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Time-Frequency Co-Movements Between Biomass Energy Consumption and Human Development in Brics Countries

Relacja czasowo-częstotliwościowa pomiędzy zużyciem energii z biomasy a rozwojem człowieka w krajach grupy Brics

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Abstract
This paper aims to investigate the influence of biomass energy consumption on human development in BRICS countries in the frequency-time domain using the wavelet frameworks. Specifically, the wavelet coherency method of Rua (2013) and the wavelet-Granger causality test of Olayeni (2016) are utilized to quantify the strength and direction of causal relationships through time and across various frequencies simultaneously. The empirical findings uncovered that the causal linkages between human development and biomass energy consumption in the BRICS countries are not homogeneous in different time and frequency scales. We also discover the strong relationship between the two variables in China, Russia, Brazil, and South Africa after the global financial crisis 2008 at low and medium frequencies, while this connection is somewhat low in India over the sample period. This study suggests the importance of biomass energy for human development in BRICS countries.

Key words: biomass energy, human development, BRICS countries, wavelet analysis, sustainable development

Streszczenie
Niniejszy artykuł ma na celu zbadanie wpływu zużycia energii z biomasy na rozwój człowieka w krajach grupy BRICS w relacji częstotliwościowo-czasowej przy użyciu ram falkowych. W szczególności wykorzystano metodę koherencji falkowej Rua (2013) i test przyczynowości falkowej-Grangera Olayeni (2016) do ilościowego określenia siły i kierunku związków przyczynowych w czasie i na różnych częstotliwościach jednocześnie. Wyniki empiryczne ujawniły, że powiązania przyczynowe między rozwojem społecznym a zużyciem energii z biomasy w krajach BRICS nie są jednorodne w różnych skalach czasu i częstotliwości. Wykazano również silny związek między dwiema zmiennymi w Chinach, Rosji, Brazylii i RPA po globalnym kryzysie finansowym w 2008 r. przy niskich i średnich częstotliwościach, podczas gdy związek ten w Indiach jest niski w tym okresie próby. Niniejsze badanie sugeruje duże znaczenie energii z biomasy dla rozwoju człowieka w krajach BRICS.

Słowa kluczowe: energia biomasy, rozwój człowieka, kraje grupy BRICS, analiza falkowa, rozwój zrównoważony

Introduction

Energy is an integral element of economic and societal growth, and the biomass energy consumption is a vital part of energy sources and is as old as humanity. The utilization of biomass energy contributes to job creation, agricultural growth, transportation, and trade openness, resulting in poverty alleviation and sustainable human development (Bilgili et al., 2017; Adewuyi and Awodumi, 2017). Nevertheless, conventional biomass use is not widely used across the world since it has not met the energy needs of the economy in recent years (Ozturk and Bilgili, 2015). Fossil fuel energy has gained popularity, and conventional biomass usage has diminished because the economy has considerably developed. Specifically, developing energy consumption has become the key determinant in industrialization, and the conventional usage of biomass energy has lost its popularity (Bildirici and Özaksoy, 2018; Drastichová and Filzmoser, 2019). According to Wang et al. (2020), Biomass energy use plays a crucial role in enhancing a country's economy, and then it influences human welfare. Put differently, modern education, health, and communication facilities are intrinsically linked to the available energy supply. Poor health services, fewer chances for education and development, and a high possibility of poverty in the population may be occurred due to the scarcity of energy resources. Therefore, biomass energy consumption needs to create a sufficient amount of energy for the modernization process to facilitate sustainable development. This paper wishes to add to the existing literature by investigating the impacts of biomass energy consumption on human development. United Nations Development Program (UNDP) introduced the concept of human development, known as the expansion of human opportunities and choices. As per Wang et al. (2020), this index has eventually replaced GDP to become the key factor in assessing human development. Human development based on long and healthy life, knowledge, and decent living standard can reflect the entire quality of human being. Improving this index becomes a target for almost every nation. Governments and policymakers must consider all three dimensions of sustainable development, namely environmental, cultural, and social issues. As a result, a better understanding of the interconnection between biomass energy consumption and human development may provide them with clear evidence of the influence of biomass energy consumption on human development.

A systematical understanding of the relationship between biomass energy usage and human development is fundamental. The biomass energy-human development nexus has a very vital implication for policymakers and governments that care about human development on the one hand and the environment and scarcity of natural resources on the other hand. They have to understand whether renewable energy consumption promotes human development or whether human development causes energy use since suitable energy and environmental policy selections rely on nature or the causal association between renewable energy consumption and human development (Ozturk and Bilgili, 2015; Ouedraogo, 2013; Pirlogea, 2012; Khan et al. 2019; Hung, 2021). Consequently, the renewable energy consumption-human development relationship has been extensively examined by many scholars utilizing various econometric techniques and data set.

