	(0.012)	(0.044)	(0.042)	(0.014)	(0.015)
pop_urban (log)	-0.0007	-0.0035	0.2149	0.2576*	-0.0195***	-0.0215***
	(0.006)	(0.073)	(0.142)	(0.138)	(0.005)	(0.004)
GDP/Cap (log)	0.2886**	0.0582	0.1422	0.1065	-0.2763***	-0.2394**
	(0.122)	(0.089)	(0.194)	(0.167)	(0.102)	(0.111)
GDP/Cap.SQ (log)	0.0118	0.0060	-0.0085	-0.0050	0.0428***	0.0414***
	(0.007)	(0.005)	(0.012)	(0.010)	(0.006)	(0.006)
FDI_inflow	0.0061***	0.0015***	0.0015	0.0018*	0.0070*	0.0083**
	(0.002)	(0.001)	(0.001)	(0.001)	(0.004)	(0.003)
renewable_ener	-0.0208***	-0.0178***	-0.0252***	-0.0244***	-0.0227***	-0.0224***
	(0.001)	(0.002)	(0.003)	(0.003)	(0.001)	(0.001)
electricity_acc	0.0107***	0.0060***	-0.0035	-0.0044	0.0105***	0.0108***
	(0.001)	(0.001)	(0.004)	(0.004)	(0.001)	(0.001)
industry_adde	0.0208***	0.0071***	0.0080***	0.0077***	0.0206***	0.0192***
	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)	(0.001)
Constant	-3.0249***	-0.7230	-2.9353	-3.8874**	-0.2279	-0.3752
	(0.468)	(0.838)	(1.829)	(1.701)	(0.517)	(0.659)
Observations	2,023	2,023	665	665	1,358	1,358
F-Stat	16062***	2067***	164.9***	282.3***	23747***	20617***
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table A5: Effect of value chains (FVA, DVX) on environmental pollution in developing countries (use of mobile phone as digitalization proxy)

Variables	Developing Countries		Sub-Saharan Africa		Other Developing Countries	
	FVA	DVX	FVA	DVX	FVA	DVX
FVA (log)	0.0641		-0.2295		0.0072	
	(0.047)		(0.491)		(0.041)	
FVA_square (log)	0.0002		-0.1343		-0.0019	
	(0.010)		(0.115)		(0.008)	
DVX (log)		-0.1813		0.0564		0.0112
		(0.231)		(0.564)		(0.184)
DVX_square (log)		-0.0252		0.1154		-0.0268
		(0.069)		(0.186)		(0.060)
mobile_phone (log)	-0.0173*	-0.0111	-0.1985***	-0.0292	-0.0914***	-0.0988***
	(0.009)	(0.008)	(0.022)	(0.024)	(0.012)	(0.012)
pop_urban (log)	0.0137	0.0197	0.1410***	0.3557**	-0.0219***	-0.0246***
	(0.071)	(0.064)	(0.033)	(0.132)	(0.004)	(0.004)
GDP/capita (log)	0.1054	0.0725	1.0634**	0.0922	-0.1286	-0.0762
	(0.085)	(0.081)	(0.423)	(0.236)	(0.116)	(0.128)
GDP/Capita_SQ (log)	0.0044	0.0060	-0.0302	-0.0009	0.0330***	0.0306***
	(0.005)	(0.004)	(0.027)	(0.018)	(0.006)	(0.007)
FDI_inflow	0.0019***	0.0021***	0.0093***	0.0022**	0.0068*	0.0082**
	(0.001)	(0.001)	(0.002)	(0.001)	(0.004)	(0.003)
renewable_energy	-0.0181***	-0.0179***	-0.0182***	-0.0245***	-0.0225***	-0.0221***
	(0.002)	(0.002)	(0.002)	(0.003)	(0.001)	(0.001)
electricity_access	0.0060***	0.0061***	0.0157***	-0.0028	0.0105***	0.0108***
	(0.001)	(0.001)	(0.001)	(0.004)	(0.001)	(0.001)
industry_added	0.0066***	0.0068***	0.0191***	0.0070***	0.0214***	0.0200***
	(0.002)	(0.001)	(0.003)	(0.002)	(0.001)	(0.001)
Constant	-0.8630	-1.1606	-8.2738***	-5.4754***	-0.7249	-0.8623
	(0.916)	(0.789)	(1.469)	(1.812)	(0.527)	(0.678)
Observations	2,036	2,036	667	667	1,369	1,369
F-Stat	3978***	4829***	8555***	127.5***	12834***	26265***
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table A6: Effect of value chains (FVA, DVX) on environmental pollution in developing countries (using digitalization index constructed by the principal component analysis)

