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The power of financial innovation in neutralizing carbon emissions: the case of mobile money in Somalia

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Abstract
Financial innovation is a crucial component of financial sector development that impacts economic well-being. This study examines the causal link between mobile money and carbon emissions in Somalia to determine the link between financial innovation and carbon emissions. This study used quarterly data from 2010 to 2020 and the bound cointegration and Johansen methods to investigate the cointegration between variables. This study uses an autoregressive distributed model to estimate the model's short-run dynamics and long-term effects. Carbon emission is the dependent variable, while energy consumption, affluence, mobile money, population growth, and urbanization are the explanatory variables. This study reveals that mobile money and affluence reduce carbon emissions in the short and long run. Moreover, although population growth and urbanization are positively related to carbon emissions in the long run, their short-run impacts on carbon emissions are insignificant. The study also revealed that energy consumption insignificantly affects carbon emissions in the short and long run. Urbanization is the dominant factor contributing to carbon emissions, whereas mobile money effectively reduces carbon emissions. Our results imply that mobile money is instrumental in providing financial services such as insurance, credit savings, remittances, and government transfers to people dealing with environmental realities.

Keywords Mobile money · Financial innovation · Carbon emissions · Environmental quality

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1 Introduction

Financial innovation has a long-reaching effect on financial sector development and the health of the entire economy. This is due to its ability to effectively manage adverse economic shocks and influence industrial reformation, household consumption, and environmental well-being (Nasreen et al., 2017; Ziaei, 2015). However, financial development can have positive and negative effects on the environment. For example, it can protect the environment by providing necessary resources, but it can also finance consumption that depreciates the ecological quality (Adebayo & Odugbesan, 2021; Baloch et al., 2021; Kirikkaleli et al., 2021).

The economic literature is widely divided on the role of financial development in the environment. Financial development has been found to promote access to credit and allow households to purchase energy-consuming home appliances and cars that pollute the environment (Su et al., 2023; Acheampong, 2019; Sadorsky, 2010; Xing et al., 2017). Credit availability helps firms invest in new equipment and undertake an industrial restructuring, increasing carbon emissions (Aye & Edoja, 2017). Meanwhile, empirical studies have indicated that financial development promotes environmental sustainability by facilitating research and development, easing capital accessibility, and enabling firms and governments to invest in green technology and mitigate climate change (Manzoor et al., 2021; Acheampong, 2019; Gok, 2020; Tamazian & Rao, 2010; Tamazian et al., 2009; Yuxiang & Chen, 2010).

Studies have also associated climate vulnerability with low financial development in East African communities. Approximately 73 percent of adults in Kenya, 56 percent in Tanzania, and 46 percent in Uganda are financially excluded and cannot access financial services (Demirguc-Kunt et al., 2017; Van Hove & Dubus, 2019). A lack of access to financial services prevents farmers from adopting clean and smart agricultural technology and forces them to continue using old equipment and traditional practices that raise carbon emissions and exacerbate climate change exposure (Asongu and Acha-Anyi, 2017; Asongu et al., 2016). Furthermore, the diffusion of financial technology can expand financial services and reduce financial exclusion (Shaikh et al., 2023; Wellalage et al., 2022).

Mobile money is an innovative financial technology widely embraced in Africa and is used to make payments, transfer money, and provide access to finance for the unbanked population (Johnson, 2016). Several studies have looked at the economic impacts of mobile money in Africa (Mohamed & Nor, 2021; Afawubo et al., 2020; Rugemintwari et al., 2018; Jack & Suri, 2014; Jack et al., 2013; Munyegera & Matsumoto, 2016; Aker et al., 2016) and documented that mobile money aids financial inclusion and development. Somalia is an African country in which mobile money has a high adoption rate and is utilized for various functions of money (World Bank, 2018). Mobile money can foster financial and environmental sustainability by providing eco-friendly financial services and pioneering innovative payment systems that promote financial development. The existing literature suggests that low-income countries have lower levels of financial development and are susceptible to the adverse effects of climate change. Therefore, policymakers are determined to implement measures to reduce carbon emissions and are interested in the potentiality of mobile money in this regard. However, the literature in this domain is almost nonexistent in Somalia. While several studies, including those by Shahbaz et al. (2016); Bekhet et al. (2017); Zaidi et al. (2019); Nathaniel and Iheonu (2019); and Asongu et al., (2019), have investigated the relationship between financial development and environmental quality, these studies used different metrics to measure financial development and did not consider the widespread use of mobile money in East African countries like Somalia.

This study contributes to the literature by separating the long-run and short-run effects of mobile money on carbon emissions. This econometric procedure is used to unveil information that benefits policymakers attempting to cope with the adverse effects of climate change in Somalia and Africa. The series behavior of the variables is checked through the augmented Dickey–Fuller (ADF) test and the Phillips–Perron (PP) unit root test, while cointegration between the variables is examined using the Johansen cointegration test. Autoregressive distributed lag (ARDL) is applied to uncouple the long-run relationship and short dynamics of the coefficients.

Moreover, this study follows a unique approach by modeling the factors contributing to Somalia's carbon emissions, including mobile money. It also highlights the significance of expanding financial access to promote the adoption of green technology and emphasizes the effectiveness of mobile money for reaching financial inclusion. The findings of this study suggest that mobile money can consolidate carbon control endeavors since it can offer access to clean and affordable energy sources that reduce carbon emissions. Mobile money provides affordable financial services such as insurance, remittances, and government transfers to those struggling with climate shocks. It can also complement climate adaptation efforts and facilitate clean energy availability via solar-powered energy, which reduces carbon emissions. The remainder of this paper is organized as follows. Section 2 reviews the related literature. Section 3 discusses the theoretical framework and methodology. Section 4 presents the estimated results and discussion. Finally, Sect. 5 provides conclusions and policy implications.

2 Literature review

The effect of financial innovation on the environment has recently received considerable attention, though different researchers have provided different conclusions. A substantial amount of recent literature (e.g., Muganyi et al., 2021; Qin et al., 2022, 2023) has examined the role of financial technology in carbon neutralization. Specifically, Qin et al. (2023) studied the impact of blockchain markets and green finance on carbon neutrality in China and found that both blockchain markets and green finance promoted carbon neutrality, though the effect of green finance was stable and slow. Likewise, Su et al. (2022a) employed the Granger causality test to investigate how green credit can reduce emissions, revealing that it had no significant impact during its early stages. However, the continuous improvement of the green credit system positively impacted air quality.