In this paper, we focus on the causal associations between these indicators in the BRICS countries. The reason for choosing Brazil, Russia, India, China, and South Africa (BRICS) nations for the current study is that the share of biomass energy usage in renewable energy in BRICS countries was high at 36.8%, according to the 2009 International Energy Agency report (IEA). Besides, there were newly industrialized economies in these nations raising concerns about energy security and environmental pollution, which requests for alternative energy sources (IEA). Several incentives have already been carried out in the BRICS economies to increase biomass energy production, leading to a remarkable rise in biomass production (IEA). More specifically, the large share of global carbon dioxide emissions was a significant indication of the BRICS economy's need for alternative energy sources (Aydin, 2019).

The last few decades have been some empirical works with regard to biomass energy consumption and human development (Dias et al., 2016; Wang et al. 2018; Khan et al. 2019; Reiter and Steensma, 2010). Nevertheless, very few studies have been done in the BRICS countries context (Sinha and Sen, 2016). Also, the present literature describes mixed opinions on the nexus between the two examined indicators. Traditionally, there are two aspects of biomass energy-human development relationship-direct and indirect. The direct connection is studied by Shahbaz et al. (2016) and Aydin et al. (2019), and indirect impact is investigated in terms of economic growth and environmental pollution (Wang, 2019, Wang et al., 2020). Mostly, the emphasis on the adoption of renewable energy sources is a result of environmental issues and climate change (Khan et al., 2019). Consequently, the direct influence of biomass energy usage on human development is subject to the modernization of technique under practice to utilize alternative energy sources in an economy, which requires careful statistical information to construct the interlinkage between human development and biomass energy consumption in BRICS countries.

Taking into consideration the causal relationship, Sinha and Sen (2016), Shahbaz et al. (2016), Wang (2019), and Aydin (2019) employ GMM models, and the latest papers are conducted by Wang et al. (2020). These works concentrate on establishing possible long-run causal relationship among energy consumption, economic development, CO_2 emission, and human development by using time-domain methods including cointegration, ARDL, NARDL, fully modified OLS, and dynamic OLS, which restrict the information effectiveness on policies of economic development as well as human welfare (Adebayo, 2021). As a result, in addition to these techniques utilized, the current paper applies the wavelet framework to capture lead-lag relationships. Put it another way, this approach allows us to explore the causality and association between human development and biomass energy consumption in BRICS countries at different time and frequency domains. Causation between these indicators continues to be a significant subject of investigation for governments and policymakers, not only the nexus it entails but also because of the expectations on prediction. Knowing how and when a certain indicator causes another helps policymakers identify the usage of their resources, right policies, and strategy for sustainable development purposes.

An in-depth analysis of the importance of biomass energy consumption for human development and the existing energy use pattern in BRICS nations also motivates us to look into the connection between biomass energy usage and human development to explore whether biomass energy use impacts the human development process in these countries. Therefore, our study contributes to the existing literature on renewable energy-human development nexus and uses the wavelet cohesion framework of Rua (2013), wavelet coherence, and a novel approach to causality applying a time-frequency technique developed by Olayeni (2016), which is much easier to interpret. The application of wavelets allows us to capture the interrelatedness of the concerned variables in time and frequency domains, boosting our understanding of possible dependences. Unlike previous works on biomass energy-human development relationship, our study provides additional insights into governments and policymakers with a better understanding of the effects of biomass energy on human development in the BRICS countries because conventional techniques do not allow the estimation of continual variations in the lead-lag connection between variables, nor allow for the causal association of short-and long-run sustainable development strategies. Employing wavelets, we can examine nonlinearities, structural breaks, and various lead-lag scenarios between biomass energy consumption and human development.

The rest of this article is structured as follows. Section 2 describes the literature review. Section 3 represents the data and methodology. Section 4 documents the empirical results, and Section 5 sums up the conclusions and some policy implications.

Literature review

An extensive body of studies has concentrated on the interrelatedness between energy consumption, economic growth, carbon emission, and human development, finding evidence of causality, dependence, and spillovers (Bildirici and Özaksoy, 2018). Several articles confirmed energy to be a dramatic contributor to human development, while few uncovered energy to be irrelevant for a country's development process (Dias et al., 2016; Khan et al., 2019). The current study aims to examine the causal association between biomass energy consumption and human development. Academic researchers have unveiled that biomass energy can impact the environment, economy, and resources toward guaranteeing sustainable development. The relationship between biomass usage and human development in causality has been studied in many papers in recent years. The empirical findings of such papers provided a mix of results due to using various data sets, econometric techniques ad countries' properties (Wang 2019; Wang et al. 2020).

