Economic Growth, CH$_4$ and N$_2$O Emissions in Sudan: Where Should the Policy Focus Be?

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Abstract

This study aimed to investigate the effect of economic growth, agricultural growth and energy use on methane (CH$_4$) and nitrous oxide (N$_2$O) emissions in Sudan. Within the context of the EKC, the study applies the OLS, cointegration, vector error correction modelling (VECM) and Granger causality methods. The study has established a long run equilibrium relationship for both CH$_4$ and N$_2$O in their relation to economic growth, agricultural growth and energy use in presence of trade openness (TOP) and inflows of foreign direct investments (FDI). The estimated VECM shows that emissions of CH$_4$ are significantly affected by economic growth, TOP, and FDI with no effect of agricultural growth in the short run while CH$_4$ is found to be significantly affected by economic growth, agricultural growth, TOP and FDI in the long run. The estimated VECM for N$_2$O shows that N$_2$O emissions are more significantly affected by energy use, agricultural growth and FDI with no effect of economic growth in the short run, while N$_2$O is found to be significantly affected by economic growth, agricultural growth, TOP and FDI in the long run. The estimated VECM for N$_2$O shows that N$_2$O emissions are more significantly affected by energy use, agricultural growth and FDI with no effect of economic growth in the short run, while N$_2$O is found to be significantly affected by economic growth, agricultural growth, TOP and FDI in the long run. Consistently, findings from the estimated OLS and VECMs show that the EKC does not hold for either CH$_4$, or N$_2$O emissions, and that N$_2$O emissions are more significantly affected by economic growth, agricultural growth and energy use than emissions of CH$_4$. Findings from impulse response and variance decomposition analysis confirm that emissions of N$_2$O are more responsive to economic growth, agricultural growth and energy use than emissions of CH$_4$. Granger causality analysis shows existence of bidirectional relationship between CH$_4$ and agricultural growth, but a unidirectional relationship from CH$_4$ to FDI. For N$_2$O, the study finds a unidirectional relationship running from agricultural growth to N$_2$O, while N$_2$O emissions are found to cause GDP per capita, the squared GDP per capita, OIL consumption and FDI. In terms of causality, these results suggest that emissions of CH$_4$ and N$_2$O have been generated more by agricultural activities than by overall eco-
conomic activity, and that activities generating N$_2$O emissions in particular have been contributing significantly to economic growth. Within the context of the country’s intended nationally determined contributions, the findings of this study suggest that policies should be directed cautiously but more effectively to control N$_2$O than CH$_4$ emissions. Economic growth could be pursued without significant environmental harm from both CH$_4$ and N$_2$O emissions. However, Sudan should expand adoption of energy efficiency measures, expansion of renewable energy use, place restrictions on production and use of fuel woods and charcoal for low carbon economy and green growth.

Keywords
CH$_4$, N$_2$O, GDP per Capita, Agricultural Growth, Energy Use, Trade Openness, FDI, Cointegration, VECM, Sudan

1. Introduction

Global warming and climate changes are international environmental problems caused by emissions and concentration of greenhouse gases (GHGs) chief among them is carbon dioxide (CO$_2$). Globally, in 2016, about 72% of GHG emissions consist of CO$_2$, but non-CO$_2$ emissions, namely methane (CH$_4$) and nitrous oxides (N,O) make up shares of 19% and 6% and that CH$_4$, N$_2$O and Chlorofluorocarbons (CFCs) are the main GHGs contributing to global warming potential (WGP) (Olivier et al., 2017). CH$_4$ was the largest contributor to non-CO$_2$ GHG emissions, from non-dairy and dairy cattle and cattle manure management, while collectively coal mining, oil and natural gas production and distribution, and rice cultivation accounted for 25% and 10% of CH$_4$ emissions respectively (Olivier et al., 2017). N$_2$O emissions both anthropogenic and natural originate from soils which account for over half of total atmospheric N$_2$O inputs, (Parton et al., 2001). Emissions of N$_2$O are directly and indirectly related to land use and land cover changes (LULCC) and thus to agricultural growth and development. Sources emitting N$_2$O directly include cultivated soils and fertilized and/or grazed grassland systems, while indirect emissions result from transport of nitrous from agricultural systems into ground and surface waters, or emission as ammonia or nitrogen oxides (Smith et al., 1999). N$_2$O emissions stem also from agricultural biomass burning, industrial activities. According to the Intergovernmental Panel on Climate Change, IPCC, Climate Change (1995), compared with CO$_2$ heat trapping, a kilogram of CH$_4$ is 21 times as effective at trapping heat in the earth’s atmosphere as a kilogram (kg) of carbon dioxide within 100 years, while the per kg global warming potential (GWP) of N$_2$O is nearly 310 times that of CO$_2$ within 100 years. The same report (IPCC, Climate Change, 1995) attributes growth of CO$_2$, CH$_4$ and N$_2$O to fossil fuel use, land use change and agriculture. Moreover, it has been documented that one pound of N$_2$O warms the atmosphere almost 300 times more than one pound of CO$_2$ (United
Furthermore, releasing 1 kg of CH\(_4\) into the atmosphere is about equivalent to releasing 84 kg of CO\(_2\), while releasing 1 kg of N\(_2\)O into the atmosphere is about equivalent to releasing about 298 kg of CO\(_2\) (Climate Change Connection, 2015). Most of CH\(_4\) and N\(_2\)O emissions are related to LULCC, and intensive statistical analysis of these emissions can be found in Parton et al. (2001) and Houghton et al. (2012). Importantly, it has been recognized that policy targeting reduction of CH\(_4\) and N\(_2\)O emissions result in higher social benefits compared with reductions of CO\(_2\) emissions based on the GWP of these trace gases (Marten & Newbold, 2014).

From 1997 to 2019, a number of conferences of Parties (COPs) have been held to reach a consensus and agreement to cut GHG emissions. The most remarkable achievement was Paris Agreement adopted at COP-21 in 2015, which replaced the Kyoto Protocol (KP) signed in 1997. Analytical and empirical efforts to analyze determinants of GHG emissions have first focused on CO\(_2\) emissions as the main cause of global warming and have preceded formal climate agreements including the United Nations Framework Convention on Climate Change (UNFCCC), entered into force on 21 March 1994. Earlier studies such as of Grossman & Krueger (1991) found that concentrations of sulfur dioxide and smoke increase with per capita gross domestic product (GDP) at low levels of national income, but decrease with GDP growth at higher levels of income in 42 countries. Then, Panayotou (1993) has invented the so-called environmental Kuznets curve (EKC). These are fundamental examples of such earlier investigations of the relationships between economic growth and trade on CO\(_2\) emissions. Analysis of non-CO\(_2\) GHGs, namely CH\(_4\) and N\(_2\)O emissions is important for climate change policy that can be taken by countries, particularly in the context of the intended nationally determined contributions (INDCs) anchored in Paris 2015 Agreement. Yet, where climate change policy should be directed needs to be grounded on sound findings from rigorous empirical studies. Both mitigation and adaptation policies to climate change have costs, and thus only the most cost effective should be designed and implemented to control GHG emissions. In general, cross-sectional studies of agriculture using the Ricardian method suggest that efficient adaptation will reduce damages from climate change (Mendelsohn et al., 1994, 1996; Mendelsohn & Dinar, 1999). However, Mendelsohn (2000) upon analysis of different types of adaptations both private and public in agriculture, forestry and the energy sectors, states that adaptations against increases in climate variance are difficult to identify and are likely to have only modest net benefits.

Sudan is a low-income country; member of the UNFCCC, signed and ratified the KP and submitted its INDCs to Paris 2015 Agreement. Although mitigation is not a priority and it’s not binding with specific emission cut targets for Sudan, adaptation measures are extremely important since Sudan is vulnerable to different impacts of climate change including drought, flooding and reduced agricultural products (Nimir & Ismail, 2013). Nonetheless, for effective climate
change adaptation, the driving forces of CH$_4$ and N$_2$O emissions as the main GHGs in Sudan need to be identified and their relative importance needs to be well understood. Emissions of these gases in Sudan stem mainly from agriculture, deforestation, energy use and municipal wastes. Yet, commercial energy in terms of oil production and consumption has been steadily increasing since the late 1990s and contributing increasingly to GHGs in general and CO$_2$ emissions in particular. In Sudan, N$_2$O increased by 439.29% and CH$_4$ increased by 242.44% over the period 1970-2017 amounting to an annual rate of increase of 9.15% and 5.05% for N$_2$O and CH$_4$ respectively. Meanwhile, CO$_2$ emissions have increased by 301.33% at an annual rate of 6.28%. Emissions from agriculture account for an average of 84% and 91% form total emissions for CH$_4$ and N$_2$O respectively (calculated from World Bank, 2017). The second source of CH$_4$ and N$_2$O emissions in Sudan is the energy sector. Since agriculture also accounts for more than 35% of GDP over the period 1970-2017, GDP separately and its agricultural component jointly could be major determinants of CH$_4$ and N$_2$O emissions in Sudan.