Variables	Developing Countries		Sub-Saharan Africa		Other Developing Countries	
	FVA	DVX	FVA	DVX	FVA	DVX
FVA (log)	0.0783*		0.3641*		-0.0041	
	(0.046)		(0.191)		(0.044)	
FVA_square (log)	0.0028		0.0725		-0.0056	
	(0.010)		(0.061)		(0.009)	
DVX (log)		-0.2116		0.1164		0.0372
		(0.225)		(0.537)		(0.163)
DVX_square (log)		-0.0336		0.1537		0.0409
		(0.067)		(0.185)		(0.055)
Digit index (log)	-0.0365**	-0.0284*	-0.0497	-0.0595	-0.0237**	-0.0161*
	(0.018)	(0.015)	(0.075)	(0.065)	(0.010)	(0.009)
pop_urban (log)	0.0098	0.0254	0.2763*	0.3403**	-0.0924**	-0.0786*
	(0.073)	(0.066)	(0.145)	(0.137)	(0.046)	(0.042)
GDP/capita (log)	0.0388	0.0201	0.0294	-0.0329	0.0769	0.0159
	(0.087)	(0.083)	(0.228)	(0.192)	(0.080)	(0.095)
GDP/Capita_SQ	0.0090*	0.0099**	0.0022	0.0083	0.0076	0.0109**
	(0.005)	(0.005)	(0.015)	(0.012)	(0.005)	(0.005)
FDI_inflow	0.0015***	0.0017***	0.0018**	0.0022**	0.0009	0.0012
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)
renewable_energy	-0.0180***	-0.0179***	-0.0253***	-0.0243***	-0.0157***	-0.0158***
	(0.002)	(0.002)	(0.003)	(0.003)	(0.002)	(0.001)
electricity_access	0.0060***	0.0062***	-0.0021	-0.0028	0.0087***	0.0091***
	(0.001)	(0.001)	(0.005)	(0.004)	(0.001)	(0.001)
industry_added	0.0068***	0.0071***	0.0078***	0.0075***	0.0049***	0.0047***
	(0.002)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	-0.6165	-1.1529	-3.5954*	-4.9515***	0.5802	0.5617
	(0.892)	(0.769)	(1.886)	(1.672)	(0.733)	(0.714)
Observations	2,016	2,016	662	662	1,354	1,354
F-Stat	2077***	2141***	118.9***	135.6***	3647***	1147***
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table A7: Moderate effect of digitalization in GVCPs (FVA, DVX) on environmental pollution in developing countries (using access to the Internet as digitalization proxy)

Variables	Developing Countries		Sub-Saharan Africa		Other Developing Countries	
	FVA	DVX	FVA	DVX	FVA	DVX
FVA (log)	-0.0369		0.3595		-0.0050	
	(0.070)		(0.454)		(0.059)	
FVA_Square (log)	-0.0064		0.0035		-0.0025	
	(0.007)		(0.109)		(0.008)	
Internet (log)	-0.1112**	0.0267	-0.3372***	-0.0890**	-0.1008***	-0.1270***
	(0.047)	(0.017)	(0.114)	(0.037)	(0.030)	(0.036)
Log(FVA)*log(internet)	0.0125		-0.0324		0.0061	
	(0.018)		(0.059)		(0.010)	
DVX (log)		-0.3448		0.2259		-0.0273
		(0.268)		(0.476)		(0.263)
DVX_Square (log)		-0.0678		0.1159		-0.0371
		(0.078)		(0.178)		(0.072)
Log(DVX)log(internet)		0.0205**		-0.0875*		-0.0041
		(0.010)		(0.051)		(0.029)
pop_urban (log)	-0.0015	-0.0030	0.1290***	0.2322	-0.0199***	-0.0216***
	(0.006)	(0.072)	(0.032)	(0.149)	(0.005)	(0.005)
GDP/capita (log)	0.2989**	0.0470	0.5968	0.1581	-0.2691***	-0.2387**
	(0.119)	(0.090)	(0.397)	(0.173)	(0.096)	(0.109)
GDP/Capt-SQ	0.0112	0.0064	-0.0030	-0.0081	0.0424***	0.0414***
	(0.008)	(0.005)	(0.028)	(0.010)	(0.005)	(0.006)
FDI_inflow	0.0059***	0.0016***	0.0068***	0.0018*	0.0068*	0.0083**
	(0.002)	(0.001)	(0.002)	(0.001)	(0.004)	(0.004)
renewable_energy	-0.0208***	-0.0180***	-0.0187***	-0.0247***	-0.0227***	-0.0224***
	(0.001)	(0.002)	(0.002)	(0.003)	(0.001)	(0.001)
electricity_access	0.0107***	0.0060***	0.0187***	-0.0051	0.0105***	0.0108***
	(0.001)	(0.001)	(0.001)	(0.004)	(0.001)	(0.001)
industry_added	0.0211***	0.0068***	0.0186***	0.0082***	0.0207***	0.0193***
	(0.001)	(0.001)	(0.003)	(0.002)	(0.001)	(0.001)
Constant	-3.1122***	-0.7964	-5.8007***	-3.5816*	-0.2792	-0.3580
	(0.431)	(0.848)	(1.323)	(1.840)	(0.487)	(0.736)
Observations	2,023	2,023	665	665	1,358	1,358
F-Stat	14183	4865	13682	305.5	25528	24075
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table A8: Moderate effect of digitalization in GVCPs (FVA, DVX) on environmental pollution in developing countries (using mobile phones users as digitalization proxy)