This segment of the present study discusses prior works on the interconnections between economic growth, CO_2 emission, renewable energy consumption, and human development. The literature on the interrelatedness among economic growth, renewable energy usage, and CO_2 emission is vast. Nevertheless, there is no concrete agreement on the nexus across these economic variables. This field has become more attractive based on this lack of consensus, and more contributions are encouraged. Ozturk and Bilgili (2015) examine the long-run relationship between economic development and biomass consumption for 51 Sub-Sahara African nations. Their findings indicate that economic growth is remarkably impacted by biomass usage, trade openness, and population. Bilgili et al. (2017) investigate the co-movement and causality between biomass energy, CO_2 emissions, and economic growth in the US. They argue that biomass energy use mitigates CO_2 emissions and increases economic development, which suggests biomass energy usage can be an efficient policy framework for environmentally sustainable development in the US. Adewuyi and Awodumi (2017) investigate the interdependence between biomass energy consumption, economic growth, and carbon emissions in West Africa, and provide evidence that a comprehensive significant connectedness exists across GDP, biomass use, and carbon emission. Bildirici and Özaksoy (2018) identify the intercorrelation between biomass energy usage and economic growth for several European Transition Countries. The results indicate that there is evidence of bidirectional causality between the variables.

Several studies have examined the intercorrelation between human development and economic indicators. However, their results are mixed. For instance, Martinez and Ebenhack (2008) study the intercorrelation between UN human development and energy consumption for 120 countries, and report that three areas are isolated: a steep rise in human development with regard to energy consumption for energy-poor countries; a moderate rise for transitioning countries; and essentially no rise in human development for energy-advanced countries, consuming large amounts of modern energy. Ouedraogo (2013) studies the causality connectedness between energy consumption and human development in 15 developing countries and points out that energy consumption has a neutral influence on human development in the short run. Reiter and Steensma (2010) document that FDI has a strong relationship with human development, which limits foreign investors from entering some economic sectors. Pirlogea (2012) explores the role of energy in human development by examining the impact of energy on sustainable development and economic growth. He highlights that high levels of energy intensity of a country pose threats to its human development. Dias et al. (2016) focus on the relationship between human development, economic growth, energy consumption, and social growth. The findings shed light on the importance of hunting for alternative development for human development balance, natural resources, and environment. Recently, Wang et al. (2018) estimate the relationship between renewable energy consumption, economic growth, and human development in Pakistan, and provide evidence that renewable energy consumption does not improve the human development process in Pakistan. Specifically, the authors also document that the higher the income of the country, the lower its human development level and CO_2 emission is useful to improve the human development index in this country. Khan et al. (2019) model the nexus between information and communication technology (ICT), economic growth, and human development from 1990 to 2014 using ARDL and VECM techniques. Their results uncover that ICT enhances human development and economic growth has a positive influence on human development. Reiter and Steensma (2010) provide evidence of the links between FDI, economic growth, and human development and confirm that FDI inflows are more strongly connected to human development.

In the context of BRICS countries, Wang (2019) represents an empirical study of the connection between biomass energy consumption and environmental pollution. Applying the generalized system method of the moment model, the results of their findings show that biomass energy usage behaves as a clean energy source in reducing the environmental pollution. Shahbaz et al. (2016) also analyze the relationship among these indicators by using cointegration tests. The results show the existence of long-run equilibrium nexus between biomass energy and economic development throughout 1991-2015. Aydin et al. (2019) report the significant relationship between biomass energy consumption and economic growth from 1992 to 2013. The authors suggest these nations should increase biomass energy to a sustainable environment, enhance economic development, and reduce energy dependency. Sinha and Sen (2016) explore the causal relationship between economic growth, CO_2 emission, trade volume, and human development for BRIC countries between 1980 and 2013 using the GMM approach. The outcomes of this paper reveal that there exist bidirectional spillovers between CO_2 emissions and economic growth. More importantly, the findings support the feedback hypothesis between CO_2 emissions, human development, and economic growth. Wang et al. (2020) employ a wide range of economic techniques to explore the impact of biomass energy usage on human development in 1990-2015. The outcomes of this paper unveil that biomass energy consumption increases human development and bidirectional causality exists between these indicators.

It is clear from the reviewed previous literature that several works have examined the relationship between biomass energy usage and human development. Nevertheless, no prior paper has extensively captured the lead-lag intercorrelation structure between human development and biomass energy consumption in the BRICS countries using wavelet analysis. The advantage of this approach is that it is able to capture the causal associations between the selected variables at different time and frequency domains. As a result, the current study fills the gap in the existing literature.