Despite their importance to global warming and climate change, relatively less analytical and empirical attention has been paid to determinants of CH$_4$ and N$_2$O emissions, globally and at country level. For Sudan, no such study on determinants of CH$_4$ and N$_2$O exists, and the country’s INDCs have not been grounded on findings of rigorous empirical studies. Since the early 1990s, Toth (1995) notes that although CO$_2$ continues to be the single most important GHG, contributions of other trace gases to the aggregated global warming potential are sufficiently significant to justify their more equitable treatment in climate policy analysis. Even more recently, Sinha & Sengupta (2019) note that there are a limited number of studies on the estimation of EKC hypothesis for N$_2$O emissions, though it is one of the most harmful GHGs present in ambient atmosphere.

Upon this introduction and background information, the aim of this study is to contribute to this literature and knowledge twofold. First, how differently economic growth, agricultural growth and energy use affect emissions of CH$_4$ and N$_2$O in Sudan. Secondly, the study comparatively addresses the two most important non-CO$_2$ emissions with the same explanatory variables, in a context of a single country. Findings from such comparative analysis guide which and where policies can be directed effectively toward control of these emissions, and thus serves as evidence-based framework to climate change policy in Sudan in the context of its INDCs.

2. Literature Review

Huge empirical literature has been developing to investigate what development factors that lead to increases in GHGs emissions at the global and national levels. Studies from the field of environmental economics in the early 1990s the focus was on determining a level of per capita income at which GHGs generally and CO$_2$ emissions in particular start a reversion from upward to downward slop-
ping in the context of the EKC hypothesis (Panayotou, 1993). Empirical tests of the EKC were earlier undertaken by Selden & Song (1994) and Grossman & Krueger (1995), with focus on economic growth, trade liberalization and GHGs emissions. But, over time and across countries CO₂ emissions per capita have been found to strongly correlate with GDP per capita (Stern, 2011). The focus has shifted to investigate probable determinants of GHGs emissions but focusing mostly on CO₂ emissions, so as to design environmental and climate change policies compatible with economic development objectives.

In empirical literature, identified factors affecting GHGs emissions in general include the scale and rate of economic growth, energy use, openness to trade and flows of capital, urbanization and the contribution of the services sector to total economic output. Technological changes in the energy sector play an important role in GHGs emissions (Wheeler, 2012; Wang et al., 2012). Population density which is important factor in energy distribution and use by sectors has also been identified as important factor affecting GHGs emissions. Empirical literature on CO₂ determinants of emissions can be found in Omri (2009), with reference to the Middle East and North Africa (MENA) countries, Kerkhof et al. (2009) for Sweden, Norway, United Kingdom and the Netherlands, Musolesi et al. (2010) for a panel of countries, Iwata et al. (2010) for the Organization of Economic Cooperation and Development (OECD) countries, Sharma (2011) for 69 countries, Stolyarova (2013) for 93 countries, clustered into 7 groups, Beck & Prathibha (2015) for OECD and non-OECD countries, Heidari et al. (2015) for The Association of Southeast Asian Nations (ASEAN) countries, Lin et al. (2010) for Africa, Maryam et al. (2017) for Brazil, Russia, India, China and South Africa (BRICS) countries, Jeremiás & Attila (2017) for 164 countries, Adewuyi & Awodumi (2017) for West African countries, Bekhet et al. (2017) for the Gulf Cooperation Council (GCC) countries, and Apergis et al. (2018) for 19 developed economies. Some of these studies find support for the EKC, while many of them find no support the hypothesis that CO₂ emissions start a reversion trend with higher level of income over time.

At country level, there are numerous studies on economic growth and CO₂ emissions, including, Soytas et al. (2007) for the United States, Zhang & Cheng (2009) and Wang et al. (2012) for China, Halicioglu (2009), Kargi (2014) and Bozkurt & Yusuf (2014) for Turkey, Iwata et al. (2009) for France, Tiwari (2011) for India, Banerjee & Rahman (2012) for Bangladesh, Odhiambo (2012) for South Africa, Birgit & Getzner (2013) for Austria, Bento (2014) for Italy, Nuno (2014) for Portugal. In addition, Lau et al. (2014) who tested the EKC between economic growth and CO₂ emissions in Malaysia with incorporation of effects from foreign direct investment (FDI) and trade openness, and also Begum et al. (2015) for Malaysia, Mahmood & Shahab (2014) and Mirza & Kanwal (2017) for Pakistan, Kang et al. (2016) on EKC for China, Shabbaz et al. (2017) for Australia, Shmelev & Speck (2018) for Sweden, Mikayilov et al. (2018) for Azerbaijan, Elwasila (2018) who finds no support of EKC for Sudan, and Zheng et al. (2019)
for regional development and carbon emissions in China, among others. Systematic review of studies on CO$_2$ emissions was also undertaken by Mardani et al. (2019).

This study rather focuses on reviewing some of the literature investigating non-CO$_2$ emissions, namely CH$_4$ and N$_2$O emissions. Managi et al. (2009) find an inverse U-shaped relationship between trade openness and sulphur dioxide (SO$_2$) emissions in the case of OECD countries, but not for non-OECD countries. Zhang & Chen (2010) present inventories for CH$_4$ emissions and embodied emissions in production, consumption, and international trade for the Chinese economy in 2007, documenting that the total CH$_4$ emissions by Chinese economy in 2007 were 39,592.70 Greenhouse gas (Gg-CO$_2$ equivalent), three quarters of China’s CO$_2$ emissions from fuel combustion and greater than CO$_2$ emissions from fuel combustion of many developed countries. They identified agriculture and coal mining as the dominant direct sources of emissions, and the construction sector holds the top embodied emissions in production and consumption. They state that China is a net exporter of embodied CH$_4$ emissions with the emission embodied in exports represented 35.42% of the total direct emissions, mostly from exports of textiles, industrial raw materials, and primary machinery and equipments. They call for agricultural carbon-reduction strategies, coal bed methane recovery, export-oriented and low value added industry adjustment, and low carbon energy policies to address methane emissions. Also, Wang et al. (2016) find evidence in favour of the EKC hypothesis between economic growth and urbanization on SO$_2$ emissions in China.

For the case of Turkey, Bölük & Mert (2015) examine the effect of electricity generated from renewable energy sources in reducing GHG emissions over the period 1961-2010 using the autoregressive distributed lag (ARDL) approach. Their results show that the coefficient of electricity production from renewable sources with respect to CO$_2$ emissions is negative and significant in the long run and found a U-shaped (EKC) relationship between per capita GHGs and income, with a peak point of GDP per capita of $9920 which according to them was outside the observed sample period. Vavrek & Chovancova (2016) evaluate the relationship between economic development and GHGs emissions based on decoupling theory in the case of the Czech Republic, Hungary, Poland and Slovakia over the period of 1991-2012. Their results suggest that observed partial variables indicate strong decoupling of economic growth and GHGs emissions. The authors state that in order to meet their 2050 objectives to reduce GHG emissions, these countries need to accelerate restructuring the ways how they meet their demand for energy, food, transport and housing.

Utilizing time series data between 1970 and 2012 and the ARDL approach, Manuel & Mario (2017) analyze the relationship between N$_2$O emissions, economic growth, agricultural land used and exports in Germany. Their results show a quadratic long run relationship between N$_2$O emissions and economic growth, confirming the existence of an EKC for Germany. They estimated a
turning point at $27,880 which according to them was within the sample and implies that Germany was in the decreasing part of the curve of environmental degradation. They also find that agricultural land area affects N₂O emissions positively, whereas exports affect emissions negatively. The paper shows that, contrary to testing the EKC in less developed countries, mitigation of N₂O emissions does not negatively affect growth in Germany and as such, it is feasible to undertake any conservative policy in order to reduce emissions without major consequences on economic sectors. Using panel unit root and cointegration tests, Cho et al. (2014) analyze determinants of total GHG, CH₄ and N₂O emissions. They found a quadratic relationship in the long run for OECD countries. They also found effects of trade openness on GHG emissions. Although exports may not affect N₂O emissions according to Kearsley & Riddel (2010) the existence of an EKC for exports may be because of the pollution haven hypothesis (PHH) asserting transfer of pollution across countries instead of mitigating it which could be described as an inverse U-shaped relationship between exports and economic growth. For the European countries, Gielen & Kram (1998) find evidences that CH₄, N₂O and CFCs play a significant role in meeting Kyoto targets by EU member states, and that their emission reductions were forecast to contribute one quarter to the total emission reduction in 2010, given the emission reduction goals of individual European countries. Furthermore, Gambhir et al. (2017) find non-CO₂ mitigation measures are less costly than CO₂ mitigation measures, with the majority of their abatement potential achievable at US$2005$100/tCO₂e or less throughout the 21st century compared to a marginal CO₂ mitigation cost which was estimated to be already greater than this by 2030 in the most stringent mitigation scenario.