Variables	Developing Countries		Sub-Saharan Africa		Other Developing Countries	
	FVA	DVX	FVA	DVX	FVA	DVX
FVA (log)	0.0641		-0.2652		-0.0165	
	(0.053)		(0.402)		(0.045)	
FVA_square (log)	0.0002		-0.1372		-0.0097	
	(0.010)		(0.106)		(0.010)	
mobile (log)	-0.0173	-0.0116	-0.1829**	-0.0812**	-0.0219**	-0.1401***
	(0.018)	(0.015)	(0.069)	(0.039)	(0.009)	(0.033)
Log(FVA)*log(mobile)	-0.0000		0.0081		-0.0070	
	(0.008)		(0.038)		(0.005)	
DVX (log)		-0.1775		0.2043		0.1782
		(0.265)		(0.468)		(0.259)
DVX_square (log)		-0.0242		0.1216		0.0027
		(0.078)		(0.167)		(0.074)
Log(DVX)*log(mobile)		-0.0003		-0.0428		-0.0265
		(0.009)		(0.033)		(0.022)
pop_urban (log)	0.0137	0.0198	0.1399***	0.3393**	-0.0931**	-0.0254***
	(0.071)	(0.062)	(0.029)	(0.139)	(0.047)	(0.004)
GDP/capita (log)	0.1053	0.0729	1.0808***	0.1338	0.1044	-0.0606
	(0.098)	(0.081)	(0.395)	(0.229)	(0.082)	(0.128)
GDP/capita_SQ (log)	0.0044	0.0060	-0.0313	-0.0032	0.0052	0.0298***
	(0.005)	(0.004)	(0.025)	(0.017)	(0.005)	(0.007)
FDI_inflow	0.0019***	0.0021***	0.0093***	0.0022**	0.0025	0.0077**
	(0.001)	(0.001)	(0.002)	(0.001)	(0.002)	(0.004)
renewable_energy	-0.0181***	-0.0179***	-0.0181***	-0.0245***	-0.0156***	-0.0220***
	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.001)
electricity_access	0.0060***	0.0061***	0.0156***	-0.0031	0.0087***	0.0107***
	(0.001)	(0.001)	(0.001)	(0.004)	(0.001)	(0.001)
industry_added	0.0066***	0.0068***	0.0192***	0.0075***	0.0044**	0.0203***
	(0.001)	(0.002)	(0.003)	(0.002)	(0.002)	(0.001)
Constant	-0.8627	-1.1611	-8.3832***	-5.2385**	0.5486	-0.7353
	(0.856)	(0.778)	(1.350)	(1.970)	(0.747)	(0.729)
Observations	2,036	2,036	667	667	1,369	1,369
F-Stat	3671***	4711***	9539***	205.3***	1482***	44206***
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table A9: Moderate effect of digitalization in GVCPs (FVA, DVX) on environmental pollution (using digitalization index constructed by the principal component analysis)