Another study by Su et al. (2022b) utilized a wavelet-based quantile-on-quantile approach to analyze the effectiveness of renewable energy and technological innovation in promoting net zero emissions in the USA. The researchers found that renewable energy consumption effectively mitigated emissions, whereas technological innovation did not significantly reduce emissions. A similar study by Qin et al. (2022) examined the role of sustainable finance and renewable energy in promoting carbon neutrality in the USA. Their results show that renewable energy has a short-term negative impact on carbon emissions, whereas sustainable finance has a more prolonged and substantial impact than renewable energy.

Muganyi et al. (2021) presented comparable results using a difference-in-differences approach to study the relationship between green finance, fintech, and environmental protection in China. Specifically, they found that green finance significantly reduced industrial gas emissions, while fintech reduced sulfur dioxide emissions. Similarly, Yang et al. (2021) examined the link between green finance, fintech, and the quality of economic development in China. Their findings revealed that green finance facilitated high-quality economic development, which, in turn, positively affected environmental efficiency and economic structure; meanwhile, fintech strengthened the role of green finance in driving economic development.

Empirical evidence from the panel data confirms the provenance of financial technology in controlling carbon emissions. Tao et al. (2022) investigated the role of fintech in facilitating the transition to a low-carbon economy from a global perspective and found that fintech supported the reduction of greenhouse gases and the transition to a low-carbon economy. Furthermore, Elhedadd et al. (2021) studied the effect of the Fourth Industrial Revolution on the environment, specifically examining the link between electronic finance and pollution in the Organization of Economic Co-operation and Development (OECD) countries. This study utilized fixed effects and random effects models and found that electronic finance reduces carbon emissions. In other research, Ahmed et al. (2021) examined the asymmetric effect of innovation shocks on carbon emissions in OECD countries and found that positive shocks improve the environment, whereas negative shock of innovation harms the environment.

Financial development plays a crucial role in carbon emissions and environmental sustainability. However, the effect of financial development on carbon emissions is a dynamic and evolving field. Many empirical studies have investigated the association between financial development and environmental quality, though the results have varied. Dogan and Seker (2016), Xiong and Qi (2016), Saidi and Mbarek (2017), Xing et al. (2017), Farhani and Solarin (2017), Zaidi et al. (2019), Zafar et al. (2019), and Shuai et al. (2019) stated that financial development negatively impacts carbon emissions. Furthermore, Dogan and Seker (2016) examined the relationship between financial development and carbon emissions using panel data from 1985 to 2011 collected from 23 countries and found that financial development reduced carbon emissions. Saidi and Mbarek (2017) presented a similar result; after studying the impact of financial development and carbon emissions in 19 emerging countries using panel data from 1990 to 2013, they revealed a negative relationship between financial development and carbon emissions. In another study, Zaidi et al. (2019) examined globalization, access to finance, and carbon emissions in 17 Asian countries and discovered long-run and short-run negative relationships between financial development and carbon emissions.

Xing et al. (2017) investigated financial development and carbon emissions in China and concluded that financial development diminishes carbon emissions. Moreover, Farhani and Solarin (2017) studied financial development and the energy demand in the USA from 1973 to 2014, finding that financial development diminished energy consumption. Zafar et al. (2019) reported a similar result, stating that financial development reduces carbon emissions and promotes environmental quality.

In contrast, other studies have indicated that financial development contributes to carbon emissions and environmental degradation. For example, Al-Mulali (2015) examined financial development, pollution, economic growth, and trade openness in Europe and found that financial development contributed to carbon emissions. Shahbaz et al. (2016) presented a comparable result indicating that financial development and carbon emissions are unidirectionally related and that positive shocks of financial development increase carbon emissions. Furthermore, Riti et al. (2022) confirmed that financial development accelerated carbon emissions, and Pata (2018) stated that financial development increased carbon emissions, whereas exports decreased carbon emissions in Turkey. Another study in Turkey by Cetin et al. (2018) revealed a positive link between financial development and carbon emissions.

Moreover, Ali et al. (2019) found positive and significant long-run and short-run relationships between financial development and carbon emissions. In other research, Hao et al. (2016) addressed the role of financial development in environmental degradation, revealing that a high level of financial development led to environmental degradation. Meanwhile, several other studies exploring the neutrality hypothesis found no significant relationship between financial development and carbon emissions or environmental degradation (Omri et al., 2015; Abbasi & Riaz, 2016; Ayeche et al., 2016; Ghorashi and Rad, 2018).

Mobile money has the potential to influence economic activities and, consequently, impact carbon emissions. Some empirical studies have concentrated on how mobile money can intersect with economic activities. Such studies include that by Mohamed and Nor (2022), who found that mobile money has broad macroeconomic benefits and contributes to income and consumption in Somalia. Furthermore, according to Abiona and Koppensteiner (2020), mobile money increased consumption during shock periods and improved capital investment. Batista and Vicente (2020) added that mobile money improves the savings of smallholder farmers. Ahmed and Cowan (2021) revealed that mobile money facilitates informal browning and helps households access health care services. The literature also shows the vast economic impact of mobile money; however, a knowledge gap remains regarding its environmental effects.

A brief review of the relevant literature reveals that considerable efforts have been made to study the relationship between financial development and environmental sustainability. However, the findings of previous studies are inconsistent and inconclusive, raising the need for further research to clarify the relationship between financial development and environmental quality. Therefore, this study aims to shed light on the overall carbon emissions linked to digital technologies, specifically mobile money, emphasizing that mobile money has the potential to contribute to reduced carbon emissions and facilitate sustainable development when compared to traditional financial services and cash-based transactions.

3 Theoretical framework and methodology

This study applies the Stochastic Impact by Regression on Population, Affluence, and Technology (STIRPAT) framework to illustrate the link between mobile money and carbon emissions. Ehrlich and Holdren (1971) explored the correlation between environment, population size, and human well-being. They created an IPAT model, which comprises the four factors of environment (I), population (P), affluence (A), and technology (T). A mathematical presentation of the model is given in Eq. (1):

$$I = P \times A \times T \tag{1}$$

The model is generally used to examine the factors that impact environmental quality. However, the IPAT model has several limitations that complicate its empirical application. For one, the model cannot test the hypotheses, as it assumes that population, affluence, and technology have proportional effects on the environment. Moreover, the IPAT model can only control a single variable that may not reflect the factors that lead to environmental pressure. To overcome these limitations, Dietz and Rosa (1997) modified the model and developed the STIRPAT model. This model permits hypothesis testing and can conduct an unproportionate statistical analysis of the impact of population and affluence on the environment. Equation (2) is the STIRPAT equation:

$$I_i = aP_i^b A_i^c T_i^d e_i \tag{2}$$

In the above equation, I is the environment; P is the population; A is affluence; T is technology; and a, b, c, and d are the parameters to be estimated. The model in Eq. (2) is converted to a logarithm to test the hypothesis; Eq. (3) is obtained as a result:

$$\ln\left(I_{it}\right) = a + b\ln\left(P_{it}\right) + c\ln\left(A_{it}\right) + d\ln\left(T_{it}\right) + e_i \tag{3}$$