Benavides et al. (2017) use the ARDL method to investigate the relationship between emissions of CH₄, GDP, electricity production from renewable energy sources (excluding hydro) and trade openness in Austria. They find an inverted U-shaped between GDP per capita and CH₄ emissions as well as a unidirectional causality between CH₄, GDP per capita and electricity production. Applying econometric methods on annual data for 1981-2012, Maralgua (2017) investigates the EKC hypothesis for N₂O emissions, income, exports, urbanization, and growth in different sectors of the economy for Mongolia. The author finds a highly significant and robust long-run U-shaped relationship between N₂O emissions and income. Furthermore, exports, urbanization, and growth in the industrial and services sectors were found to decrease N₂O, while growth in the agricultural sector was found to increase N₂O emissions. The author found significant short- and long-run Granger causal relationships amongst the variables. However, until recently, Sinha & Sengupta (2019) argue for better understanding of the impact of energy consumption pattern on N₂O emissions and revision of energy policies. They analyzed the impact of renewable and fossil fuel energy consumption on N₂O emissions for Asia Pacific Economic Cooperation (APEC) countries over the period of 1990-2015 in the context of the EKC hypothesis. They indicate that the efficacy of the renewable energy solutions help to reduce
the level of \( N_2O \) emissions, and energy policies should be designed to be compatible with objectives of sustainable development goals (SDGs) in these nations. In conclusions, the findings of the above reviewed studies indicate that policy measures could be effective and less costly to be directed to non-CO\(_2\) emissions that directly targeting reduction of CO\(_2\) emissions.

3. Methodology

This study investigates the effects of economic growth, agricultural growth and energy use with separate inclusion of oil consumption (OIL) on emissions of CH\(_4\) and N\(_2\)O in Sudan in presence of trade openness (TOP) and inflows of foreign direct investments (FDI). The study utilizes annual time series data over the period 1970-2016. Within the context of the EKC, the study applies the ordinary least squares (OLS), cointegration, vector error correction modelling (VECM) and Granger causality methods. The study departs with a graphical analysis of total GHGs, CH\(_4\) and N\(_2\)O emissions over time. Figure 1 shows some type of co-movements of CH\(_4\) and N\(_2\)O emissions in Sudan, but recently emissions of N\(_2\)O started to overtake CH\(_4\). The figure also depicts that total GHG emissions have been steadily increasing over the study period. Over this period, Sudan has also experienced positive economic growth rates with some years of slowdown, as well as agricultural expansion with increased production and consumption of modern energy sources, namely oil and electricity but also biomass energies.

3.1. OLS Modelling

General two OLS models to analyze how differently economic growth, agricultural growth and energy use affect CH\(_4\) and N\(_2\)O emissions in presence of (TOP) and (FDI) in natural logarithms (\( L \)) are written as follows:

\[
L(\text{CH}_4) = \alpha + \beta_1 L(\text{GDPP}) + \beta_2 L(\text{GDPP})^2 + \beta_3 L(\text{CPIN}) + \beta_4 L(\text{EUP}) + \beta_5 L(\text{OIL}) + \beta_6 L(\text{TOP}) + \beta_7 L(\text{FDI}) + \mu \tag{1}
\]

\[
L(\text{N}_2\text{O}) = \alpha + \beta_1 L(\text{GDPP}) + \beta_2 L(\text{GDPP})^2 + \beta_3 L(\text{CPIN}) + \beta_4 L(\text{EUP}) + \beta_5 L(\text{OIL}) + \beta_6 L(\text{TOP}) + \beta_7 L(\text{FDI}) + \mu \tag{2}
\]

The variables are defined as follows:

- CH\(_4\) is Methane emissions measured in Kiloton (Kt) of CO\(_2\) equivalent.
- N\(_2\)O is Nitrous Oxide emissions measured in thousand metric tons of CO\(_2\) equivalent.
- GDPP is GDP per capita measured in current US Dollars.
- EUP is the energy use per capita measured in kg of oil equivalent per capita.
- Oil is oil consumption measured in kg per capita.
- CPIN is crop production index which shows agricultural production for each year relative to the base period 2004-2006. It includes all crops except fodder crops.
- TOP is trade openness measured as exports plus imports as percentage of GDP.
FDI is the inflow of foreign direct investments to Sudan, measured in current US Dollars.

The study departs with descriptive statistical analysis for both CH₄ and N₂O emissions together with the set of explanatory variables, as presented in Table 1. Based on Jarque-Bera (J-B) statistics, CH₄, N₂O and GDPP are not normally distributed.

The correlation matrix in Table 2 shows that CH₄ is positively correlated with GDPP, CPIN and FDI. N₂O is highly positively correlated with GDPP and the squared value of GDPP, CPIN and FDI. The squared value of GDPP is highly positively correlated with GDPP and of the other independent variables only FDI and CPIN, OIL and FDI are highly positively correlated.

The correlation matrices give an initial idea that N₂O emissions are more affected by economic growth and agricultural growth than CH₄ emissions.

Equation (1) is estimated by the method of OLS to investigate the relationship between CH₄ and economic and agricultural growth. The OLS results indicate that CH₄ is positively and significantly affected by economic growth in terms of the squared value of GDPP, agricultural growth and to less extent by trade openness, while negatively and significantly affected by the actual value of GDPP and energy use. OIL consumption and FDI have no significant effects on CH₄ emissions. For N₂O, the OLS results indicate that N₂O emissions are positively and significantly affected by the squared value of GDPP, agricultural growth and trade openness, while negatively and significantly affected by the actual value of GDPP and energy use. OIL and FDI have no significant effects on N₂O emissions. For both CH₄ and N₂O emissions, the OLS results are summarized in Table 3.

The OLS estimates show that the coefficients of N₂O emissions with respect to economic growth are much higher than the coefficients of CH₄ with respect to economic growth. Results of the two models for both types of emissions show that low level of economic growth is also associated with low level of emissions, and emissions increase monotonically with increases in GDP per capita over time. But, both of the OLS models for CH₄ and N₂O appear unstable on the basis of the plots of cumulative sum of squares of CUSUM of the recursive residuals. Therefore the OLS estimators for both CH₄ and N₂O emissions are not reliable as shown by Figures 2-5.
Figure 2. CH₄ stability CUSUM.

Figure 3. CH₄ stability CUSUM of squares.

Figure 4. N₂O stability CUSUM.

Figure 5. N₂O stability CUSUM of squares.
Table 1. CH$_4$ and N$_2$O descriptive statistics.

|       | Mean   | Maximum | Minimum | Std. Dev. | J-B  | Prob.  | Obs. |
|-------|--------|---------|---------|-----------|------|--------|------|
| CH$_4$| 59,487.03 | 125,045.0 | 30,622.10 | 25,947.86 | 6.12 | 0.000  | 47   |
| N$_2$O| 50,978.73 | 130,632.7 | 20,251.59 | 35,263.29 | 12.54 | 0.002  | 47   |
| GDPP  | 713.28  | 2684.63 | 175.63  | 606.57    | 34.19 | 0.000  | 47   |
| GDPP$^2$| 868,869.2 | 7,207,238 | 30,844.57 | 1,556,282.0 | 131.82 | 0.000  | 47   |
| CPIN  | 70.78   | 108.26 | 38.06   | 24.68     | 5.37  | 0.068  | 47   |
| EUP   | 410.22  | 491.38 | 350.84  | 36.33     | 3.41  | 0.182  | 47   |
| OIL   | 0.07    | 0.09   | 0.04    | 0.02      | 2.29  | 0.319  | 47   |
| TOP   | 26.87   | 47.58  | 11.09   | 9.62      | 1.27  | 0.529  | 47   |
| FDI   | 556.36  | 2311.46 | 0.000   | 764.57    | 7.90  | 0.019  | 47   |

Table 2. CH$_4$ and N$_2$O correlation matrix.

