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Does biomass energy drive environmental sustainability? An SDG perspective for top five biomass consuming countries

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ABSTRACT

Efficient use of biomass energy is integral to achieving many of the Sustainable Development Goals (SDGs). Their contributions, trade-off patterns, and implementation vary geographically, requiring in-depth analysis to sustainably manage its impact. Here, we analyzed the contribution of biomass energy intensity and efficiency on sustainable development across the top five biomass energy-consuming countries—Brazil, China, Germany, India, and the US. We compared the impact of biomass energy consumption, economic development, urbanization, and trade openness on carbon dioxide emissions and ecological footprint. Using annual frequency data from 1970 to 2016, we utilized continuously-updated fully-modified, and continuously-updated bias-corrected panel estimation techniques that control for cross-section dependence among sampled countries. Our empirical analysis shows income level escalates ecological footprint and emissions by 0.05–0.21%. Similarly, urban sprawl increases long-term emissions and ecological footprint by 0.07–0.17%. Biomass energy consumption increases ecological footprint by 0.18–0.90% but declines emissions by 0.02–0.09%. However, trade openness reduces both ecological footprint and CO_2 emissions by 0.34–0.55%. Our results reveal income level stimulates biomass consumption in early stages of growth, but declines in technologically oriented industrial-based economy, yet, outgrows in service-inspired economy. This shows biomass extraction in developed countries can surpass regenerative capability, necessitating sustainable domestic material consumption management.

1. Introduction

Natural resource extraction and material flow remain the heartbeat of production-based economies. However, the nature of extraction, production, and consumption determine its impact on environmental sustainability. Thus, accounting for domestic material consumption is a useful tool in assessing material footprint and natural resource security [1]. Domestic material consumption typically encompasses biomass, fossil fuels, metal ores, and nonmetal ores. Though fossil fuel sources are finite whereas renewable energy resources are infinite but remain the global economic powerhouse — driving the world's economic growth through production and consumption [2]. Meanwhile, the current and potential future fluctuations in energy security and climate change would require the adoption of clean and renewable energies to safeguard the environment and livelihoods [3]. Thus, renewable energy development, use, and economic growth are some of the pressing tri-variate nexuses in the climate change discourse and sustainable development agenda [4]. The heterogeneity in socio-economic and geographical dimensions in the development and use of renewable energy in an integrated system of future energy supply is poorly understood [5]. These disparities have incited a renewed opportunity for studying the contribution of renewable energy to sustainable development agenda in energy-growth economy.

Biomass energy is "any source of heat energy produced from non-fossil biological materials" [6]. By 2016, biomass energy accounted for 5%, 4%, 11%, 31%, and 21% of the total energy use in the US, China, Germany, Brazil, and India, respectively [7]. Sources of bioenergy are chiefly biofuels, wood and wood-derived biomass, and municipal waste. It is projected that the global biomass potential of energy crops would range from 11 EJ (Exajoule) in the sustainable land use scenario in 2020 to 96 EJ in the business-as-usual scenario in 2050. These projections are equivalent to about 2–19% of the primary energy demand in 2010 [~500 EJ] [8]. Despite the potential of bioenergy to replace traditional fossils, it's generally considered more eco-friendly [9,10], however, land

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area requirements for energy crops limit their production. In competing and displacing agricultural and marginal lands [11,12], increased biomass energy production and consumption could double the price of food commodities on the global market [13,14].

In contrast, biomass energy consumption is reported to enhance economic growth and environmental degradation. From an economic perspective, biomass energy consumption is stronger for economic development in developing countries compared to developed countries. A short- and long-run causality analysis indicated that biomass energy supports the growth of countries in economic transitions [15]. On the other hand, biomass energy use can slow down economic development depending on the source, nature of renewable energy, and technology requirements [5,16]. These studies resonate further with the idea that optimizing the benefits of wood biomass as a renewable source of energy could likely reduce its adverse socio-environmental effects. Although, partially significant linkages are observed between GDP and biomass, the inclusion and use of energy-efficient technologies can reduce the prevailing high energy intensity of output in developing countries including Nigeria, Burkina Faso, the Gambia, Mali, and Togo [17]. Shocks in food production system could alter biomass energy consumption patterns, requiring modernized biomass energy to support and improve long-term energy use efficiency in developed countries [16].

In addition to biomass use, emissions, and environmental quality, discussions in extant literature include trade openness and urbanization [1,18,19]. The openness of trade could have a positive or negative on environmental performance depending on the economic status of nations and methodologies employed. Trade openness can augment the production capacities of high exporting countries and affect agricultural and marginal lands, forests, and global commodity markets. Thus, technological spillover effects of trade openness occur through export activities which reduce the EF in the long run [20]. For instance, trade openness was found to intensify ecological degradation in Middle East and North African nations between 1996 and 2012 and in 93 countries between 1980 and 2008 [21,22]. Trade openness was found to substantially reduce the ecological degradation of 24 OECD countries between 1980 and 2014 using panel methodologies [23]. The increasing urban sprawl means a rise in demand for resources would require more development of new areas for housing, social amenities, commercial and other urban land uses [24]. Yet empirical studies have reported tentative results. Thus, urbanization exacerbates environmental degradation through its positive effect on the ecological footprints of lower-middle-, upper-middle- and high-income countries, including changes in urban domestic sewage, industrial efffuent, and solid waste [22].

The motivation of this paper is to investigate the combined impacts of biomass energy consumption and economic growth on environmental quality using ecological footprint and carbon emissions. We test the hypothesis that biomass energy utilization does not affect wealth. This paper augments the existing consensus on biomass-environmental quality relationships and their potential impacts on sustainable development goals. Thus, assessing the impact of biomass energy on carbon emissions and environmental performance in high consuming nations (Brazil, China, Germany, India, and the US) are crucial to informing policies on the development of efficient renewable energy technologies—which reduces the energy footprint of these nations while enhancing development. The innovation of this study is the inclusion of interaction between economic growth and bioenergy consumption indicators to account for the combined impact on environmental quality and the SDGs (sustainable development goals). To the best of our knowledge, no study has informed environmental policies from this perspective. Besides, we ascertain the connection between environmental impacts of biomass consumption and country-specific stages in development, viz. structural transformation processes. As a result, we examine the possibility of a parabolic relationship between country-specific income levels and biomass energy use.

The remaining sections of the study are organized as follows: Section 2 "*Materials & Method*" outlines the empirical strategy used for model estimation; Section 3 presents the results of the parameter estimation; Section 4 presents discussion of the results while Section 5 summarizes the study findings.