Variables	Developing Countries		Sub-Saharan Africa		Other Developing Countries	
	FVA	DVX	FVA	DVX	FVA	DVX
FVA (log)	-0.1004		1.0618**		1.0618**	
	(0.201)		(0.508)		(0.508)	
FVA_square (log)	-0.0400		0.2097		0.2097	
	(0.056)		(0.131)		(0.131)	
DIG (log)	-0.0487	-0.1462	-0.3286	-0.4077**	-0.3286	-0.4077**
	(0.032)	(0.107)	(0.250)	(0.192)	(0.250)	(0.192)
Log(FVA)*log(DIG)	0.0080		0.0106		0.0106	
	(0.008)		(0.041)		(0.041)	
DVX (log)		-0.1648		5.8707***		5.8707***
		(0.239)		(0.908)		(0.908)
DVX_square (log)		-0.0947		2.3295***		2.3295***
		(0.070)		(0.350)		(0.350)
Log(DVX)*log(DIG)		-0.0018		0.0070		0.0070
		(0.027)		(0.033)		(0.033)
pop_urban (log)	-0.1645**	-0.0145*	0.1888***	0.1209***	0.1888***	0.1209***
	(0.081)	(0.007)	(0.023)	(0.012)	(0.023)	(0.012)
GDP/capit (log)	0.6120***	0.4435***	-2.8987***	-3.0519***	-2.8987***	-3.0519***
	(0.194)	(0.130)	(0.464)	(0.572)	(0.464)	(0.572)
GDP/Cap.SQ (log)	-0.0219*	0.0079	0.2266***	0.2463***	0.2266***	0.2463***
	(0.012)	(0.008)	(0.032)	(0.037)	(0.032)	(0.037)
FDI_inflow	-0.0008	0.0039	0.0085	0.0044	0.0085	0.0044
	(0.001)	(0.003)	(0.007)	(0.005)	(0.007)	(0.005)
renewable_ene	-0.0186***	-0.0197***	-0.0181***	-0.0174***	-0.0181***	-0.0174***
	(0.002)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
electricity_acc	0.0081***	0.0066***	0.0110***	0.0071***	0.0110***	0.0071***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
industry_added	0.0027	0.0183***	0.0233***	0.0084***	0.0233***	0.0084***
	(0.003)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)
Constant	-0.4974	-3.8192***	6.6149***	10.5466***	6.6149***	10.5466***
	(1.289)	(0.639)	(1.488)	(2.741)	(1.488)	(2.741)
Observations	775	775	167	167	167	167
F-Stat	395.5***	50890***	121930***	8855***	121930***	8855***
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table A10: Correlation matrix

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
(1) lnGVCPs	1.000												
(2) lnDVX	-0.442***	1.000											
(3) lnFVA	0.429***	0.028	1.000										
(4) lnCO2_per_capita	0.094***	0.016	0.022	1.000									
(5) access to electricity	0.126***	-0.248***	-0.067***	0.832***	1.000								
(6) Labour	-0.027	-0.035*	-0.006	-0.254***	-0.302***	1.000							
(7) lpUrban population	-0.363***	0.190***	-0.113***	-0.032*	0.020	-0.064***	1.000						
(8) renewable_energy	-0.174***	0.177***	-0.057***	-0.875***	-0.811***	0.355***	0.055***	1.000					
(9) industry_added	-0.208***	0.209***	0.052***	0.509***	0.332***	-0.177***	0.201***	-0.364***	1.000				
(10) ln(fixed_cap)	-0.162***	0.126***	0.030	0.448***	0.465***	-0.175***	0.799***	-0.379***	0.391***	1.000			
(11) Ln(internet)	0.126***	0.045**	0.209***	0.435***	0.523***	-0.045**	0.064***	-0.394***	0.132***	0.448***	1.000		
(12) ln(mobile_phone)	0.105***	0.116***	0.243***	0.333***	0.392***	-0.034*	0.085***	-0.298***	0.101***	0.429***	0.921***	1.000	
(13) ln(DIG)	0.115***	0.078***	0.229***	0.399***	0.472***	-0.032*	0.075***	-0.352***	0.142***	0.445***	0.976***	0.954***	1.000

Notes: ***, **, and * denote significance at 1%, 5%, and 10%, respectively.

Mission

To strengthen local capacity for conducting independent, rigorous inquiry into the problems facing the management of economies in sub-Saharan Africa.

The mission rests on two basic premises: that development is more likely to occur where there is sustained sound management of the economy, and that such management is more likely to happen where there is an active, well-informed group of locally based professional economists to conduct policy-relevant research.

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