Ihsan et al. (2022), Trinh et al. (2023), Saidi and Mbarek (2017), and Abdelfattah et al. (2018) used the STRIPAT model to examine factors that affect carbon emissions. Meanwhile, the present study utilizes the STIRPAT framework to examine the link between mobile money and carbon emissions. The model was developed as shown in Eq. (4):

$$\ln CO_{2t} = \beta_0 + \beta_1 \ln \mathrm{ENC}_t + \beta_2 \ln \mathrm{MM}_\mathrm{t} + \beta_3 \ln \mathrm{AFFL}_t + \beta_4 \ln \mathrm{P.G.}_t + \beta_5 \ln \mathrm{U.R.}_t + \varepsilon_t \tag{4}$$

In the above equation, CO_2 is carbon emission, ENC is carbon emission, AFFL is affluence, MM is mobile money, U.R. is urbanization, t is time, and e is the error term.

3.1 Model specification

This study examines the power of financial innovation to control carbon emissions by studying the link between carbon emissions and energy use, mobile money, affluence, population growth, and urbanization. Equation (4) shows the association between carbon emissions, energy use, mobile money, affluence, population growth, and urbanization. The ARDL model requires the cointegration between the variables of interest to be checked. The long-run relationship between the variables is essential for this method, and the means and variance must be constant.

The time-series variables do not always ensure the consistency of the variance and the means, and most cointegration methods encounter estimation or interpretation errors. These problems are overcome in this study by using the ARDL bound test approach to test the cointegration between the variables. The ARDL approach is utilized in this study for small-sized data, and the ARDL method is specified as follows.

$$\begin{aligned}
\mathrm{InCO}_{2t} = {} & \psi_0 + \psi_1 \sum_{i-1}^{p} \Delta\mathrm{InCO}_{2t-1} + \psi_2 \sum_{i-1}^{p} \Delta\mathrm{InENC}_{t-1} + \psi_3 \sum_{i-1}^{p} \Delta\mathrm{InMM}_t \\
& + \psi_4 \sum_{i-1}^{p} \Delta\mathrm{InAFFL}_{t-1} + \psi_5 \sum_{i-1}^{p} \Delta\mathrm{InP.G.}_{t-1} + \psi_6 \sum_{i-1}^{p} \Delta\mathrm{InU.R.}_{t-1} \\
& + \delta_1 \mathrm{InCO}_{2t-1} + \delta_2 \mathrm{InENC}_{t-1} + \delta_3 \mathrm{InMM}_{t-1} \\
& + \delta_4 \mathrm{InAFFL}_{t-1} + \delta_5 \mathrm{InP.G.}_{t-1} + \delta_6 \mathrm{InU.R.}_{t-1} + \varepsilon_t
\end{aligned} \tag{5}$$

In Eq. (5), Δ is the difference operator, ψ represents the short-run coefficient, Δ represents the long-run coefficient, and ε_t is the error term. F-statistics are used to determine the long-run co-movements between the considered variables. The ARDL cointegration model is strong enough to deal with variables integrating with different orders, which becomes complicated with small sample-sized variables with one long-run linkage. F-statistics are also utilized to identify the long-run linkage between the variables. A long-run relationship between the variables exists when the F-statistic exceeds the critical value. This approach is useful because it can identify cointegrating vectors among many cointegrating vectors. If a cointegration relationship is found between CO_2 emissions, energy consumption, mobile money, affluence, population growth, and urbanization, the long-run relationship is estimated using Eq. (6):

$$\begin{aligned} \ln CO_{2t} = \omega_0 + \omega_1 \sum_{i-1}^{p} \ln CO_{2t-1} + \omega_2 \sum_{i-1}^{p} \ln ENC_{t-1} + \omega_3 \sum_{i-1}^{p} \ln MM_{t-1} \\ + \omega_4 \sum_{i-1}^{p} \ln AFFL_{t-1} + \omega_5 \sum_{i-1}^{p} \ln P.G._{t-1} + \omega_6 \sum_{i-1}^{p} \ln U.R._{t-1} + \varepsilon_t \end{aligned} \tag{6}$$

If a long-run relationship is found, then the short-run relationship between the variables is estimated using Eq. (7):

$$\begin{aligned} \Delta \ln CO_{2t} = \varphi_0 + \varphi_1 \sum_{i-1}^{p} \Delta \ln CO_{2t-1} + \varphi_2 \sum_{i-1}^{p} \Delta \ln ENC_{t-1} + \varphi_3 \sum_{i-1}^{p} \Delta \ln MM_{t-1} \\ + \varphi_4 \sum_{i-1}^{p} \Delta \ln AFFL_{t-1} + \varphi_5 \sum_{i-1}^{p} \Delta \ln P.G._{t-1} + \varphi_6 \sum_{i-1}^{p} \Delta \ln U.R._{t-1} + \phi ECT_{t-1} + \varepsilon_t \end{aligned} \tag{7}$$

In Eq. (7), ϕ is the error correction coefficient representing the speed of the modification, and the error correction method shows the speed of the adjustment of the restoring equilibrium with respect to the short-run shock.

3.2 Description of the data and the variables

This study uses quarterly data from 2010 to 2020, and Table 1 presents the data sources. Mobile money usage commenced in Somalia in 2010 and has transformed how business is conducted and financial services are delivered. In addition, mobile money has been substituted for Somalia Shilling, and most transactions are now completed via mobile money payments. The dependent variable is carbon emissions, while the explanatory variables are energy consumption, mobile money, affluence, population growth, and urbanization.

Table 1 data sources and the measurements

Variable	Symbol	Measurement	Source
Carbon emission	CO_2	Tons	WWI
Energy consumption	ENC	Energy intensity ratio	WWI
Mobile money	MM	Million USD	Telecom Co
Affluence	AFFL	GDP per capita	WWI
Population growth	P.G	Percentage	WWI
Urbanization	U.R	Percentage of urban Population	WWI

*WWI: World Development Indicators

Following Poumanyvong and Kaneko (2010) and Liddle (2015), carbon emissions are measured as metric tons per capita; the population is measured in millions, energy consumption is measured by energy intensity ratio, affluence is measured by real GDP per capita, and urbanization is measured as the percentage of the urban population comprising the total population. The number of mobile money transactions is a measure of mobile money. Data on carbon emission, energy consumption, affluence, population, and urbanization were collected from the World Development Indicators. Mobile money data were retrieved from telecom companies in Somalia.