2. Materials & Methods

2.1. Data

Based on our main hypothesis and existing studies, we construct two different models to categorize environmental degradation as carbon dioxide emissions and ecological footprint—by incorporating the impact of economic growth, biomass energy consumption, urbanization, and trade openness. The first empirical model constructed to observe the impact of biomass consumption on carbon emissions can be expressed as:

$$CO_2 = f(GDP, BIO, URB, TR) \tag{1}$$

Whereas the second empirical model constructed to examine the impact of biomass consumption on ecological footprint is expressed as:

$$EF = f(GDP, BIO, URB, TR) \tag{2}$$

Here, CO_2 is carbon emissions, representing the first degradation indicator measured in tons per capita. EF is ecological footprint, used as a proxy for second degradation indicator measured in gha per capita. GDP refers to economic growth, measured as per capita real gross domestic product in 2010 constant US dollars. BIO is per capita biomass energy, measured as biomass extraction in tons; URB denotes urbanization level measured as % share in total population. TR is trade openness total trade (sum of export and import) measured as % share in gross domestic product. The model specification of Equation (2) using ecological footprint is a more comprehensive indicator of environmental degradation. The ecological footprint indicator includes different sub-dimensions including cropland, grazing land, fishing grounds, and forest land. Therefore, analysis within the scope of Model 2 with biomass energy consumption is essential in assessing specific targets of the Sustainable development goals—including responsible consumption and production (SDG 12), Life below Water (SDG 14), and Life on Land (SDG 15).

All variables used for the empirical analyses were in natural logarithmic form for the annual dataset. The temporal series of our data were limited to the period 1970–2016 because of data availability for Brazil, China, Germany, India, and the US. Data for CO_2 emissions were retrieved from OurWorldInData of Ritchie and Roser [25], whereas data for EF were obtained from Global Footprint Network. The dataset for BIO was retrieved from the Global Material Flows Database whereas data for URB and TR were downloaded from the World Development Indicators of the World Bank. For empirical analysis, we utilized the Gaussian software.

2.2. Empirical strategy

2.2.1. Preliminary tests

For the estimates to be reliable and consistent for policy suggestions, it is crucial to select appropriate estimators for the model and perform some pre-tests. In panel data analysis, the first of these pre-tests is the cross-sectional dependency test—which examines shock permeability between cross-sections (countries in our case). In line with this, we used CD test based on null hypothesis of no cross-sectional dependence, developed by Pesaran [26]. The next important issue is to examine the stationarity process of the variables. For stationary test, it is necessary to decide suitable unit root test based on the results of cross-section dependence tests. Therefore, under null hypothesis of unit root, the CIPS panel unit root test by Pesaran [27] was performed. After observing the stationary properties of variables, we employed ECM-based panel cointegration method [28] with null hypothesis of no cointegration. This cointegration test allows cross-section dependence among observed countries. Another reason for choosing this cointegration test is the suitability for our empirical model characteristics. Westerlund [28] argues that error-correction-based tests show better accuracy than residual-based cointegration test in a situation where the explanatory variables are weakly exogenous.

2.2.2. Panel cointegrated regressions

To validate cross-sectional dependent cointegration among variables, the coefficient of cointegrated regressor is used to search for an estimation technique that allows cross-sectional dependence. Thus, we used CUP-FM (continuously-updated and fully-modified) and CUP-BC (continuously-updated and bias-corrected) estimators developed by Bai et al. [29]. These estimators augment the basic panel regression model and assume cross-sectional dependence and error term (ε_{it}) as follows [30]:

$$y_{it} = a_i + \beta x_{it} + \varepsilon_{it}. \tag{3}$$

$$\varepsilon_{it} = \lambda_i^{'} F_t + \mu_{it}. \tag{4}$$

where F_t, $\lambda_i^{'}$ and μ_{it} indicate the vector of common factors, corresponding factor loadings, and the idiosyncratic component of the error term, respectively. The computation process of CUP-FM is based on repeatedly estimating coefficients and long-run co-variance matrix until reaching the convergence as follows:

$$\widehat{\beta}_{Cup} = \left[\sum_{i=1}^{N} \left(\sum_{t=1}^{T} \widehat{y}_{it}^{+} \left(\widehat{\beta}_{Cup} \right) \left(X_{it} - \overline{X}_i \right)^{'} - T \left(\left(\lambda_i^{'} \left(\widehat{\beta}_{Cup} \right) \widehat{\Delta}_{F\varepsilon i}^{+} \left(\widehat{\beta}_{Cup} \right) + \widehat{\Delta}_{\mu\varepsilon i}^{+} \left(\widehat{\beta}_{Cup} \right) \right) \right) \right) \right] \times \left[\sum_{i=1}^{N} \sum_{t=1}^{T} \left(x_{i,t} - \overline{X}_i \right) \left(x_{i,t} - \overline{X}_i \right)^{'} \right]^{-1}. \tag{5}$$

where $\widehat{y}_{it}^{+} = y_{it} - (\widehat{\lambda_i^{'}} \widehat{\Omega}_{F\varepsilon i} + \widehat{\Omega}_{\mu\varepsilon i}) \widehat{\Omega}_{\varepsilon i}^{-1} \Delta X_{it}$, $\widehat{\Omega}_{F\varepsilon i}$ and $\widehat{\Omega}_{\mu\varepsilon i}$ are estimated long-run co-variance matrices and $\widehat{\Delta}_{F\varepsilon i}^{+}$ and $\widehat{\Omega}_{\mu\varepsilon i}$ are estimated one-sided long-run co-variance.

There are theoretical reasons for using the CUP-FM and CUP-BC estimators in this study. First, similar to our preferred cointegration test, these estimators are also consistent tests in the case of exogenous explanatory variables. Also, these estimators can be used for variables that are integrated of different orders. Besides, the CUP-FM estimator is a test developed based on the fully modified OLS estimator—which uses the Bartlett-Kernel procedure, hence, can also be used in possible autocorrelation and heteroskedasticity situations (Kiefer and Vogelsang [31]; Khan and Ulucak [32]. Finally, both estimators are robust in the case of endogeneity [29].

3. Empirical results

3.1. Descriptive analysis

Descriptive statistical analysis is critical to understanding the characteristics of data series. The maximum per capita carbon dioxide emission, ecological footprint, and GDP are 22.123 tons, 11.097 gha, and US$ 52,534.370, which is equivalent to the environmental degradation and economic status of the US in 1973, 1973, and 2016, respectively (Table 1). The share of trade in economic development is highest in Germany among other four countries (86.514% of GDP in 2012). The highest per capita biomass energy consumption (BIO = 12.633 tons) occurs in 2016, which is attributed to Brazil. CO_2, EF, GDP, and URB exhibit platykurtic distribution whereas BIO and TR exhibit leptokurtic distribution. All variables except URB are positively skewed; BIO has the highest skewness. The Jargue-Bera statistic shows all variables are not normally distributed — requiring logarithmic transformation during the empirical analysis to provide a more stable data variance.