Wavelet methodology

This paper attempts to explore the causal associations between human development and biomass energy consumption in the BRICS countries. By doing so, we employ continuous wavelets, cross wavelet transforms, wavelet coherence, and causality in continuous wavelet transforms are used to capture how the domestic variance and covariance of two-time series co-vary as well as the co-movement interdependence between two variables in the time-frequency domain. Moreover, the correlation measure in continuous wavelet transforms (CWT) developed by Rua (2013) offers the background for the lead-lag relationship between variables under study. In this section, we briefly introduce wavelet techniques.

Continuous wavelet transform

The continuous wavelet transform $W_x(s)$ allow us to explore the joint behavior of time series for both frequency and time. The wavelet is defined as:

$$W_x(s) = \int_{-\infty}^{\infty} x(t)\frac{1}{\sqrt{s}}\psi^*\left(\frac{t}{s}\right) \quad (1)$$

where * represents the complex conjugate and the scale parameter s determines whether the wavelet can detect higher or lower elements of the series $x(t)$, possible when the admissibility condition yields.

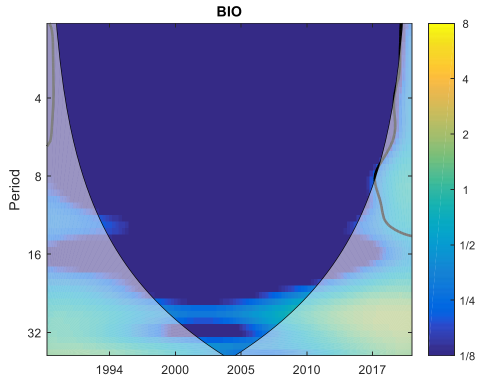
Wavelet coherence

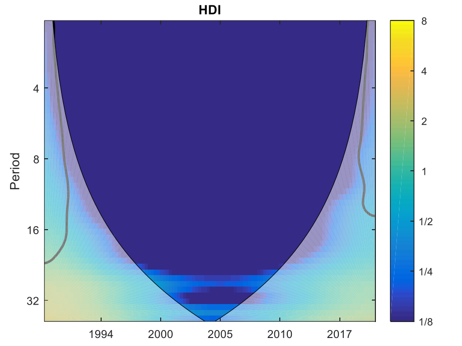
The wavelet coherence is computed based on the cross-wavelet transform and wavelet power spectrum of each variable. More accurately, while the wavelet power spectrum measures contribute to the variance of the series at each time scale, cross-wavelet power estimates covariance contribution in the time-frequency space. The cross-wavelet of two series $x(t)$ and $y(t)$ can be defined as:

$$W_n^{XY}(u,s) = W_n^X(s,\tau)W_n^{Y*}(s,\tau) \quad (2)$$

where u denotes the position, s is the scale, and * denotes the complex conjugate. Consequently, the wavelet coherence can be calculated as follows:

Brazil





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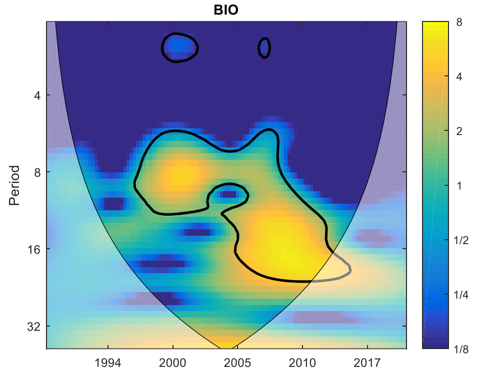
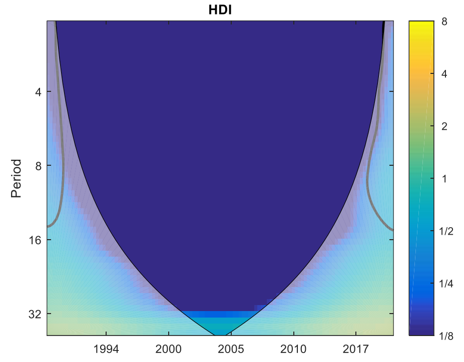
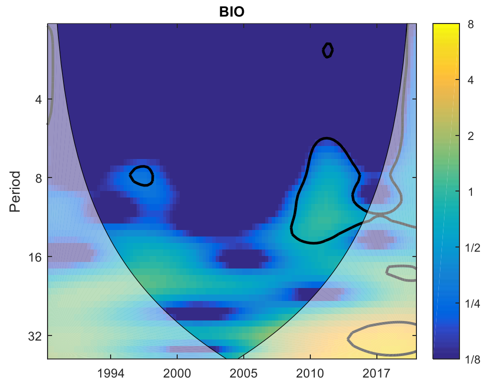
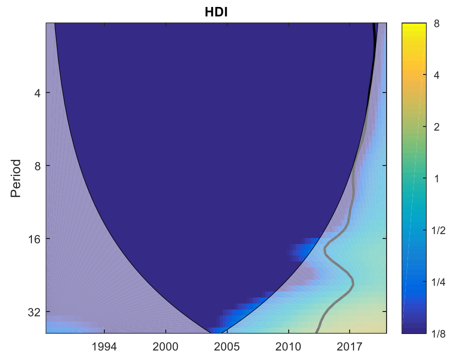