|       | CH$_4$ | GDPP | (GDPP)$^2$ | CPIN | EUP | OIL | TOP | FDI |
|-------|--------|------|------------|------|-----|-----|-----|-----|
| CH$_4$| 1.00   |      |            |      |     |     |     |     |
| GDPP  | 0.80   | 1.00 |            |      |     |     |     |     |
| (GDPP)$^2$ | 0.72 | 0.97 | 1.00      |      |     |     |     |     |
| CPIN  | 0.91   | 0.70 | 0.63       | 1.00 |     |     |     |     |
| EUP   | −0.68  | −0.40 | −0.25      | −0.67 | 1.00 |     |     |     |
| OIL   | 0.67   | 0.65 | 0.57       | 0.66 | −0.22 | 1.00 |     |     |
| TOP   | 0.27   | −0.01 | −0.07      | 0.32 | 0.03 | 0.59 | 1.00 |     |
| FDI   | 0.90   | 0.75 | 0.65       | 0.92 | −0.60 | 0.83 | 0.44 | 1.00 |

|       | N$_2$O | GDPP | (GDPP)$^2$ | CPIN | EUP | OIL | TOP | FDI |
|-------|--------|------|------------|------|-----|-----|-----|-----|
| N$_2$O| 1.00   |      |            |      |     |     |     |     |
| GDPP  | 0.89   | 1.00 |            |      |     |     |     |     |
| (GDPP)$^2$ | 0.82 | 0.97 | 1.00      |      |     |     |     |     |
| CPIN  | 0.83   | 0.70 | 0.63       | 1.00 |     |     |     |     |
| EUP   | −0.56  | −0.40 | −0.25      | −0.67 | 1.00 |     |     |     |
| OIL   | 0.71   | 0.65 | 0.57       | 0.66 | −0.22 | 1.00 |     |     |
| TOP   | 0.23   | −0.01 | −0.07      | 0.32 | 0.03 | 0.59 | 1.00 |     |
| FDI   | 0.87   | 0.75 | 0.65       | 0.92 | −0.60 | 0.83 | 0.44 | 1.00 |
Table 3. CH₄ and N₂O OLS summary results.

| Variable | CH₄  |     |     | N₂O  |     |     |
|----------|------|-----|-----|------|-----|-----|
|          | Coefficient | t-Statistic | Prob. | Coefficient | t-Statistic | Prob. |
| L(GDPP)  | −1.52 | −2.937 | 0.006* | −4.03 | −5.633 | 0.000* |
| L(GDP)²  | 0.13  | 3.285 | 0.002* | 0.34  | 6.205  | 0.000* |
| L(CPIN)  | 0.51  | 5.332 | 0.000* | 0.41  | 3.059  | 0.004* |
| L(EUP)   | −1.63 | −4.687 | 0.000* | −2.30 | −4.773 | 0.000* |
| L(OIL)   | −0.17 | −1.562 | 0.126 | −0.23 | −1.553 | 0.129 |
| L(TOP)   | 0.12  | 1.657 | 0.106 | 0.31  | 3.057  | 0.004* |
| L(FDI)   | 0.004 | 0.973 | 0.336 | −0.000| −0.030 | 0.976 |
| C        | 22.03 | 6.091 | 0.000* | 32.76 | 6.564  | 0.000* |

R-squared = 0.94; Adjusted R-squared = 0.93; SER = 0.107; SSR = 0.443; LL = 42.940; AIC = −1.487; SC = −1.172; HQC = −1.368; F-statistic = 92.24 (P. 0.000); DW = 1.76

Diagnostic Tests

| Stat.   | Prob. | DW |
|---------|-------|----|
| Normality (J-B) | 0.011 | 1.76 |
| Autocorrelation F | 0.754 | 1.98 |
| Heteroskedasticity F | 0.578 | 2.46 |
| Stability RESET F | 0.259 | 1.87 |

R-squared = 0.95; Adj. R-squared = 0.94; SER = 0.147; SSR = 0.843; LL = 27.80; F. Stat. = 96.06 (P. 0.000); AIC = −0.843; SC = −0.528; HQC = −0.724; DW = 1.73

Diagnostic Tests

| Stat.   | Prob. | DW |
|---------|-------|----|
| Normality (J-B) | 0.190 | 1.73 |
| Autocorrelation F | 0.667 | 2.00 |
| Heteroskedasticity F | 0.390 | 2.61 |
| Stability RESET F | 0.276 | 1.68 |

* indicates significance at 1% level.

3.2. Dynamic Econometric Modelling

As some of the main variables of the study, i.e., CH₄, N₂O and GDPP are found to follow non-normal distribution, and the likelihood that the variables may not follow an autoregressive (AR), and a first differenced random walk I(1), which in fact were reflected by the unreliability of the above estimated OLS models, the study proceeds to dynamic econometric methods of cointegration, VECM and Granger causality analysis.

Stationarity and Cointegration

1) Stationarity Analysis

For meaningful estimation of time series econometric models and for reliable results, the stationarity of the variables must be established otherwise, estimations may be spurious (Granger, 2001). The non-stationarity and presence of a unit root in the series implies that and any shock will have a permanent effect on the system of variables. Unit root tests, namely Augmented Dickey-Fuller (ADF), Dickey & Fuller (1981), and Philips Perron (PP), Phillips & Perron (1988) tests are commonly used for establishment of stationarity. This study uses the ADF and PP unit root tests. The general ADF test equation with p lags is written as:

\[ Δy_i = γ y_{i-1} + β_1 Δy_{i-1} + ⋯ + β_p Δy_{i-p} + ε_i \]  (3)

The null hypothesis (non-stationarity) is that \( H_0: γ = 0 \), and the alternative (sta-
tionarity) AR process $H_1$: $γ < 0$. Assuming a drift (a random walk with a nonzero mean period-to-period change) against stationarity, the ADF function is written as:

$$\Delta y_t = \alpha + γ y_t + β_1 Δy_{t-1} + \cdots + β_p Δy_{t-p} + ε_t$$  (4)

With a linear trend in order to test whether the series is $I(1)$ against the alternative that it is stationary around a fixed linear trend, a trend term component needs to be added along with the constant, i.e.,

$$\Delta y_t = \alpha + δt + γ y_t + β_1 Δy_{t-1} + \cdots + β_p Δy_{t-p} + ε_t$$  (5)

The lag $p$ should be large enough to make the error term $ε$ white noise. The estimated ADF statistics is compared with the simulated MacKinnon (2010) critical values, which employ a set of simulations to derive asymptotic results and to simulate critical values for arbitrary sample sizes. The ADF statistics must be larger than critical values in absolute value and have a minus sign. For $CH_4$, using the ADF and PP unit root tests, with the assumption of intercept only, and with trend and intercept, all variables included in the study are found to be nonstationary at level $I(0)$, but they all turn to be stationary at first difference $I(1)$ at 5 percent level of significance as presented in Table 3. For $N_2O$, using the ADF and PP unit root tests the study variables are found to be nonstationary at level but they all turn to be stationary at first difference $I(1)$ at 5 percent level of significant as presented in Table 4.

2) Cointegration

Given that all variables are found to be integrated at the first order, the long run nature of the relationships between $CH_4$, $N_2O$ and their explanatory variables included in the model are tested by the Johansen cointegration method. Applying this method, for $CH_4$ with the assumption of intercept only, the maximum Eigen value statistics indicate existence of at least three cointegrating vectors. With the assumption of intercept and trend in data, the maximum Eigen value statistics indicate existence of at least two cointegrating vectors as summarized in Table 5. For $N_2O$ with the assumption of intercept only, the trace statistics indicates existence of seven cointegrating vectors while the maximum Eigen value statistics indicate existence of at least four cointegrating vectors. With the assumption of intercept and trend in data, the maximum Eigen value statistics indicate that $N_2O$ is cointegrated with four vectors as summarized in Table 5.