3.2. Conditional panel-based tests

First, we used Pesaran's CD test to control for the presence of shock-dependency among observed countries (Table 2). The tests strongly rejected the null hypothesis of no cross-sectional dependence (CSD) for all variables, indicating the importance of CSD due to globalization in our country-based panel data analysis. It was therefore imperative to account for these CD shocks in the panel methodologies.

Table 2
CD and CIPS unit root tests.

Tests	EF	CO_2	GDP	BIO	URB	TR
CD test	-3.420 [0.001]	-2.330 [0.020]	20.480 [0.000]	15.690 [0.000]	20.690 [0.000]	18.330 [0.000]
			Unit Root			
CIPS (level)	-1.916	-1.542	-2.191	-1.892	-1.628	-1.955
CIPS (first differences)	-5.802	-4.895	-4.897	-6.420	-3.324	-5.326

Note: The critical values of CIPS unit root tests are 10%: -2.710, 5%: -2.860, 1%: -3.150. CO_2: Carbon dioxide emissions, EF: Ecological footprint, GDP: Gross domestic product, BIO: Biomass energy consumption, URB: Urbanization, TR: Trade openness.

Table 1
Descriptive statistics of data series.

Statistics	CO_2	EF	GDP	BIO	URB	TR
Mean	7.477	4.319	16471.150	3.687	56.734	30.332
Median	2.486	2.975	8389.979	2.549	72.503	24.685
Maximum	22.123	11.097	52534.370	12.633	86.042	86.514
Minimum	0.352	0.644	228.906	1.237	17.184	4.921
Std. Dev.	7.484	3.315	16850.440	2.453	23.901	18.264
Skewness	0.698	0.664	0.646	1.638	−0.469	1.225
Kurtosis	1.903	2.055	1.902	5.587	1.479	4.093
Jarque-Bera	30.842	26.018	28.155	170.627	31.259	70.451
Probability	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Note: CO_2: Carbon dioxide emissions, EF: Ecological footprint, GDP: Gross domestic product, BIO: Biomass energy consumption, URB: Urbanization, TR: Trade openness.

Table 3
ECM-Based cointegration test.

—	CO_2 Model		EF Model	
	Statistic	Bootstrapped *p-value*	Statistic	Bootstrapped *p-value*
$G\tau$	−3.855	0.280	−6.829**	0.030
$G\alpha$	−6.711**	0.020	−15.057***	<0.001
$P\tau$	−0.597	0.720	−2.898	0.330
$P\alpha$	−10.873***	<0.001	−18.915***	<0.001

Note: *, ** and *** indicates the statistical significance at 10, 5, and 1% level, respectively.

Next, we examined the unit root process of the variables at level and first-difference to determine the order of integration (Table 2). The null hypothesis of a unit root process cannot be rejected, indicating all variables are non-stationary at level form. However, variables are deemed stationary in first difference. These findings were point of reference for cointegrating the relationship between variables for both models.

The results of ECM-based cointegration test for the existence of long-run relationship between variables for each model are shown in Table 3. For CO_2 model, the test statistics for $G\alpha$ and $P\alpha$ are −10.873 ($p < 0.01$) and −6.711 ($p < 0.05$) respectively, rejecting the null hypothesis of no cointegration. Similarly, the null of no cointegration is rejected for EF model given $G\tau$ (-6.83, $p < 0.05$), $G\alpha$ (-15.06, $p < 0.01$), and $P\alpha$ (-18.92, $p < 0.01$). Therefore, we examined the long-run parameters of economic development, per capita biomass energy, trade, and urbanization.

3.3. *Drivers of ecological footprint and CO_2 emissions*

The results of long-run impact of biomass consumption on environmental degradation indicators are summarized in Table 4. In CO_2 emissions function (Table 4), we observe increasing effect of income level escalates atmospheric emissions by 0.08–0.21% —confirming the scale effect hypothesis. As hypothesized, economic development significantly increases emissions in the top five biomass-consuming countries. While the long-term effect of urbanization on emissions is insignificant and unnoticeable, the incorporation of interaction effect of income and biomass consumption stimulates urban sprawl to trigger CO_2 emissions by 0.09–0.13%. In contrast, 1% increase in trade openness reduces carbon market failures, thus, reducing long-term emissions by 0.34–0.55% across sampled countries. Similarly, increasing consumption of biomass by 1% spur CO_2 emissions by 0.18–0.90%. Biomass energy usage seems efficient on carbon mitigation, hence, increasing biomass energy consumption substantially reduces carbon dioxide emissions. The interaction between GDP and biomass energy consumption reduces long-term emissions by 0.18–0.26%. These findings are consistent in both estimation strategies.

The empirical results in Table 5 show income level increases ecological footprint by 0.05–0.09% across sampled countries for both estimators. This perhaps occurs in linear economies with dependence on natural resource-extraction and limited circular economic structure. Similarly, increasing trade openness by 1% reduces ecological footprint by 0.27–0.72%, implying long-term ecological reserve. Surprisingly, unlike the CO_2 emissions model, increasing biomass energy consumption by 1% harms environmental quality (ecological footprint in our case) by 0.18–0.90%. Besides, growth in urbanization increases ecological footprint of sampled countries by 0.07–0.17%. The interaction between GDP and biomass consumption increases ecological

Table 4
Estimates of CUP-FM and CUP-BC for CO_2 emissions Model.

Dep. Var: CO_2	CUP-FM		CUP-BC	
	(I)	(II)	(III)	(IV)
GDP	0.210***	0.076*	0.158***	0.101**
BIO	−0.094*	−0.033*	−0.070*	−0.021***
URB	0.031	0.125***	0.056	0.092***
TR	−0.554***	−0.371***	−0.363**	−0.336***
GDP * BIO	–	−0.262***	–	−0.184***

Note: *, ** and *** indicates the statistical significance at 10, 5, and 1% level, respectively. CO_2: Carbon dioxide emissions, EF: Ecological footprint, GDP: Gross domestic product, BIO: Biomass energy consumption, URB: Urbanization, TR: Trade openness.

Table 5
Estimates from CUP-FM and CUP-BC for EF model.