4 Results and discussion

4.1 Summary of descriptive statistics

The mean, standard deviation, and maximum and minimum values of all variables were calculated and are presented in Table 2. The results show that the mean carbon emission was 649 metric tons with a standard deviation of 15.90. Furthermore, the maximum carbon emission value was 690 metric tons, while the minimum amount of emission was 630 metric tons. The mean energy consumption was 0.048, with a standard deviation of 0.0021 and minimum and maximum values of 0.04523 and 0.0523. The mean affluence was $91.13, with a standard deviation of 3.12, a minimum value of $88.93, and a maximum value of $104.

The mean value of mobile money was $151.7 million, the maximum value was $230 million, and the minimum was $648,000. The mean population growth was 0.0205 percent, with a maximum of 0.1693 percent and a minimum of 0.0108 percent. Furthermore, the mean urbanization was 42.60 percent, with a maximum of 44.97 percent and a minimum of 39.31 percent. Mobile money and affluence had large standard deviations, indicating that people vary in terms of how many mobile money transactions they perform and their income level.

Figure 1 depicts the carbon emissions that Somalia has produced within the past 10 years. The upward trend in carbon emissions is attributed to the widespread use of technology-dependent devices, including machines, vehicles, and appliances, which are known to be the main sources of emissions in the region. Furthermore, the increased stability and security of large cities have resulted in longer business hours, consequently raising carbon emissions levels in Somalia.

Figure 2 displays the fluctuation in energy consumption throughout the decade, with a noticeable decrease in the consumption ratio. This decrease is attributed to various factors, such as economic growth, fluctuations in energy prices, and structural changes in

Table 2 Descriptive statistics of the variables

Statistics	CO_2	ENC	AFFL	MM	PG	UR
Mean	649.0909	0.048355	91.13306	151.752	0.020562	42.60383
Std. dev	15.90767	0.002129	3.126935	696792.2	0.047137	1.519367
Maximum	690.0000	0.052309	104.0000	230.00	0.169369	44.97100
Minimum	630.0000	0.045239	88.93688	0.648200	−0.010841	39.31000

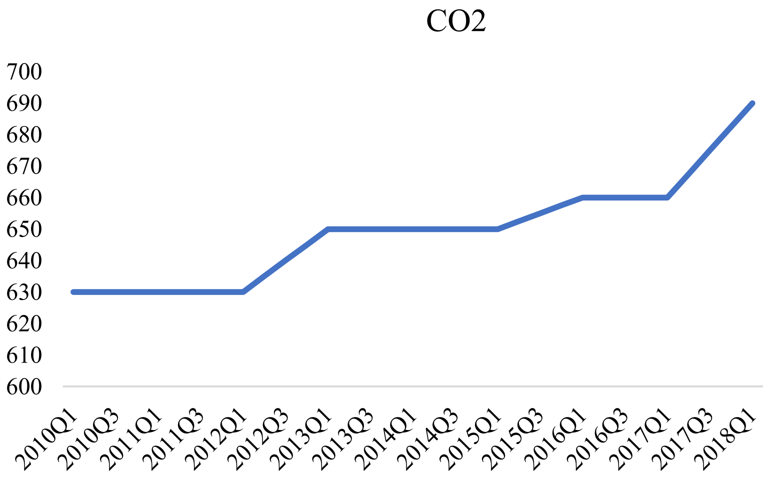

Fig. 1 CO_2

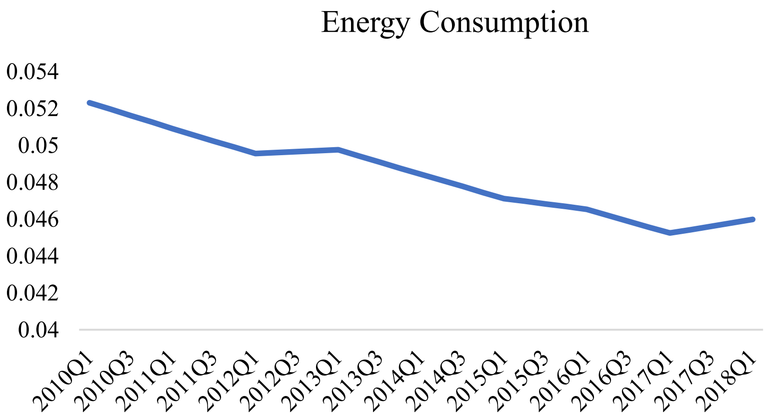

Fig. 2 Energy consumption

the economy. The service sector has seen significant growth, and international trade has expanded, which has impacted energy consumption in Somalia.

Figure 3 shows the level of consumer affluence in Somalia, which has remained stable over time. However, in the past decade, affluence has increased rapidly, primarily due to improvements in institutional quality and economic growth. The government has also positively impacted consumer affluence by increasing its budget and expanding federal expenditures.

Figure 4 illustrates the mobile money transactions in Somalia over the past 10 years. EVC Plus, the mobile money service in Somalia, is utilized for various financial transactions, such as purchasing goods and services, paying bills, and carrying out all kinds of monetary transactions.

Figure 5 shows the population growth in Somalia, which could impact carbon emissions. The population of Somalia is affected by climate-induced diseases, drought, and conflicts that weaken the growth rate of the population. Most of Somalia's population