Thus, stationarity of the study variables is established by the unit root tests and a long run equilibrium relationship is confirmed for both $CH_4$ and $N_2O$ with economic growth, agricultural growth and energy use in presence of trade openness and inflows of FDI. Moreover, it appears that emissions of $N_2O$ have more and persistent co-movements with economic growth, agricultural growth and energy use than emissions of $CH_4$. Upon establishment of stationarity at $I(1)$ and the cointegration of the variables, the study proceeds to estimate an unrestricted vector autoregressive VAR model upon which an optimal lag length is selected for estimation of VECM. Results of the optimal lag length are summarized in Table 6.
### Table 4. CH₄ and N₂O ADF & PP stationarity test results.

| Variable | Intercept | Trend & Intercept | Intercept | Trend & Intercept | Order of integration |
|----------|-----------|-------------------|-----------|-------------------|----------------------|
|          | ADF I(1)  | ADF I(1)          | PP I(1)   | PP I(1)           |                      |
| L(CH₄)   | −8.176*   | −8.110*           | −8.971*   | −8.971*           | I(1)                 |
| L(GDPP)  | −6.149*   | −6.129*           | −6.129*   | −6.129*           | I(1)                 |
| L(GDPP)² | −6.066*   | −6.056*           | −6.056*   | −6.056*           | I(1)                 |
| L(EUP)   | −8.887*   | −9.501*           | −9.510*   | −9.510*           | I(1)                 |
| L(OIL)   | −5.496*   | −5.595*           | −5.578*   | −5.578*           | I(1)                 |
| L(CPIN)  | −10.295*  | −10.188*          | −10.546*  | −10.546*          | I(1)                 |
| L(TOP)   | −8.381*   | −8.284*           | −8.171*   | −8.171*           | I(1)                 |
| L(FDI)   | −7.266*   | −7.190*           | −25.252*  | −25.252*          | I(1)                 |

* indicates stationary at 1% level; for the sake of space and ease of exposition only ADF and PP statistics for I(1) are reported.

| Intercept | Trend & Intercept | Intercept | Trend & Intercept | Order of integration |
|-----------|-------------------|-----------|-------------------|----------------------|
| L(N₂O)   | −7.443*           | −7.528*   | −7.443*           | −7.535* I(1)         |
| L(GDPP)  | −6.149*           | −6.129*   | −6.149*           | −6.129* I(1)         |
| L(GDPP)² | −6.066*           | −6.056*   | −6.004*           | −6.056* I(1)         |
| L(EUP)   | −8.887*           | −9.501*   | −9.046*           | −9.501* I(1)         |
| L(OIL)   | −5.496*           | −5.595*   | −5.482*           | −5.578* I(1)         |
| L(CPIN)  | −10.295*          | −10.188*  | −10.659*          | −10.546* I(1)        |
| L(TOP)   | −8.381*           | −8.284*   | −8.260*           | −8.171* I(1)         |
| L(FDI)   | −7.266*           | −7.190*   | −22.946*          | −25.252* I(1)        |

### Table 5. CH₄ and N₂O cointegration test results.

| H₀   | Intercept                | Trend & Intercept     | Intercept                | Trend & Intercept     |
|------|--------------------------|-----------------------|--------------------------|-----------------------|
|      | Eigen Value | Trace Statistic | Max-Eigen Statistic | Eigen Value | Trace Statistic | Max-Eigen Statistic |
| r = 0 | 0.823       | 269.837*      | 76.083*                   | 0.823       | 293.710*      | 76.256*                   |
| r ≤ 1 | 0.781       | 193.755*      | 66.783*                   | 0.781       | 217.454*      | 66.788*                   |
| r ≤ 2 | 0.600       | 126.972*      | 40.267*                   | 0.600       | 150.667*      | 42.636*                   |
| r ≤ 3 | 0.472       | 86.705*       | 28.135                    | 0.472       | 108.030*      | 35.021                    |
| r ≤ 4 | 0.382       | 58.570*       | 21.200                    | 0.382       | 73.009*       | 21.903                    |
| r ≤ 5 | 0.34        | 37.370*       | 18.679                    | 0.34        | 51.106*       | 19.510                    |
| r ≤ 6 | 0.306       | 18.676*       | 10.055                    | 0.306       | 31.596*       | 16.617                    |
| r ≤ 7 | 0.058       | 2.621         | 2.621                     | 0.058       | 14.980*       | 14.980                    |

| H₀   | Intercept                | Trend & Intercept     | Intercept                | Trend & Intercept     |
|------|--------------------------|-----------------------|--------------------------|-----------------------|
|      | Eigen Value | Trace Statistic | Max-Eigen Statistic | Eigen Value | Trace Statistic | Max-Eigen Statistic |
| r = 0 | 0.869       | 284.211*      | 89.313*                   | 0.869       | 300.806*      | 89.385*                   |

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Continued

| r ≤ 1 | 0.727 | 194.898* | 57.067* | 0.727 | 211.421* | 57.096* |
| r ≤ 2 | 0.651 | 137.832* | 46.301* | 0.658 | 154.325* | 47.243* |
| r ≤ 3 | 0.565 | 91.530* | 36.586* | 0.591 | 107.082* | 39.354* |
| r ≤ 4 | 0.370 | 54.945* | 20.351 | 0.371 | 67.728* | 20.394 |
| r ≤ 5 | 0.338 | 34.594* | 18.136 | 0.348 | 47.335* | 18.844 |
| r ≤ 6 | 0.267 | 16.458* | 13.688 | 0.331 | 28.490* | 17.706 |
| r ≤ 7 | 0.061 | 2.770  | 2.770   | 0.217 | 10.785  | 10.785 |

Note: * denotes rejection of the null hypothesis at the 0.05 level.

**Table 6.** CH4 and N2O lag length selection.

|       | Lag | LL     | LR     | FPE    | AIC   | SC    | HQ    |
|-------|-----|--------|--------|--------|-------|-------|-------|
| **CH4** |     |        |        |        |       |       |       |
| 1     | 1   | 168.081| NA     | 1.26e-12| −4.731| −2.136*| −3.769*|
| 2     | 2   | 236.975| 87.684*| 1.29e-12| −4.953| 0.237 | −3.029|
| 3     | 3   | 324.441| 79.515 | 9.71e-13*| −6.020*| 1.766 | −3.133|
|       |     |        |        |        |       |       |       |
| **N2O** |     |        |        |        |       |       |       |
| 0     | 0   | −85.378| NA     | 9.63e-09| 4.244 | 4.569 | 4.365 |
| 1     | 1   | 167.445| 402.218| 1.89e-12| −4.338| −1.419*| −3.256*|
| 2     | 2   | 237.800| 86.345*| 1.89e-12| −4.627| 0.887 | −2.582|
| 3     | 3   | 325.599| 75.826 | 1.56e-12*| −5.709*| 2.401 | −2.701|

Note: LR: sequentially modified LR test statistic (each test at 5% level); FPE: Final prediction error; AIC: Akaike information criterion; SC: Schwarz information criterion; HQ: Hannan-Quinn information criterion.

### 3.3. VECM Model Estimations

A VECM version of Equation (1) is estimated for CH4 emissions and of Equation (2) for N2O emissions, both on lag length of 2 according to LR criterion as in **Table 6**. Summary results of the estimated VECM for CH4 and N2O emissions are reported in **Table 7**.

The VECM models estimates show that the coefficients of N2O emissions with respect to economic growth and agricultural growth are much higher and more significant than the coefficients of CH4 with respect to economic growth and agricultural growth. Results of the two models for both types of emissions show that low level of economic growth is also associated with low level of emissions, but while it is found that emissions of CH4 increase significantly with the squared value of the GDP per capita, this does not hold for emissions of N2O in the long run. Positive coefficients for both CH4 and N2O emissions with respect to the squared value of GDP per capita contradict predictions of the EKC in the case of Sudan, more strongly and clearly for CH4 emissions. Also, N2O emissions are better correctly adjusting back to equilibrium than CH4 emissions in response to shocks in the system. The VECM models for both types of emissions proved to be stable and not miss-specified as depicted by **Figure 6** for CH4 and in **Figure 7** for N2O.
### Table 7. CH$_4$ and N$_2$O VECM summary results.

**CH$_4$ VECM**

| Variable  | Short Run Coefficient | Short Run T. stat. | Short Run P. value | Long Run Coefficient | Long Run T. stat. |
|-----------|------------------------|--------------------|--------------------|-----------------------|-------------------|
| $ECT_{t-1}$ | -0.34                  | -3.404             | 0.001**            | $I(CH_4)_{t-1}$      | 1.00              |
| $dL(CH_4)_{t-1}$ | 0.06                  | 0.334              | 0.739              | $I(GDP)_{t-1}$       | -1.55             |
| $dL(CH_4)_{t-2}$ | 0.08                  | 0.514              | 0.608              | $I(GDP)_{t-1}$       | 0.09              |
| $dL(GDP)_{t-1}$ | 0.60                  | 0.341              | 0.733              | $I(CPIN)_{t-1}$      | -2.03             |
| $dL(GDP)_{t-2}$ | 1.42                  | 0.744              | 0.458              | $I(EUP)_{t-1}$       | 0.59              |
| $dL(GDP)_{t-3}$ | -0.06                 | -0.428             | 0.669              | $I(OIL)_{t-1}$       | 0.15              |
| $dL(GDP)_{t-2}$ | -0.14                 | -0.917             | 0.365              | $I(TOP)_{t-1}$       | -1.01             |
| $dL(CPIN)_{t-1}$ | -1.01                 | -4.855             | 0.000***           | $I(FDI)_{t-1}$       | 0.09              |
| $dL(CPIN)_{t-2}$ | -0.55                 | -2.485             | 0.014**            | $I(FDI)_{t-2}$       | 0.09              |
| $dL(EUP)_{t-1}$ | 1.82                  | 2.766              | 0.006**            | $I(FDI)_{t-2}$       | 0.09              |
| $dL(EUP)_{t-2}$ | 0.69                  | 1.080              | 0.282              | C                     | 4.08              |
| $dL(OIL)_{t-1}$ | 0.38                  | 1.689              | 0.095*             | C                     | 4.08              |
| $dL(OIL)_{t-2}$ | -0.33                 | -1.490             | 0.138              | C                     | 4.08              |
| $dL(TOP)_{t-1}$ | -0.03                 | -0.198             | 0.844              | C                     | 4.08              |
| $dL(TOP)_{t-2}$ | -0.17                 | -1.102             | 0.272              | C                     | 4.08              |
| $dL(FDI)_{t-1}$ | 0.02                  | 2.241              | 0.026**            | C                     | 4.08              |
| $dL(FDI)_{t-2}$ | 0.01                  | 2.129              | 0.035**            | C                     | 4.08              |
| $C$         | 0.10                  | 3.807              | 0.000***           | C                     | 4.08              |