Dep. Var: EF	CUP-FM		CUP-BC	
	(V)	(VI)	(VII)	(VIII)
GDP	0.058*	0.048*	0.090***	0.087**
BIO	0.896***	0.181***	0.444***	0.196***
URB	0.131***	0.174***	0.066**	0.115***
TR	−0.273***	−0.716***	−0.191***	−0.432***
GDP * BIO	–	1.093***	–	1.113***

Note: *, ** and *** indicates the statistical significance at 10, 5, and 1% level, respectively. CO_2: Carbon dioxide emissions, EF: Ecological footprint, GDP: Gross domestic product, BIO: Biomass energy consumption, URB: Urbanization, TR: Trade openness.

Table 6
Parameter estimation of biomass-wealth nexus.

Country — Income Group	Parameters	Coefficient	t-Value	Prob>|t|	Curve-type
Brazil — Upper middle income					
BIO	Intercept	32.2200 [5.5090]	5.849	<0.001	Inverted-N-shaped
BIO	GDP	−0.0114 [0.0021]	−5.413	<0.001	
BIO	GDP ^{2}	<0.0001 [<0.0001]	5.54	<0.001	
BIO	GDP ^{3}	<-0.0001 [<0.0001]	−5.072	<0.001	
China — Upper middle income					
BIO	Intercept	1.1910 [0.0224]	53.11	<0.001	N-shaped
BIO	GDP	0.0007 [<0.0001]	18.71	<0.001	
BIO	GDP ^{2}	<-0.0001 [<0.0001]	−9.403	<0.001	
BIO	GDP ^{3}	<0.0001 [<0.0001]	6.712	<0.001	
Germany — High income					
BIO	Intercept	−4.2730 [1.745]	−2.449	0.0185	N-shaped
BIO	GDP	0.0006 [0.0002]	3.62	<0.001	
BIO	GDP ^{2}	<-0.0001 [<0.0001]	−3.516	0.0010	
BIO	GDP ^{3}	<0.0001 [<0.0001]	3.515	0.0011	
India — Lower middle income					
BIO	Intercept	1.2940 [0.1371]	9.439	<0.001	N-shaped
BIO	GDP	0.0015 [0.0005]	3.162	0.0029	
BIO	GDP ^{2}	<-0.0001 [<0.0001]	−2.454	0.0183	
BIO	GDP ^{3}	<0.0001 [<0.0001]	2.213	0.0323	
USA — High income					
BIO	Intercept	−5.9760 [3.9620]	−1.508	0.1388	N-shaped
BIO	GDP	0.0008 [0.0003]	2.495	0.0165	
BIO	GDP ^{2}	<-0.0001 [<0.0001]	−2.382	0.0217	
BIO	GDP ^{3}	<0.0001 [<0.0001]	2.347	0.0236	

Notes: Where [.] denotes Standard Error. GDP: Gross domestic product, BIO: Biomass energy consumption.

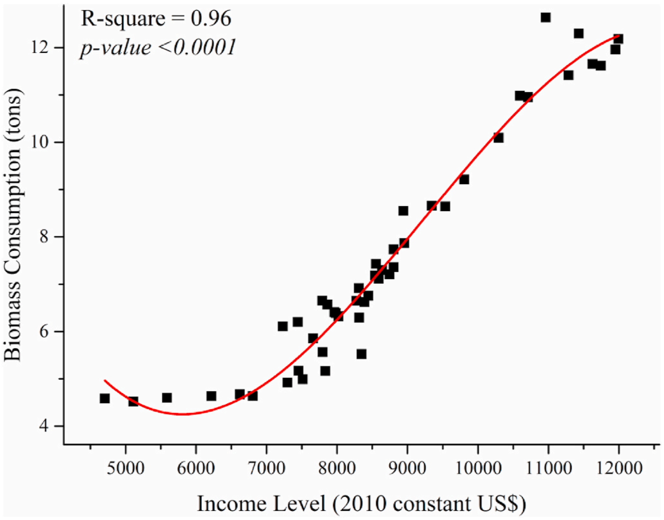

Fig. 1. Biomass consumption—wealth nexus in Brazil.

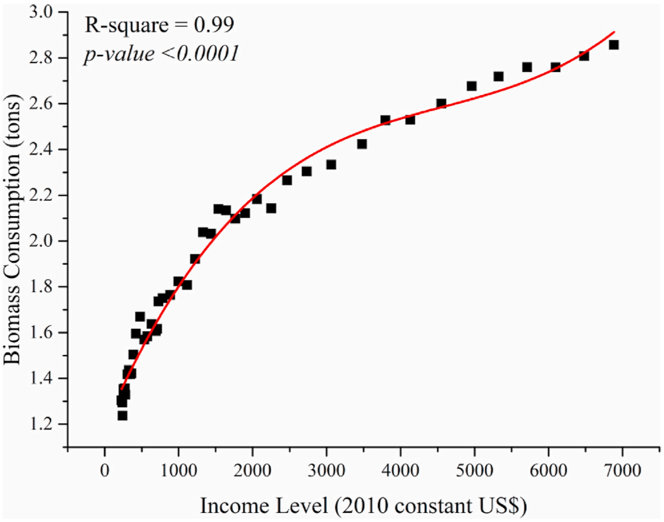

Fig. 2. Biomass consumption—wealth nexus in China.

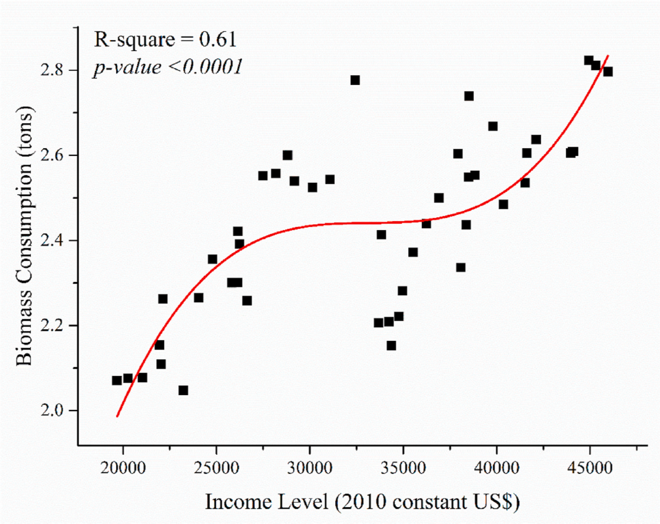

Fig. 3. Biomass consumption—wealth nexus in Germany.

footprint by 1.09–1.11% in both estimators.