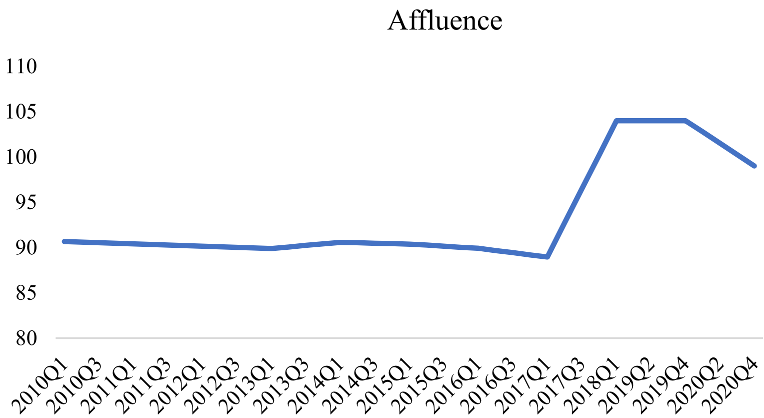

Fig. 3 Affluence

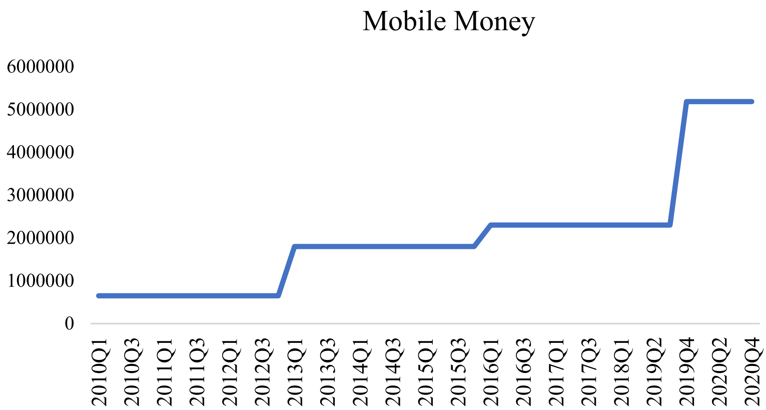

Fig. 4 Mobile money

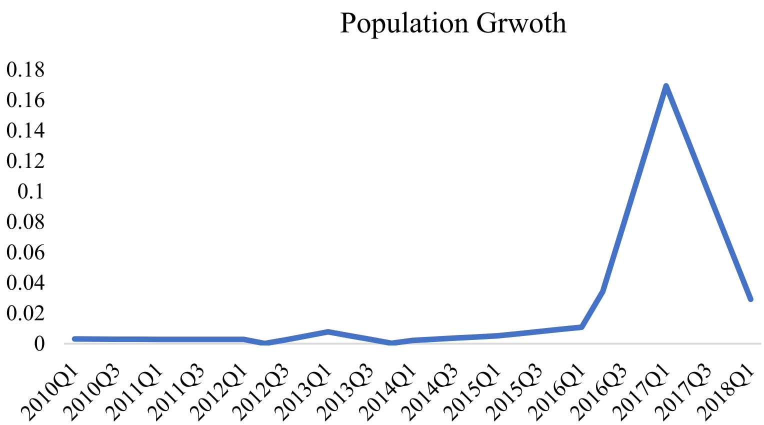

Fig. 5 Population growth

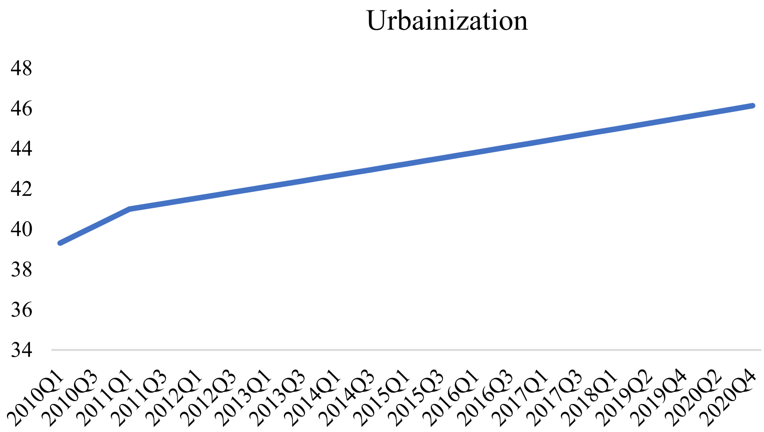

Fig. 6 Urbanization

Table 3 Correlation coefficients

Correlation	CO_2	ENERGY	MM	GDPPC	PG	UR
CO_2	1					
ENERGY	0.8725	1				
MM	−0.8906	0.8959	1			
GDPPC	−0.6518	0.3223	0.3123	1		
PG	0.5423	0.6273	0.5468	0.1996	1	
UR	0.9204	0.9836	0.9027	0.4150	0.5872	1

is young, indicating that the population will grow fast, which may negatively affect the environment.

Figure 6 displays urbanization trends, which are a vital driver of carbon emissions in Somalia. The portion of the urban population has risen over the last decade, and many people have migrated from rural areas to large cities. Migration from rural areas is attributed to extreme climate events that deplete crop production and livestock in rural areas.

4.2 Correlation analysis

The results in Table 3 show that energy consumption, population growth, and urbanization correlate positively and significantly with carbon emissions. Urbanization and energy consumption were the dominant contributors to Somalia's carbon emissions. Conversely, mobile money and affluence had a negative and significant relationship with carbon emissions. Mobile money is negatively correlated with carbon emissions and positively correlated with affluence, implying that mobile money enables green finance and clean technology usage.

4.3 Unit root test

Unit roots tests are vital for observing the series behavior of variables in time-series data. This study used the ADF and PP methods to test the Unit Root of the data. The Dickey–Fuller test is linked to the AR(1) process, and the reality is that a simple autoregression model cannot explain the stochastic behavior of the time series variable. Said and Dickey (1984) developed ADF test, an extension of the standard unit root test that accommodates ARMA (p, q) models. The null hypothesis of the ADF test is that the time series has the unit root and is nonstationary, y_t is I(1), whereas the alternative hypothesis is I(0). We incorporated augmented terms and converted them into AR(1) for a time series that follows a higher-order autoregressive process. The model exemplified in Eq. (8),

$$y_t = \emptyset_0 + \emptyset_1 y_{t-1} + \emptyset_2 y_{t-2} + \varepsilon_t \tag{8}$$

can be modified as Eq. (9):

$$\begin{aligned} y_t &= \emptyset_0 + \emptyset_1 y_{t-1} + \emptyset_2 y_{t-2} + \varepsilon_t \\ &= \emptyset_0 + \left(\emptyset_1 + \emptyset_2\right) y_{t-1} + \emptyset_2 \left(y_{t-1} - y_{t-2}\right) + \varepsilon_t \\ &= \emptyset_0 + \left(\emptyset_1 + \emptyset_2\right) y_{t-1} + \beta_1 \Delta y_{t-1} + \varepsilon_t \\ \beta_1 &= -\emptyset_2 \\ \Delta y_t &= \emptyset_0 + \rho y_{t-1} + \beta_1 \Delta y_{t-1} + \varepsilon_t \end{aligned} \tag{9}$$

In the above equation, $\rho = \emptyset_1 + \emptyset_2 - 1$.