**N$_2$O VECM**

| Variable  | Short Run Coefficient | Short Run T. stat. | Short Run P. value | Long Run Coefficient | Long Run T. stat. |
|-----------|------------------------|--------------------|--------------------|-----------------------|-------------------|
| $ECT_{t-1}$ | -0.16                  | -2.063             | 0.040*             | $I(CH_4)_{t-1}$      | 1.00              |
| $dL(CH_4)_{t-1}$ | 0.00                  | 4.9e-05            | 1.000              | $I(GDP)_{t-1}$       | 0.32              |
| $dL(CH_4)_{t-2}$ | -1.45                 | -1.260             | 0.209              | $I(CPIN)_{t-1}$      | -1.88             |
| $dL(GDP)_{t-1}$ | 0.75                  | 0.600              | 0.549              | $I(EUP)_{t-1}$       | -0.27             |
| $dL(GDP)_{t-2}$ | 12.93                 | 1.98               | 0.09                | $I(OIL)_{t-2}$       | -0.584             |
| $dL(GDP)_{t-2}$ | -0.08                 | -0.742             | 0.459              | $I(TOP)_{t-1}$       | -0.53             |
| $dL(CPIN)_{t-1}$ | -0.47                 | -3.145             | 0.002**            | $I(FDI)_{t-1}$       | 0.07              |
| $dL(CPIN)_{t-2}$ | -0.24                 | -1.611             | 0.109              | $I(FDI)_{t-2}$       | 6.515***           |
| $dL(EUP)_{t-1}$ | 0.97                  | 2.202              | 0.029*             | $I(FDI)_{t-2}$       | 6.515***           |
| $dL(EUP)_{t-2}$ | 0.19                  | 0.439              | 0.661              | $I(FDI)_{t-2}$       | 6.515***           |
| $dL(OIL)_{t-1}$ | 0.18                  | 1.199              | 0.232              | $I(FDI)_{t-2}$       | 6.515***           |
| $dL(OIL)_{t-2}$ | -0.20                 | -1.309             | 0.192              | $I(FDI)_{t-2}$       | 6.515***           |
| $dL(TOP)_{t-1}$ | 0.08                  | 0.762              | 0.447              | $I(FDI)_{t-2}$       | 6.515***           |
| $dL(TOP)_{t-2}$ | 0.03                  | 0.279              | 0.781              | $I(FDI)_{t-2}$       | 6.515***           |
| $dL(FDI)_{t-1}$ | 0.01                  | 1.245              | 0.215              | $I(FDI)_{t-2}$       | 6.515***           |
| $dL(FDI)_{t-2}$ | 0.01                  | 1.344              | 0.180              | $I(FDI)_{t-2}$       | 6.515***           |
| $C$         | 0.06                  | 3.237              | 0.001**            | $I(FDI)_{t-2}$       | 6.515***           |
As presented in Table 8 the estimated VECM for both CH₄ and N₂O pass robustness requirements and all validity diagnostic tests of normality, autocorrelation, and heteroscedasticity. Data in the table also show that the N₂O VECM model is better fitted than that of CH₄.

### Table 8. Robustness and diagnostic tests.

|            | CH₄                      | N₂O                      |
|------------|--------------------------|--------------------------|
| **Robustness** | R-squared = 0.48; Adj. R-squared = 0.14; SSR = 0.183; SER = 0.084; F. stat. = 1.42; LL = 58.15; AIC = −1.82; SC = −1.10 | R-squared = 0.58; Adj. R-squared = 0.30; SSR = 0.400; SER = 0.124; F. stat. = 2.10; LL = 40.99; AIC = −1.05; SC = −0.32; SW = 2.02 |
| **Diagnostic Tests** | Stat. | P. value | Stat. | P. value |
| Normality | 27.91 | 0.032 | 15.41 | 0.495 |
| Autocorrelation | 116.40 | 0.576 | 113.06 | 0.661 |
| Heteroskedasticity | 1237.75 | 0.386 | 1233.51 | 0.418 |
| Stability: VEC specification imposes 7 unit roots, none of them is outside the unit root circle | |

**Figure 6.** CH₄ VECM stability: inverse roots of AR characteristic polynomial.

**Figure 7.** N₂O VECM stability: inverse roots of AR characteristic polynomial.
Granger non-causality or exogeneity of variables is also tested through the Wald test in order to judge which variables lead and which lag the others, for both CH₄ and N₂O emissions. As in Table 9, EUP and CPIN are found to be lagging (endogenous variables) and all other variables of interest are leading highly exogenous, which is consistent with the results of cointegration and VECM results. For N₂O, all variables are found leading highly exogenous and only N₂O is found to be lagging (endogenous variable).

In accordance with the VECM, impacts on CH₄ and N₂O and their volatility with economic and agricultural growth shocks are also assessed through the impulse response function (IRF). As in Table 10 CH₄ is largely explained by its own lagged shocks, followed by TOP, FDI, and the squared value of GDPP, with the least contribution coming from GDPP and CPIN. Table 10 also shows that N₂O is largely explained by its own lagged shocks, followed by TOP, FDI, and the GDPP, with the least contribution coming from squared value of GDPP, OIL and CPIN.

The method of variance decomposition shows that variations in CH₄ are much explained by CH₄ itself, TOP and FDI, than by EUP and CPIN. GDPP contributes the least in explaining variations in CH₄ as reported in Table 11. Also, the method of variance decomposition shows that variations in N₂O are much explained by N₂O itself, TOP and FDI, than by GDPP, OIL. CPIN, the squared value of GDPP and EUP contribute the least in explaining variations in N₂O as reported in Table 11.

### Table 9. CH₄ and N₂O Granger causality/block exogeneity Wald test.

| Dependent Variable | Chi-sq  | DF  | Prob. | Decision |
|--------------------|---------|-----|-------|----------|
| L(CH₄) | L(GDPP), L(GDPP)², L(EUP), L(OIL), L(CPIN), L(TOP), L(FDI) | 21.05  | 14  | 0.100 | Reject |
| L(GDPP) | L(CH₄), L(GDPP), L(EUP), L(OIL), L(CPIN), L(TOP), L(FDI) | 13.82  | 14  | 0.463 | Accept |
| L(GDPP)² | L(CH₄), L(GDPP), L(EUP), L(OIL), L(CPIN), L(TOP), L(FDI) | 13.97  | 14  | 0.452 | Accept |
| L(CPIN) | L(CH₄), L(GDPP), L(GDPP)², L(EUP), L(OIL), L(TOP), L(FDI) | 23.22  | 14  | 0.057 | Reject |
| L(EUP) | L(CH₄), L(GDPP), L(GDPP)², L(OIL), L(CPIN), L(TOP), L(FDI) | 23.77  | 14  | 0.049 | Reject |
| L(OIL) | L(CH₄), L(GDPP), L(GDPP)², L(EUP), L(CPIN), L(TOP), L(FDI) | 14.85  | 14  | 0.389 | Accept |
| L(TOP) | L(CH₄), L(GDPP), L(GDPP)², L(EUP), L(OIL), L(CPIN), L(FDI) | 14.63  | 14  | 0.404 | Accept |
| L(FDI) | L(CH₄), L(GDPP), L(GDPP)², L(EUP), L(OIL), L(CPIN), L(TOP) | 7.65   | 14  | 0.907 | Accept |