To corroborate the estimated panel models, we investigated the country-specific nexus between biomass energy consumption and income level using time series based on higher-order regression. While our panel models account for global common shocks and spillover effects, divergence in economic structure across sampled countries may hamper environmental convergence. In this regard, utilizing country-specific models is essential to account for country-specific dynamics. Based on top-bottom estimation approach, we used third-order polynomial of income level to account for complexities in biomass utilization. This scenario helps in assessing whether wealth influences the consumption of biomass across different income groups presented in Table 6. The resultant structural assessment and its predictive power are depicted in Figs. 1–5. All the estimated models were statistically significant at *p-value* < 0.001. The goodness of fit test (R-square) reported 99% predictive power for China (Figs. 2), 96% for Brazil (Figs. 1), 68% for India (Figs. 4), 61% for Germany (Figs. 3), and 53% for the US (Fig. 5). It can be observed in Figs. 1–5 that while Brazil exhibits inverted-N-shaped relationship, China, India, Germany, and the US exhibit N-shaped relationship. The parameter estimation of Biomass-Wealth nexus in Table 6 reveals that growth in income declines biomass energy consumption at the initial stages of development in Brazil, but outgrows in industrial-based economy and declines thereafter in a service-dominated economy as argued by Ref. [53]. In contrast, increasing levels of income spur biomass energy consumption at the initial developmental stage in China, India, Germany, and the US but declines in the technologically-driven industrial-based economy and outgrows afterward in a service-inspired economy. The residual plots to validate the higher-order regression estimates are presented in Appendices A-E, confirming the independence of the residuals and stability of the estimated parameters.

4. Discussion

This study compares the effect of biomass energy consumption on environmental degradation and quality. The finding that biomass energy consumption reduces carbon emissions in high biomass-consuming countries could indicate the importance of biomass as a useful tool to combat atmospheric pollution and subsequently climate change. These findings are indicative of the need for policymakers to increase the share of biomass energy in the total energy portfolio, which is integral for achieving the climate action objective of the sustainable development goal thirteen (SDG 13). The finding is consistent with similar studies by Bilgili et al. [33]; Danish and Wang [18]; Dogan and Inglesi-Lotz [34]; Sarkodie et al. [16]; Shahbaz et al. [35] and Destek and Aslan [36]. On the other hand, our finding reveals that increasing biomass energy consumption increases the ecological footprint of biomass-consuming countries. Environmental degradation metric considers more than atmospheric pollution. The results of biomass energy consumption—ecological footprint nexus reveal that biomass is not eco-friendly. Increasing biomass energy consumption directly reduces atmospheric pollution levels but leads to the deterioration of cropland, grazing land, fishing grounds, and especially, forest land. Even more unfavourable, the harmful effect of biomass energy on these ecological indicators is above the positive atmospheric impact. These findings align closely with sustainable development goals. This confirms that biomass energy consumption is an obstacle to achieving the objective of responsible consumption and production (SDG 12), Life below Water (SDG 14), and Life on Land (SDG 15).

Our study further raises an interesting question on how biomass energy consumption drives environmental sustainability while developing economically. The finding that interaction between biomass consumption and economic development is negative on carbon dioxide emissions suggests that biomass energy could enhance environmental sustainability parallel to the economic development trajectory of the US, China, Germany, India, and Brazil. Aligning biomass-based

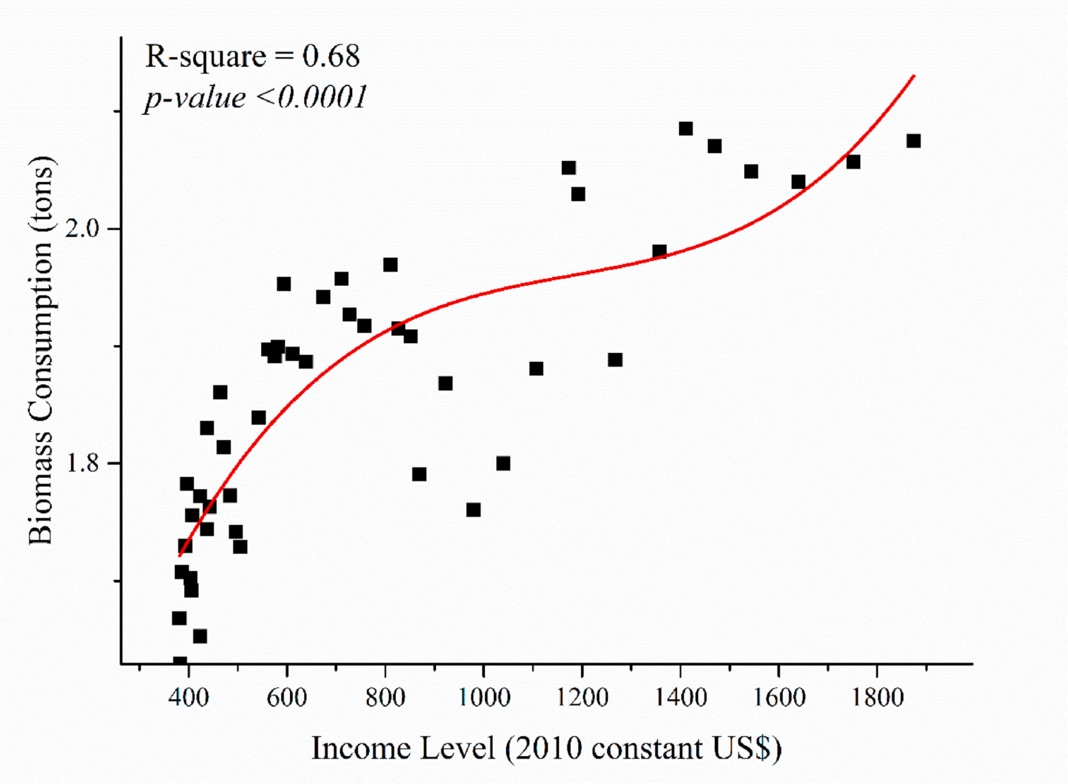

Fig. 4. Biomass consumption—wealth nexus in India.