We added augmented terms ($p - 1$) to the model if y_t followed the AR (p) process.

$$\Delta y_t = \emptyset_0 + \rho y_{t-1} + \sum_{j=1}^{p-1} \beta_j \Delta y_{t-j} + \varepsilon_t \tag{10}$$

We can add a trend component to get ADF formulation

$$\Delta y_t = \emptyset_0 + \rho y_{t-1} + \sum_{j=1}^{p-1} \beta_j \Delta y_{t-j} + \beta t + \varepsilon_t \tag{11}$$

Perron (P.P.) developed a unit root test different from the ADF and assumed heteroskedasticity and serial correlation in the error term. ADF parametrically corrects serial correlations by adding augmented terms to the model, where the lag length determines the augmented terms. In the P.P. method, serial correlation and heteroskedasticity are corrected nonparametrically, and the P.P. test estimates the following Equation:

$$\Delta y_t = \emptyset_0 + \pi y_{t-1} + \beta t + \varepsilon_t \tag{12}$$

P.P. test statistics modified the D.F. test statistics using a consistent covariance matrix estimator of autocorrelation and heteroscedasticity (Newey & West, 1987).

This study used ADF and PP with the trend and intercept to test the unit root; the results are presented in Table 4. We failed to reject the null hypothesis stating that these variables have unit roots at the level. We differenced the series to remove the unit root and make the data stationary. The unit root results are presented in Table 4.

Table 4 Unit root results

	Augmented Dickey–Fuller		Phillips–Perron	
Variable	Level	First difference	Level	First difference
CO_2	−2.2734	−4.7171	−1.0234	−5.3447
	(1.751)	(0.0042)	(1.9263)	(0.0008)
ENC	−2.4204	−4.5565	−1.2460	−5.3228
	(3.626)	(0.0061)	(1.8832)	(0.0008)
AFL	−2.9496	−5.2153	−1.8878	−5.9708
	(1.992)	(0.0010)	(1.6421)	(0.0001)
MM	−2.2494	−6.6731	−2.2494	−6.7406
	(4.514)	(0.0000)	(4.514)	(0.0000)
PG	−2.3989	−9.9107	−2.0771	−5.3134
	(3.711)	(0.0000)	(5.384)	(0.0008)
UR	−0.8646	−5.1620	−10.132	−5.1915
	(0.9490)	(0.0000)	(9.832)	(0.0007)

The unit root test results indicate that all variables are stationary at level I (1). Hence, we used the ARDL-bound method proposed by Pesaran and Shin (1998) and Pesaran et al. (2001).

4.4 Cointegration test

This study applied the ARDL bound method to examine the cointegration between the variables.

The ARDL bound approach tests the cointegration through Eqs. (13) and (14):

$$\Delta X_t = \delta_{0i} + \sum_{i=1}^{k} a_i \Delta X_{t-1} + \sum_{i=1}^{k} a_2 \Delta Y_{t-1} + \delta_1 X_{t-1} + \delta_2 Y_{t-1} + \varepsilon_{it} \tag{13}$$

$$\Delta Y_t = \delta_{0i} + \sum_{i=1}^{k} a_i \Delta Y_{t-1} + \sum_{i=1}^{k} a_2 \Delta X_{t-1} + \delta_1 Y_{t-1} + \delta_2 X_{t-1} + \varepsilon_{it} \tag{14}$$

In the above equations, k is the maximum lag order of the ARDL model, and F-statistics are determined in the joint hypothesis that the coefficients of the lagged variables are zero. Moreover, $(\delta_1 - \delta_2)$ represents the long-run relationship and $(a_1 - a_2)$ corresponds to the short-run dynamics. The hypothesis was that the coefficients of the lagged variables are zero. The ARDL bounds test results in Table 5 show that carbon emissions, energy consumption, mobile money, affluence, population growth, and urbanization are cointegrated and establish an equilibrium relationship.

Following Johansen and Juselius (1990), this study examined the long-run relationships between the variables. Table 6 shows five significant cointegrating equations (CEs) at a significance level of 5 percent; hence, the null hypothesis was rejected. We conclude that all the variables are cointegrated and constitute a long-run relationship. The cointegration

Table 5 ARDL bounds test results

$\ln CO_{2t} = f(\ln CO_{2t}/\ln ENC_t, \ln MM_t, \ln AFL_t, \ln PG_t, \ln UR_t)$ F-statistics: 5.789987		
Significance	I(0) bound	I(1) bound
Critical value bounds		
10%	3.38	4.72
5%	3.11	4.91
1%	3.43	4.02

Table 6 Johansen cointegration test results

Hypothesis		Trace	0.05	
No. of CEs	Eigen value	Statistic	Critical value	Probability
None	0.955012	250.5513	95.75366	0.0000
At most 1	0.884067	151.3078	69.81889	0.0000
At most 2	0.803843	82.356	47.85613	0.0000
At most 3	0.436766	30.23316	29.79707	0.0445
At most 4	0.301653	15.86325	11.49471	0.0164
At most 5	0.01162	3.74006	0.384147	0.0408
Max-Eigen				
None	0.955012	99.24347	40.07757	0.0000
At most 1	0.884067	68.95181	33.87687	0.0000
At most 2	0.803843	52.12284	27.58434	0.0000
At most 3	0.436766	18.36990	21.13162	0.0166
At most 4	0.301653	14.48925	11.26460	0.0313
At most 5	0.011620	3.74006	0.3841466	0.0408

Table 7 Akaike's information criterion (AIC) and Schwarz Bayesian's criterion (SBC)

Lag order	Adjusted R^2	AIC	SBC	Durbin–Watson
0	0.62 (0.000)	5.01	4.32	2.32
1	0.77 (0.000)	−6.98	−5.43	3.53
2	0.54 (0.000)	−3.32	−2.34	2.76
3	0.59 (0.000)	−3.43	−2.88	2.17
4	0.48 (0.000)	−3.11	−2.32	2.35
5	0.36 (0.000)	−2.90	−2.11	2.67

result implies that mobile money and the other variables affecting carbon emissions have an equilibrium relationship.

The ARDL model requires the determination of the optimal lag length. Akaike's information criterion (AIC) and Schwarz Bayesian's criterion (SBC) were used to select the lag length; the results are presented in Table 7. Wald or F-statistics reveal that the most significant lag order is $P = 1$, which is the optimal lag length selected in this study.

4.5 Estimating the long-run and short-run ARDL coefficients

Table 8 presents the results of the estimated long-run and short-run coefficients of the ARDL model. The long-run results indicate that mobile money and affluence have significant negative relationships with carbon emissions. A percentage increase in mobile money transactions decreases carbon emissions by approximately 0.23 percent, whereas a 1 percent rise in affluence is related to a 0.14 percent decline in carbon emissions.