| Dependent Variable | Chi-sq  | DF  | Prob. | Decision |
|--------------------|---------|-----|-------|----------|
| L(N₂O) | L(GDPP), L(GDPP)², L(EUP), L(OIL), L(CPIN), L(TOP), L(FDI) | 32.40  | 14  | 0.004 | Reject |
| L(GDPP) | L(N₂O), L(GDPP), L(EUP), L(OIL), L(CPIN), L(TOP), L(FDI) | 13.66  | 14  | 0.475 | Accept |
| L(GDPP)² | L(N₂O), L(GDPP), L(EUP), L(OIL), L(CPIN), L(TOP), L(FDI) | 13.81  | 14  | 0.464 | Accept |
| L(CPIN) | L(N₂O), L(GDPP), L(GDPP)², L(EUP), L(OIL), L(TOP), L(FDI) | 20.44  | 14  | 0.117 | Accept |
| L(EUP) | L(N₂O), L(GDPP), L(GDPP)², L(OIL), L(CPIN), L(TOP), L(FDI) | 20.12  | 14  | 0.126 | Accept |
| L(OIL) | L(N₂O), L(GDPP), L(GDPP)², L(EUP), L(CPIN), L(TOP), L(FDI) | 13.25  | 14  | 0.507 | Accept |
| L(TOP) | L(N₂O), L(GDPP), L(GDPP)², L(EUP), L(OIL), L(CPIN), L(FDI) | 15.19  | 14  | 0.365 | Accept |
| L(FDI) | L(N₂O), L(GDPP), L(GDPP)², L(EUP), L(OIL), L(CPIN), L(TOP) | 6.29   | 14  | 0.959 | Accept |
Table 10. Response of L(CH₄) and L(N₂O).

### Response of L(CH₄)

| Period | L(CH₄) | L(GDPP) | L(GDPP)² | L(CPIN) | L(EUP) | L(OIL) | L(TOP) | L(FDI) |
|--------|--------|---------|----------|---------|--------|--------|--------|--------|
| 1      | 0.084  | 0.000   | 0.000    | 0.000   | 0.000  | 0.000  | 0.000  | 0.000  |
| 2      | 0.072  | 0.006   | 0.030    | −0.014  | 0.022  | 0.022  | 0.022  | −0.017 |
| 3      | 0.063  | −0.009  | 0.013    | 0.007   | 0.014  | 0.011  | 0.028  | −0.020 |
| 4      | 0.060  | 0.009   | 0.018    | 0.011   | 0.012  | 0.005  | 0.036  | −0.026 |
| 5      | 0.070  | 0.005   | 0.001    | −0.006  | 0.013  | 0.008  | 0.028  | −0.034 |
| 6      | 0.060  | 0.006   | −0.001   | 0.008   | 0.010  | 0.016  | 0.041  | −0.032 |
| 7      | 0.062  | 0.006   | −0.013   | 0.005   | 0.009  | 0.017  | 0.040  | −0.026 |
| 8      | 0.064  | 0.003   | −0.012   | 0.005   | 0.015  | 0.023  | 0.049  | −0.031 |
| 9      | 0.063  | 0.004   | −0.019   | 0.008   | 0.014  | 0.026  | 0.052  | −0.028 |
| 10     | 0.065  | 0.004   | −0.021   | 0.007   | 0.018  | 0.026  | 0.057  | −0.025 |

### Response of L(N₂O)

| Period | L(N₂O) | L(GDPP) | L(GDPP)² | L(CPIN) | L(EUP) | L(OIL) | L(TOP) | L(FDI) |
|--------|--------|---------|----------|---------|--------|--------|--------|--------|
| 1      | 0.124  | 0.000   | 0.000    | 0.000   | 0.000  | 0.000  | 0.000  | 0.000  |
| 2      | 0.113  | −0.006  | 0.036    | −0.037  | 0.025  | 0.034  | 0.035  | −0.042 |
| 3      | 0.096  | −0.017  | 0.020    | −0.006  | 0.012  | 0.008  | 0.042  | −0.054 |
| 4      | 0.086  | 0.027   | 0.030    | 0.002   | −0.013 | −0.011 | 0.068  | −0.067 |
| 5      | 0.100  | 0.029   | 0.019    | −0.030  | −0.004 | 0.006  | 0.045  | −0.092 |
| 6      | 0.094  | 0.041   | 0.019    | −0.011  | −0.012 | 0.014  | 0.077  | −0.095 |
| 7      | 0.081  | 0.054   | 0.000    | −0.015  | −0.010 | 0.019  | 0.078  | −0.077 |
| 8      | 0.094  | 0.049   | −0.002   | −0.020  | 0.001  | 0.031  | 0.090  | −0.078 |
| 9      | 0.090  | 0.053   | −0.003   | −0.012  | 0.000  | 0.037  | 0.101  | −0.075 |
| 10     | 0.092  | 0.054   | −0.007   | −0.017  | 0.007  | 0.032  | 0.107  | −0.067 |

Table 11. Variance decomposition of L(CH₄) and N₂O.

### Variance Decomposition of L(CH₄)

| Period | S.E. | L(CH₄) | L(GDPP) | L(GDPP)² | L(CPIN) | L(EUP) | L(OIL) | L(TOP) | L(FDI) |
|--------|------|--------|---------|----------|---------|--------|--------|--------|--------|
| 1      | 0.084| 100.000| 0.000   | 0.000    | 0.000   | 0.000  | 0.000  | 0.000  | 0.000  |
| 2      | 0.123| 80.9183| 0.254   | 6.039    | 1.365   | 3.178  | 3.155  | 3.076  | 2.015  |
| 3      | 0.145| 77.591 | 0.554   | 5.157    | 1.186   | 3.290  | 2.830  | 5.997  | 3.395  |
| 4      | 0.165| 73.040 | 0.746   | 5.120    | 1.346   | 3.083  | 2.269  | 9.286  | 5.112  |
| 5      | 0.185| 72.230 | 0.669   | 4.055    | 1.160   | 2.965  | 1.977  | 9.605  | 7.339  |
| 6      | 0.203| 69.111 | 0.654   | 3.384    | 1.121   | 2.718  | 2.287  | 12.173 | 8.554  |
| 7      | 0.219| 67.479 | 0.630   | 3.244    | 1.025   | 2.526  | 2.558  | 13.756 | 8.781  |
| 8      | 0.237| 64.686 | 0.556   | 3.020    | 0.914   | 2.546  | 3.126  | 16.016 | 9.137  |
| 9      | 0.255| 62.109 | 0.505   | 3.157    | 0.893   | 2.491  | 3.712  | 18.042 | 9.091  |
| 10     | 0.273| 59.719 | 0.465   | 3.320    | 0.846   | 2.587  | 4.152  | 20.128 | 8.785  |
### 3.4. Granger Causality Analysis

Long run causal relationships between CH$_4$, N$_2$O with the same set of their explanatory variables are tested by method of Granger causality. Results show a bi-directional causal relationship between agricultural growth and CH$_4$ emissions, while a unidirectional relationship is fund to run from agricultural growth to N$_2$O emissions. For both CH$_4$ and N$_2$O emissions, causal relationships between the independent variables, causal relationships are found to be concentrated around economic and agricultural growth. Granger causality results for CH$_4$ and N$_2$O are summarized and presented in Table 12.

**Table 12.** Granger causality tests results for CH$_4$ and N$_2$O.

| CH$_4$ | H$_0$: CH$_4$ as the dependent | F-Stat. | Prob. | Decision | Direction of causality |
|---|---|---|---|---|---|
| H$_0$: L(GDPP) does not Cause L(CH$_4$) | 0.231 | 0.795 | Accept | None |
| H$_0$: L(CH$_4$) does not Cause L(GDPP) | 1.690 | 0.198 | Accept | None |
| H$_0$: L(GDPP)$^2$ does not Cause L(CH$_4$) | 0.282 | 0.756 | Accept | None |
| H$_0$: L(CH$_4$) does not Cause L(GDPP)$^2$ | 1.654 | 0.204 | Accept | None |
| H$_0$: L(CPIN) does not Cause L(CH$_4$) | 3.347 | 0.045 | Reject | CPIN to CH$_4$ |
| H$_0$: L(CH$_4$) does not Cause L(CPIN) | 2.993 | 0.062 | Reject | CH$_4$ to CPIN |
| H$_0$: L(EUP) does not Cause L(CH$_4$) | 1.016 | 0.371 | Accept | None |
| H$_0$: L(CH$_4$) does not Cause L(EUP) | 0.346 | 0.710 | Accept | None |
| H$_0$: L(OIL) does not Cause L(CH$_4$) | 0.390 | 0.680 | Accept | None |
| H$_0$: L(CH$_4$) does not Cause L(OIL) | 1.968 | 0.153 | Accept | None |
| H$_0$: L(TOP) does not Cause L(CH$_4$) | 1.201 | 0.311 | Accept | None |
| H$_0$: L(CH$_4$) does not Cause L(TOP) | 0.004 | 0.996 | Accept | None |
| H$_0$: L(FDI) does not Cause L(CH$_4$) | 0.274 | 0.762 | Accept | None |
| H$_0$: L(CH$_4$) does not Cause L(FDI) | 4.130 | 0.023 | Reject | CH$_4$ to FDI |
### H0: Independents