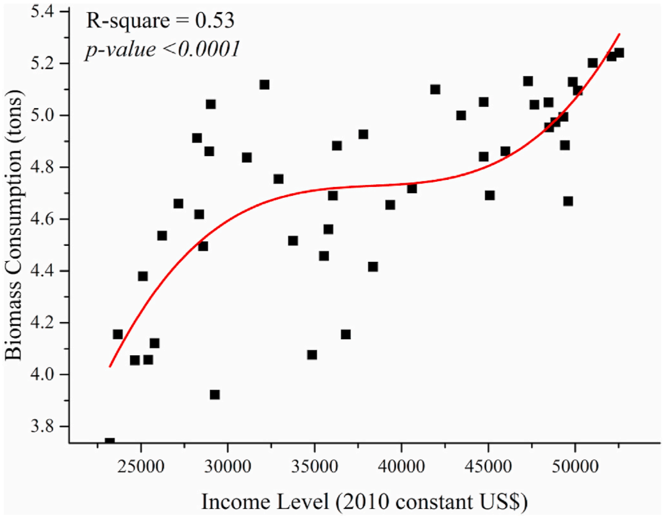

Fig. 5. Biomass consumption—wealth nexus in the US.

environmental sustainability to economic development is indicative that the development of biomass energy infrastructure and biomass energy consumption can proceed to support the environment while economic growth ensues [15]. Meanwhile, economic growth exacerbates the effects of biomass energy consumption on ecological footprints in the long run.

The source and sink hypothesis in biomass production and consumption can explain why bioenergy consumption can increase the ecological footprint while reducing carbon dioxide emissions. It is well-known that burning fossil fuels and traditional biomass spur carbon dioxide emissions. When energy crops are fully grown, almost equivalent amounts of carbon dioxide are captured through photosynthesis. Biomass energy consumption reduces carbon dioxide emissions because the rate of renewal of plants as biomass energy resources may be higher than the rate of utilization. It is reported that biomass-derived from biological sources such as agricultural, wood, and animal husbandry residues can substantially reduce anthropogenic emissions and reduce the competition of land use [37]. The increasing effect of biomass energy consumption on ecological footprint can be attributed to the weighted share of biomass energy consumption from traditional sources (wood, animal waste, and traditional charcoal). The increase in modern biomass energy (liquid biofuels, bio-refineries, and biogas) consumption could account for the decreasing share for solid biomass in recent years, hence, their consumption declining carbon dioxide emissions [37]. However, the slow rate of conversion from traditional biomass consumption to modern resources is one of the most important reasons for the increase in ecological footprint, but not accelerating this transformation may also lead to atmospheric damage. Similarly, if the destruction of forests continues at this pace to produce energy crops that only increase the ecological footprint, the atmospherically positive effect may reverse due to deforestation. Awareness of responsible land use could increase to alleviate these adverse effects of bioenergy production and consumption.

The finding that economic development increases carbon dioxide emissions and decreases ecological quality is consistent with similar studies [38–44]. The increasing effects of income level on atmospheric emissions confirm the scale effect hypothesis. The scale effect postulates economic development driven by environmental degradation, viz. natural resource exploitation, waste generation, and emissions [54]. While developed countries may limit environmental pollution through innovation and technological advancement, emissions could still be imported into wealthy countries. The transboundary effect of emissions through spillover effect of goods and services from developing countries (i.e., China, and India) could trigger a rise in emissions. The production structure of the US, China, Germany, India, and Brazil are mainly dependent on fossil-fuel energy sources. The conversion to clean energy resources is not sufficiently achieved in such production structures. Hence, increasing the share of clean energy sources in production activities could eliminate the negative impact of economic development on environmental quality.

Besides, our finding that trade openness reduces environmental degradation is consistent with the studies of Dogan and Turkekul [45]; Zhang et al. [46]; Gozgor [47]; Shahbaz et al. [48] and Destek and Sinha [23]. This finding is possibly sourced from our sampled country group consisting of middle-income and high-income countries. Increasing trade openness reduces both ecological and emission levels, hence, improving ecological reserves and environmental quality. It is common knowledge that more high-income countries have implemented pollution-reducing trade measures compared to developing countries with lax trade regulations. Thus, trade openness removes market barriers, hence, increases patronization of green trade and innovation that may serve as abatement technologies with long-term emission-reduction effects. Besides, trade openness improves natural resource market competition and drives green technology and innovations that find artificial alternatives to natural resources—which could limit anthropogenic emissions. The finding that urbanization increases ecological footprint is consistent with Sarkodie et al. [49], pointing out that urbanization is particularly harmful to agricultural lands and water resources of observed countries.

On the nexus between biomass energy consumption and income level, our study confirm that while biomass utilization decreases with increasing income level in Brazil, strong evidence that wealth increases biomass energy consumption is confirmed in the US, Germany, China, and India. This means that modern biomass resource consumption, as a supply chain of increased service is triggered by population demand in wealthy countries. The use of traditional biomass for cooking and heating purposes is reported to be rampant in developing countries with high multi-dimensional poverty [50]. It is reported that over 38% of the World's population from poor countries depend on traditional solid biomass [51]. Biomass resource consumption is mediated by resource extraction either through legal or illegal logging. It is reported that illegal logging of forest products—a source of biomass often occurs in developing countries and is driven by market pressure. For example, the market demand for endangered rosewood species is reported to have triggered illegal logging, which in effect hampers ecosystem biodiversity [52]. Thus, export-driven biomass resource extraction from developing countries may explain the consistent use of modern biomass in wealthy countries.

5. Conclusion

This study explored the impact of biomass energy consumption on both carbon emissions and ecological footprint by incorporating economic growth, trade, and urbanization in top five biomass-consuming countries (Brazil, China, Germany, India, and the US). First, we tested the hypothesis that biomass utilization does not affect emissions and ecological footprint. Second, we hypothesized wealth does not underpin biomass energy consumption. To observe how biomass energy affects environmental degradation indicators, we used annual data from 1970 to 2016 and panel data techniques that control for cross-sectional dependence across the sampled countries. Our empirical analysis demonstrated that increasing income level escalates emissions by 0.08–0.21%. While the effect of urban sprawl on CO_2 emissions was insignificant, the inclusion of interaction effect of income and biomass energy consumption causes urban sprawl to increase long-term CO_2 emissions by 0.09–0.13%. However, trade openness reduces CO_2 emissions by 0.34–0.55%. Likewise, increasing energy consumption stimulates CO_2 emissions by 0.18–0.90%.