The results of this study also reveal that a 1-percent increase in population growth leads to a carbon emission increase of approximately 0.10 percent, whereas a 1-percent rise in urbanization leads to a carbon emission rise of 0.33 percent. The short-run coefficients show that mobile money and affluence have negative and significant relationships with carbon emissions, while urbanization has a positive short-run relationship with carbon emissions. Population growth, the lagged value of affluence, and urbanization do not impact carbon emissions in the short run, while energy consumption is insignificant in both the short and long run.

Population growth increases carbon emissions and greenhouse gas concentrations, thereby elevating the temperature in Somalia. Urbanization causes an increase in greenhouse gases and triggers adverse climate effects, such as uncertain precipitation and water shortages. The agricultural sector, the most significant economic sector in Somalia, is harmed by the absence of a regular rainfall pattern, given that farmers in Somalia are smallholders and depend on rain as a primary water source. According to the United Nations Development Program (2021), the rising temperatures and variations in annual

Table 8 Error correction model results

Variable	Coefficient	Std. error	t-statistic	Prob.
Long-run coefficients				
$\ln CO_2$	1.3472	0.4330	3.1113	0.0000
lnENC	0.730	0.0572	13.5140	0.2366
lnMM	−0.2381	0.0066	−36.0758	0.0000
lnAffl	−0.1467	0.0321	4.5701	0.0000
lnP.G	0.1011	0.0060	16.8500	0.0099
lnU.R	0.3312	0.0726	4.5620	0.0100
Short-run coefficients				
$\Delta \ln CO_2$	1.2672	0.0433	29.2656	0.0000
$\Delta \ln CO_2(-1)$	0.8240	0.4640	1.7759	0.1456
ΔlnENC	0.0381	0.0860	0.4430	0.2432
ΔlnENC(−1)	0.1557	0.2218	0.7020	0.3213
ΔlnMM	−0.2449	0.0112	−21.8661	0.0001
ΔlnMM(−1)	−0.2231	0.3260	−0.6844	0.0020
ΔlnAFL	−0.3411	0.0161	−21.1863	0.0002
ΔlnAFL(−1)	−0.1517	0.1480	−1.0250	0.1120
ΔlnPG	0.0011	0.0015	0.7333	0.1379
Δln PG(−1)	0.0372	0.0856	0.4346	0.1100
ΔlnUR	2.3455	0.4321	5.4281	0.0032
ΔlnUR(−1)	3.2345	2.3421	1.3810	0.3234
ECM(−1)	1.902	0.2345	8.1109	0.0000

precipitation are the major causes of droughts and floods that negatively affect crop production in Somalia.

Affluence and financial efficiency enable firms to become socially responsible and to consider their ecological consequences. Financial development is essential to economic growth and environmental quality, as it enables manufacturing firms to expand their operations, conduct green investments, and reduce carbon emissions (Sudharshan et al., 2018).

Mobile money promotes financial development by providing financial services, such as savings and credit, to people dealing with environmental realities. Mobile money can be vital in implementing insurance that offers financial protection to smallholder farmers vulnerable to unpredictable weather conditions. Mobile money also enables farmers to access financing to invest in agricultural inputs, such as irrigation and pesticides, that can increase agricultural production and household resistance to the negative impact of climate change.

The economic benefits of mobile money include the flexibility to conduct commercial transactions from any location at any time. It is also a key driver of financial inclusivity, social stability, and integrity, thereby promoting sustainable development. The financial sector is essential in the fight against climate change, as it finances investments required to create a more sustainable economy and stimulates financing for environmental initiatives by creating renewable energy and environmental infrastructure, thereby driving ecological growth. Adverse climate shocks have weakened the economy of Somalia. This study confirms that mobile money can mitigate the effects of climate change by promoting access to clean and affordable energy sources and reducing carbon emissions.

Widespread access to financial services via mobile money enables clean energy services such as solar-powered household energy systems and clean appliances that mitigate the impacts of pollution, particularly for those at the bottom of the economic pyramid. The findings indicate that mobile money enables households to replace polluting energy sources with clean energy sources because the transition to clean energy can indirectly support education, income-generating activities, and entrepreneurship. With the help of remittances sent via mobile money, displaced people can access clean energy services as they use mobile money to pay for their solar home systems.

The results of this study are consistent with those reported by Shobande and Asongu (2021), Asongu et al. (2019), Odhiambo (2020), and Shahbaz et al. (2016), who found that the development of the financial sector promotes environmental quality and pollution reduction.

4.6 Diagnostic test

After estimating the long- and short-run coefficients of the ARDL model, this study conducted a diagnostic test to examine the model's strength (Table 9). The null hypothesis of no serial correlation was not rejected based on the Lagrange multiplier result. Similarly, the white heteroskedasticity test did not lead to the rejection of the null hypothesis and revealed the homoscedasticity of distance errors. Furthermore, the Jarque–Bera test results were insignificant, leading to the non-rejection of the null hypothesis and indicating that the data are normally distributed. Moreover, the Ramsey reset test revealed that the function form of the model was correct, with no misspecifications. Finally, the ARDL model used in this study was strong enough to assess the coefficients of the study.

Table 9 Diagnostic tests of the model

Diagnostics test		
R^2	0.82	
Adjusted R^2	0.76	
Durbin–Watson	2.85	
F-statistics	0.00	
Serial correlation	1.90	0.45
Heteroskedastic	0.71	0.72
Functional form	0.38	0.82
Normality	0.67	0.70

4.7 Stability of the Model

The connection between financial technology development and its effect on carbon emissions is pivotal for environmental regulation and efforts to manage climate change. Structural tests were conducted to assess the stability of the study coefficient. The cumulative sum of recursive residuals and the sum of squares of recursive residuals were applied to observe the stability of the model coefficient within the study period. Figures 7 and 8 show that the model coefficient falls under the critical bound, indicating that the model is stable and the relationship between the variables is predictable.