| H0: L(CPIN) does not Cause L(GDPP) | 3.377 | 0.044 | Reject | CPIN to GDPP |
| H0: L(OIL) does not Cause L(GDPP) | 5.031 | 0.011 | Reject | OIL to GDPP |
| H0: L(TOP) does not Cause L(GDPP) | 7.302 | 0.002 | Reject | TOP to GDPP |
| H0: L(OIL) does not Cause L(GDPP)² | 4.594 | 0.016 | Reject | OIL to (GDPP)² |
| H0: L(CPIN) does not Cause L(GDPP)² | 3.449 | 0.042 | Reject | CPIN to (GDPP)² |
| H0: L(TOP) does not Cause L(GDPP)² | 7.232 | 0.002 | Reject | TOP to (GDPP)² |
| H0: L(CPIN) does not Cause L(OIL) | 3.550 | 0.038 | Reject | CPIN to OIL |
| H0: L(FDI) does not Cause L(OIL) | 4.129 | 0.023 | Reject | FDI to OIL |
| H0: L(OIL) does not Cause L(FDI) | 2.430 | 0.101 | Reject | OIL to FDI |
| H0: L(CPIN) does not Cause L(FDI) | 8.518 | 0.001 | Reject | CPIN to FDI |

### N₂O

| H0: N₂O as the dependent | F-Stat. | Prob. | Decision | Direction of causality |
|---------------------------|--------|------|----------|------------------------|
| H0: L(GDPP) does not Cause L(N₂O) | 0.818 | 0.449 | Accept | None |
| H0: L(N₂O) does not Cause L(GDPP) | 2.449 | 0.099 | Reject | N₂O to GDPP |
| H0: L(GDPP)² does not Cause L(N₂O) | 0.773 | 0.468 | Accept | None |
| H0: L(N₂O) does not Cause L(GDPP)² | 2.396 | 0.104 | Reject | N₂O to (GDPP)² |
| H0: L(CPIN) does not Cause L(N₂O) | 5.826 | 0.006 | Reject | CPIN to N₂O |
| H0: L(N₂O) does not Cause L(CPIN) | 1.323 | 0.278 | Accept | None |
| H0: L(EUP) does not Cause L(N₂O) | 0.993 | 0.380 | Accept | None |
| H0: L(N₂O) does not Cause L(EUP) | 1.137 | 0.331 | Accept | None |
| H0: L(OIL) does not Cause L(N₂O) | 0.953 | 0.394 | Accept | None |
| H0: L(N₂O) does not Cause L(OIL) | 2.562 | 0.090 | Reject | N₂O to OIL |
| H0: L(TOP) does not Cause L(N₂O) | 1.139 | 0.331 | Accept | None |
| H0: L(N₂O) does not Cause L(TOP) | 0.093 | 0.912 | Accept | None |
| H0: L(FDI) does not Cause L(N₂O) | 0.715 | 0.495 | Accept | None |
| H0: L(N₂O) does not Cause L(FDI) | 2.872 | 0.068 | Reject | N₂O to FDI |

### H0: Independents

| H0: L(CPIN) does not Cause L(GDPP) | 3.377 | 0.044 | Reject | CPIN to GDPP |
| H0: L(OIL) does not Cause L(GDPP) | 5.031 | 0.011 | Reject | OIL to GDPP |
| H0: L(TOP) does not Cause L(GDPP) | 7.302 | 0.002 | Reject | TOP to GDPP |
| H0: L(OIL) does not Cause L(GDPP)² | 4.594 | 0.016 | Reject | OIL to (GDPP)² |
| H0: L(CPIN) does not Cause L(GDPP)² | 3.449 | 0.042 | Reject | CPIN to (GDPP)² |
| H0: L(TOP) does not Cause L(GDPP)² | 7.232 | 0.002 | Reject | TOP to (GDPP)² |
| H0: L(CPIN) does not Cause L(OIL) | 3.550 | 0.038 | Reject | CPIN to OIL |
| H0: L(FDI) does not Cause L(OIL) | 4.129 | 0.023 | Reject | FDI to OIL |
| H0: L(OIL) does not Cause L(FDI) | 2.430 | 0.101 | Reject | OIL to FDI |
| H0: L(CPIN) does not Cause L(FDI) | 8.518 | 0.001 | Reject | CPIN to FDI |
4. Discussions and Conclusion

This study comparatively investigated the effects of economic growth, agricultural growth and energy use on methane and nitrous oxide emissions in Sudan using annual time series data over the period 1970-2016. The estimated OLS models for emissions of both gases indicate positively signed and statistically significant coefficients of the relationship between the squared GDP per capita and CH₄ and N₂O emissions. These results indicate that the EKC hypothesis does not hold for both gas emissions in Sudan. However, the study has established a long run equilibrium relationship for emissions of both CH₄ and N₂O in their relation to economic growth, agricultural growth and energy use in presence of trade openness and inflows of foreign direct investments. Emissions of N₂O are found to have more and persistent co-movements with economic growth, agricultural growth and energy use than emissions of CH₄. For CH₄ emissions, the estimated VECM shows that emissions of this trace gas are significantly affected by economic growth, TOP and FDI with no effect of agricultural growth in the short run, while its emissions are found to be significantly affected by economic growth, agricultural growth, TOP and FDI in the long run. It also shows nonexistence of an EKC in the long run which is consistent with the OLS finding. For N₂O, the VECM model results show that emissions of this trace gas are more significantly than CH₄ affected by energy use, agricultural growth and FDI in the short run, while significantly affected by economic growth, agricultural growth, TOP and FDI in the long run. Also, no EKC is found for N₂O emissions. Impulse response and variance decomposition analysis confirm that emissions of N₂O are more significantly than CH₄ affected by economic growth, agricultural growth and energy use than emissions of CH₄. Granger causality test shows existence of only one bidirectional relationship between CH₄ and agricultural growth and only one unidirectional relationship running from CH₄ to FDI. For N₂O there exists only one unidirectional relationship running from agricultural growth to N₂O while there is unidirectional relationship running from N₂O emissions to GDPP, the squared value of GDPP, OIL consumption and FDI with no sign of significant feedback effects. These results suggest that policies toward control of N₂O emissions will have significant negative effects on economic growth, and inflows of FDI may likely be discouraged with stringent environmental policies toward nitrous oxide emissions.

The study concludes that N₂O emissions are more responsive to changes in economic and agricultural growth compared with CH₄ emissions. Furthermore, energy use only affects N₂O emissions with no effect on CH₄ emissions. Oil consumption has no effect on emissions of both CH₄ and N₂O. Results from Granger causality analysis suggest that economic growth could be pursued without significant environmental harm from both CH₄ and N₂O emissions. However, policies toward control of N₂O emissions in particular should be set and implemented with caution as their effects on emissions will be transmitted to negatively affecting economic growth, and inflows of FDI. Furthermore, the
findings suggest that Sudan should adopt energy efficiency measures, expansion of production and use of liquified petroleum gas and place restrictions on production and use of fuel woods and charcoal for low carbon economy and green growth. Again, such policy measures should more effective if cautiously directed to control of N₂O emissions within the country INDCs for the purpose of dealing with climate change obligations, more through than to CH₄ emissions control. As a least developed country (LDC) Sudan is not obliged to pursue a GHG emission reduction target. However, the country has set plans to reduce GHG emissions and pursue low-carbon development, promoting sustainable resource management in balancing national economic objectives and sustainable development requirements. Notwithstanding that Sudan INDCs give priority to energy, forestry and waste sectors in mitigation of CO₂, CH₄ and N₂O emissions, Sudan Intended Nationally Determined Contributions (Republic of Sudan, 2015). Also, within the INDCs, the energy intensity of the economy defined as total primary energy use per unit of GDP can also be reduced by relocation of resources from energy intensive sectors to labour and capital intensive sectors. The emission intensity of energy, represented by CO₂ per unit of energy can also be decreased by substitution of fuels (with lower emission factors) and through increases of renewable energies in the country’s energy mix.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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