The key empirical findings showed increasing biomass energy consumption is conducive to expanding the ecological footprint. In contrast, our study found biomass energy consumption as efficient tool for carbon mitigating policies. While economic growth and urbanization were found to deteriorate the environment, the mitigation effect of trade openness improves environmental quality. We observe that a shift in biomass consumption patterns has additional benefits of moderating the impact of economic development on environmental sustainability. In the context of policy implication, our results show that focusing only on one goal in the implementation of policies to achieve sustainable development targets may be an obstacle in attaining other targets. As observed, the leading countries in biomass consumption have implemented biomass policies with a focus on reducing atmospheric pollution, however, biomass consumption-led environmental damage has been neglected. Therefore, accelerating and managing the transformation from the use of traditional biomass to modern biomass could improve the green effects of biomass consumption, hence, reducing environmental deterioration. This transformation could improve energy efficiency attributable to biomass energy production, thus, allowing for more possibility to renew forest lands. Besides, a possible introduction of policies and measures that enable facilities operating in modern biomass industries will limit the exploitation of endangered biomass resources. Similarly, to prevent the destruction of agricultural lands, awareness-raising activities on the effective use of agricultural lands could be instituted. Due to the limitation of sampled countries, future research could examine the global perspective of the theme by expanding the sample size.

Data availability

Sources to data used for the model estimation have been correctly specified in the data sub-section of Materials and Method.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2021.106076.

References

[1] T.O. Wiedmann, H. Schandl, M. Lenzen, D. Moran, S. Suh, J. West, K. Kanemoto, The material footprint of nations, Proc. Natl. Acad. Sci. Unit. States Am. 112 (2015) 6271–6276.

[2] S.A. Sarkodie, Causal effect of environmental factors, economic indicators and domestic material consumption using frequency domain causality test, Sci. Total Environ. 736 (2020), 139602, https://doi.org/10.1016/j.scitotenv.2020.139602, 20 September 2020.

[3] Irena, The international renewable energy agency, Retrieved from, https://www.irena.org, 2018.

[4] Technical summary, in: D. Arvizu, T. Bruckner, H. Chum, O. Edenhofer, S. Estefen, A. Faaij, M. Fischedick, G. Hansen, G. Hiriart, O. Hohmeyer, K.G.T. Hollands, J. Huckerby, S. Kadner, Å. Killingtveit, A. Kumar, A. Lewis, O. Lucon, P. Matschoss, L. Maurice, M. Mirza, C. Mitchell, W. Moomaw, J. Moreira, L.J. Nilsson, J. Nyboer, R. Pichs-Madruga, J. Sathaye, J. Sawin, R. Schaeffer, T. Schei, S. Schlömer, K. Seyboth, R. Sims, G. Sinden, Y. Sokona, C. von Stechow, J. Steckel, A. Verbruggen, R. Wiser, F. Yamba, T. Zwickel, O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (Eds.), IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2011.

[5] I.K. Maji, C. Sulaiman, Renewable energy consumption and economic growth nexus: a fresh evidence from West Africa, Energy Rep. 5 (2019) 384–392.

[6] Christopher B. Field, J. Elliott Campbell, David B. Lobell, Biomass energy: the scale of the potential resource, Trends Ecol. Evol. 23 (2) (2008) 65–72.

[7] Enerdata, Global energy statistical yearbook 2019, Retrieved from, https://yearbook.enerdata.net, 2019.

[8] D. Thrän, T. Seidenberger, J. Zeddies, R. Offermann, Global biomass potentials—resources, drivers and scenario results, Energy for sustainable development 14 (3) (2010) 200–205.

[9] M.F. Seleiman, A. Santanen, F.L. Stoddard, P. Mäkelä, Feedstock quality and growth of bioenergy crops fertilized with sewage sludge, Chemosphere 89 (10) (2012) 1211–1217.

[10] M.F. Seleiman, A. Santanen, S. Jaakkola, P. Ekholm, H. Hartikainen, F.I. Stoddard, P.S. Mäkelä, Biomass yield and quality of bioenergy crops grown with synthetic and organic fertilizers, Biomass Bioenergy 59 (2013) 477–485.

[11] D.K. Bryngelsson, K. Lindgren, Why large-scale bioenergy production on marginal land is unfeasible: a conceptual partial equilibrium analysis, Energy Pol. 55 (2013) 454–466.

[12] A. Ignaciuk, F. Vöhringer, A. Ruijs, E.C. Van Ierland, Competition between biomass and food production in the presence of energy policies: a partial equilibrium analysis, Energy Pol. 34 (10) (2016) 1127–1138.

[13] D.J. Johansson, C. Azar, A scenario based analysis of land competition between food and bioenergy production in the US, Climatic Change 82 (3–4) (2007) 267–291.

[14] R.L. Naylor, A.J. Liska, M.B. Burke, W.P. Falcon, J.C. Gaskell, S.D. Rozelle, K. G. Cassman, The ripple effect: biofuels, food security, and the environment, Environment 49 (9) (2007) 30–43.

[15] M. Bildirici, F. Özaksoy, An analysis of biomass consumption and economic growth in transition countries, Economic research-Ekonomska istraživanja 31 (1) (2018) 386–405.

[16] S.A. Sarkodie, V. Strezov, H. Weldekidan, E.F. Asamoah, P.A. Owusu, I.N.Y. Doyi, Environmental sustainability assessment using dynamic autoregressive-distributed lag simulations—nexus between greenhouse gas emissions, biomass energy, food and economic growth, Sci. Total Environ. 668 (2019) 318–332, https://doi.org/10.1016/j.scitotenv.2019.02.432.

[17] O.A. Adewuyi, O.B. Awodumi, Biomass energy consumption, economic growth and carbon emissions: fresh evidence from West Africa using a simultaneous equation model, Energy 119 (2017) 453–471.

[18] K. Danish, Z. Wang, Does biomass energy consumption help to control environmental pollution? Evidence from BRICS countries, Sci. Total Environ. 670 (2019) 1075–1083.

[19] E.G. Hertwich, G.P. Peters, Carbon footprint of nations: a global, trade-linked analysis, Environ. Sci. Technol. 43 (2009) 6414–6420.

[20] Z. Mrabet, M. Alsamara, Testing the Kuznets Curve hypothesis for Qatar: a comparison between carbon dioxide and ecological footprint, Renew. Sustain. Energy Rev. 70 (2017) 1366–1375.

[21] U. Al-Mulali, I. Ozturk, The effect of energy consumption, urbanization, trade openness, industrial output, and the political stability on the environmental degradation in the MENA (Middle East and North African) region, Energy 84 (2015) 382–389.

[22] U. Al-Mulali, C. Weng-Wai, L. Sheau-Ting, A.H. Mohammed, Investigating the environmental Kuznets curve (EKC) hypothesis by utilizing the ecological footprint as an indicator of environmental degradation, Ecol. Indicat. 48 (2015) 315–323.

[23] M.A. Destek, A. Sinha, Renewable, non-renewable energy consumption, economic growth, trade openness and ecological footprint: evidence from organisation for economic Co-operation and development countries, J. Clean. Prod. 242 (2020) 118537.