4.8 Granger causality

The regression model estimates statistical relationships but does not show a causal relationship between the variables. Granger (1969) proposed the Granger causality method, which tests causality between variables. The variable x_1 Granger causes x_2 if the present or lagged value of x_1 can help predict the future value of the x_2. Moreover, if x_1 fails to Granger cause x_2, then x_2 is exogenous in the time series framework and not linearly formative to the future values of x_2. We present the following reduced form of the bivariate VAR form in Eq. (15):

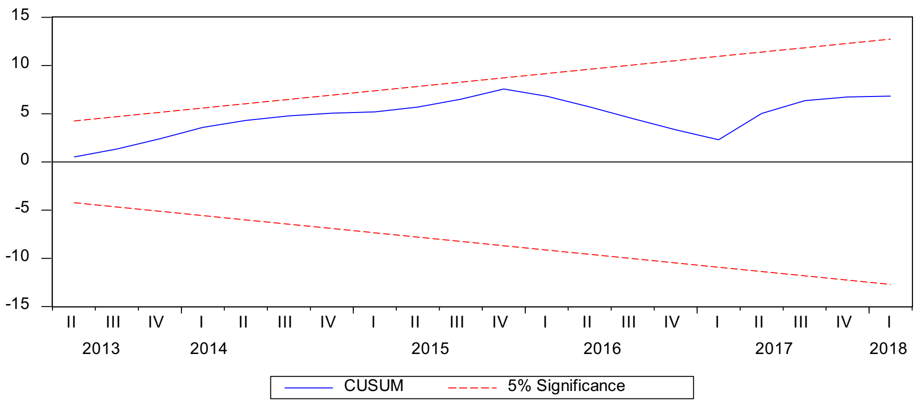

Fig. 7 Cumulative sum of recursive residuals

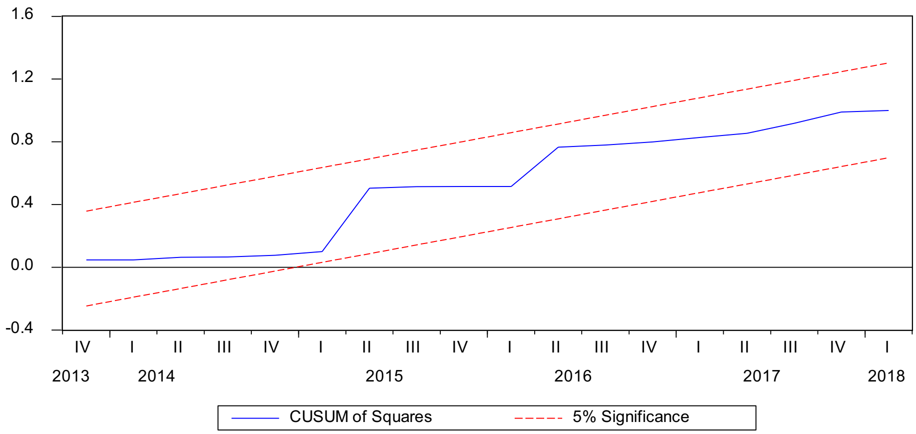

Fig. 8 Cumulative sum of squares of recursive residuals

$$\begin{bmatrix} x_{1t} \\ x_{2t} \end{bmatrix} = \begin{bmatrix} \pi_1 \\ \pi_2 \end{bmatrix} + \begin{bmatrix} \pi_{11} & 0 \\ \pi_{21} & \pi_{22} \end{bmatrix} \begin{bmatrix} x_{1t} & -1 \\ x_{2t} & -1 \end{bmatrix} + \begin{bmatrix} e_{1t} \\ e_{2t} \end{bmatrix} \quad (15)$$

Equation (15) shows that the lower triangular value coefficients that present the lagged value of x_2 are zero if x_2 does not Granger cause x_1. Moreover, if x_1 does not Granger cause x_2, the VAR coefficient is diagonal.

This study examined the causality between mobile money and carbon emissions in Somalia. The results of Granger causality are presented in Table 10. We rejected the null hypothesis related to the causality between mobile money and carbon emissions. The null hypothesis was rejected at the 5 percent significance level, indicating that mobile money has a causal relationship with carbon emissions, while carbon emissions does not have a causal relationship with mobile money. Hence, we conclude that mobile money and carbon emissions have a unidirectional relationship.

5 Conclusion and policy implications

This study examined the causal link between mobile money and carbon emissions to explore the ability of mobile money to control carbon emissions and address climate change. This study utilized the STIRPAT to study the theoretical association between mobile money and carbon emissions. The unit root of the data was examined using ADF and P.P. unit root tests. Furthermore, the cointegration between the variables was investigated through bound cointegration and Johansen and Julius methods. This study also employed the ARDL model to estimate the model parameters.

This study found that mobile money and affluence have a long-run negative relationship with carbon emissions, whereas population growth and urbanization are positively related to carbon emissions in the long run. The results of this study show that the effects of mobile money and affluence are significant in the short run, while the population has no immediate effect on carbon emissions. Furthermore, the effect of energy consumption on carbon emission is insignificant in the short and long run. The results

Table 10 Granger causality test results

Null hypothesis	F-statistic	Prob.
ENC → CO_2	0.15137	0.7001
CO_2 → ENC	0.47619	0.4956
AFL → CO_2	4.88845	0.0351
CO_2 → AFL	5.87109	0.0219
MM → CO_2	24.9519	0.0000
CO_2 → MM	7.38985	0.0110
PG → CO_2	5.03055	0.0327
CO_2 → PG	0.00191	0.9655
UR → CO_2	0.14689	0.7043
CO_2 → UR	11.3632	0.0021
AFL → ENC	6.66619	0.0151
ENC → AFL	7.31213	0.0113
MM → ENC	12.6898	0.0013
ENC → MM	2.03330	0.1646
PG → ENC	3.92639	0.0571
ENC → PG	1.12202	0.2982
UR → ENC	0.35841	0.5540
ENC → UR	6.71022	0.0148
MM → AFL	0.91815	0.3442
AFL → MM	5.30234	0.0270
PG → AFL	60.6288	1.E−08
AFL → PG	11.0061	0.0025
UR → AFL	1.79255	0.1888
AFL → UR	8.90121	0.0050
PG → MM	0.00048	0.9827
MM → PG	1.20372	0.2816
UR → MM	4.46378	0.0414
MM → UR	5.55902	0.0238
UR → PG	0.46962	0.4986
PG → UR	4.55243	0.0415

also show that urbanization is the dominant factor contributing to carbon emissions, whereas financial innovations, such as mobile money, effectively counteract carbon emissions.

This study's findings have several practical implications. First, mobile money could contribute to both carbon neutralization and climate adaptation by transforming how products and services are delivered. In particular, mobile money has emerged as a powerful tool for promoting financial inclusion and is increasingly being used as a platform for investing in environmentally sustainable assets and mitigating the impacts of climate change. Thus, mobile money penetration should be given sufficient consideration by the public and private sectors.

Second, mobile money is instrumental in leveraging financial services designed to serve marginalized and underprivileged populations, providing the opportunity to enhance efforts to address climate change. Therefore, mobile money can be used to develop solutions for financial inclusion in climate change and its associated challenges.

Third, population growth and urbanization harm the environment and increase carbon emissions in Somalia. Hence, the government should strengthen its institutions to manage these aspects and preserve the environment. A limitation of this study is that it only examined Somalia; future research should focus on more countries that use mobile money.

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Data availability The datasets generated during and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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