[24] X.Q. Zhang, The trends, promises and challenges of urbanisation in the world, Habitat Int. 54 (2016) 241–252.

[25] H. Ritchie, M. Roser, "Renewable energy". *Published online at OurWorldInData.org*, Retrieved from: https://ourworldindata.org/renewable-energy, 2020 [Online Resource].

[26] M.H. Pesaran, General Diagnostic Tests for Cross Section Dependence in Panels, 2004.

[27] M.H. Pesaran, A simple panel unit root test in the presence of cross-section dependence, J. Appl. Econom. 22 (2) (2007) 265–312.

[28] J. Westerlund, Error correction based panel cointegration tests, Oxf. Bull. Econ. Stat. 69 (2007) 709–748.

[29] J. Bai, C. Kao, S. Ng, Panel cointegration with global stochastic trends, J. Econom. 149 (1) (2009) 82–99.

[30] J. Bai, C. Kao, On the estimation and inference of a panel cointegration model with cross-sectional dependence, Contrib. Econ. Anal. 274 (2006) 3–30.

[31] N.M. Kiefer, T.J. Vogelsang, Heteroskedasticity-autocorrelation robust standard errors using the Bartlett kernel without truncation, Econometrica 70 (5) (2002) 2093–2095.

[32] D. Khan, R. Ulucak, How do environmental technologies affect green growth? Evidence from BRICS economies, Sci. Total Environ. (2020) 136504.

[33] F. Bilgili, I. Öztürk, E. Koçak, Ü. Bulut, Y. Pamuk, E. Muğaloğlu, H.H. Bağlıtaş, The influence of biomass energy consumption on CO 2 emissions: a wavelet coherence approach, Environ. Sci. Pollut. Control Ser. 23 (19) (2016) 19043–19061.

[34] E. Dogan, R. Inglesi-Lotz, Analyzing the effects of real income and biomass energy consumption on carbon dioxide (CO2) emissions: empirical evidence from the panel of biomass-consuming countries, Energy 138 (2017) 721–727.

[35] M. Shahbaz, D. Balsalobre, S.J.H. Shahzad, The influencing factors of CO 2 emissions and the role of biomass energy consumption: statistical experience from G-7 countries, Environ. Model. Assess. 24 (2) (2019) 143–161.

[36] M.A. Destek, A. Aslan, Disaggregated renewable energy consumption and environmental pollution nexus in G-7 countries, Renew. Energy 151 (2020) 1298–1306.

[37] P.A. Owusu, S. Asumadu-Sarkodie, A review of renewable energy sources, sustainability issues and climate change mitigation, Cogent Eng. 3 (1) (2016) 1167990, https://doi.org/10.1080/23311916.2016.1167990.

[38] S. Wang, Q. Li, C. Fang, C. Zhou, The relationship between economic growth, energy consumption, and CO2 emissions: empirical evidence from China, Sci. Total Environ. 542 (2016) 360–371.

[39] S. Kais, H. Sami, An econometric study of the impact of economic growth and energy use on carbon emissions: panel data evidence from fifty eight countries, Renew. Sustain. Energy Rev. 59 (2016) 1101–1110.

[40] F. Belaid, M. Youssef, Environmental degradation, renewable and non-renewable electricity consumption, and economic growth: assessing the evidence from Algeria, Energy Pol. 102 (2017) 277–287.

[41] M. Salahuddin, K. Alam, I. Ozturk, K. Sohag, The effects of electricity consumption, economic growth, financial development and foreign direct investment on CO2 emissions in Kuwait, Renew. Sustain. Energy Rev. 81 (2018) 2002–2010.

[42] S. Erdogan, D.Ç. Yildirim, A. Gedikli, Investigation of causality analysis between economic growth and CO2 emissions: the case of BRICS–T countries, Int. J. Energy Econ. Pol. 9 (6) (2019) 430–438.

[43] M.A. Destek, S.A. Sarkodie, Investigation of environmental Kuznets curve for ecological footprint: the role of energy and financial development, Sci. Total Environ. 650 (2019) 2483–2489, https://doi.org/10.1016/j.scitotenv.2018.10.017.

[44] M.A. Baloch, J. Zhang, K. Iqbal, Z. Iqbal, The effect of financial development on ecological footprint in BRI countries: evidence from panel data estimation, Environ. Sci. Pollut. Control Ser. 26 (6) (2019) 6199–6208.

[45] E. Dogan, B. Turkekul, CO 2 emissions, real output, energy consumption, trade, urbanization and financial development: testing the EKC hypothesis for the USA, Environ. Sci. Pollut. Control Ser. 23 (2) (2016) 1203–1213.

[46] S. Zhang, X. Liu, J. Bae, Does trade openness affect CO 2 emissions: evidence from ten newly industrialized countries? Environ. Sci. Pollut. Control Ser. 24 (21) (2017) 17616–17625.

[47] G. Gozgor, Does trade matter for carbon emissions in OECD countries? Evidence from a new trade openness measure, Environ. Sci. Pollut. Control Ser. 24 (36) (2017) 27813–27821.

[48] M. Shahbaz, S. Nasreen, K. Ahmed, S. Hammoudeh, Trade openness–carbon emissions nexus: the importance of turning points of trade openness for country panels, Energy Econ. 61 (2017) 221–232.

[49] S.A. Sarkodie, P.A. Owusu, T. Leirvik, Global effect of urban sprawl, industrialization, trade and economic development on carbon dioxide emissions, Environ. Res. Lett. 15 (3) (2020), 034049, https://doi.org/10.1088/1748-9326/ab7640.

[50] S.A. Sarkodie, S. Adams, Electricity access, human development index, governance and income inequality in Sub-Saharan Africa, Energy Rep. 6 (2020) 455–466, https://doi.org/10.1016/j.egyr.2020.02.009.

[51] IEA, World energy outlook special report. Africa energy outlook, Retrieved from, http://www.iea.org/publications/freepublications/publication/WEO2014_AfricaEnergyOutlook.pdf, 2014.

[52] M.A. Barrett, J.L. Brown, M.K. Morikawa, J.N. Labat, A.D. Yoder, CITES designation for endangered rosewood in Madagascar, Science 328 (5982) (2010) 1109–1110.

[53] M.A. Destek, Deindustrialization, reindustrialization and environmental degradation: evidence from ecological footprint of Turkey, J. Clean. Prod. (2021) 126612.

[54] S.A. Sarkodie, Environmental performance, biocapacity, carbon & ecological footprint of nations: drivers, trends and mitigation options, Sci. Total Environ. 751 (2021) 141912, https://doi.org/10.1016/j.scitotenv.2020.141912.