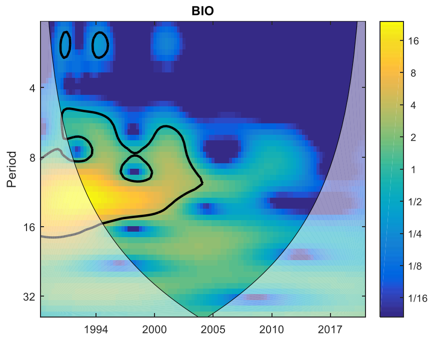


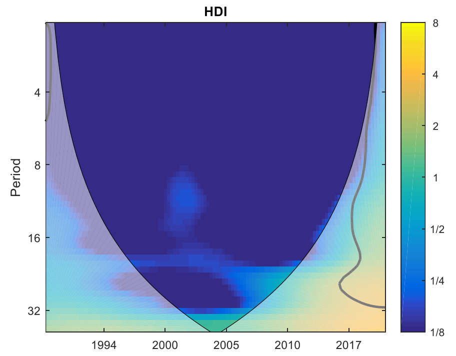
Russia





South Africa





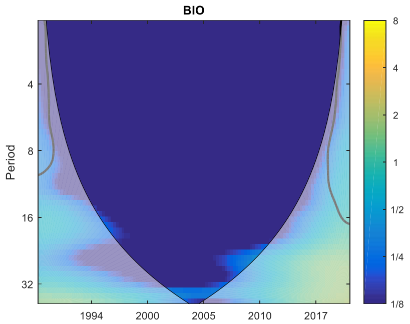
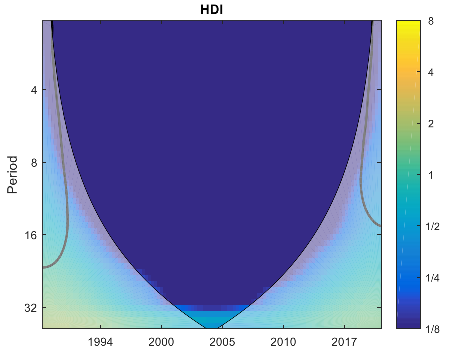
China		

Figure 1. The continuous wavelet power spectrum of BIO and HDI in BRICS countries.
Notes: The vertical axis is the frequency element while the horizontal axis is the time period; the thick black contour illustrates a significant area at the 5% level, and the curved black line represents a cone of influence. The color code for power ranges from blue (low) to yellow (high).

$$R_n^2(s,\tau)=\frac{|S\left(s^{-1}W_n^{XY}(s,\tau)\right)|^2)}{S\left(s^{-1}|W_X(s,\tau)|^2\right)S\left(s^{-1}|W_Y(s,\tau)|^2\right)} \quad (3)$$

where S connotes smoothing process for both time and frequency at the same time. $R_n^2(s,\tau)$ is in the range $0 \le R^2(s,\tau) \le 1$.

Wavelet correlation

To provide the background for the casual association between variables, the Rua (2013) wavelet correlation measure is given by:

$$\rho_{XY}(s,\tau)=\frac{\xi\left\{s^{-1}|\Re\left(W_{XY}^m(s,\tau)\right)|\right\}}{\xi\left\{s^{-1}\sqrt{|W_X^m(s,\tau)|^2}\right\}.\xi\left\{s^{-1}\sqrt{|W_Y^m(s,\tau)|^2}\right\}} \quad (4)$$

where $\xi(Q)=\xi_{scale}\left(\xi_{time}(Q)\right)$ with ξ_{scale} as the smoothing operator along scale axis, while ξ_{time} as the smoothing operator along the time axis. As a traditional correlation analysis, $\rho_{XY}(s,\tau)$ is bounded from -1 to +1.

Causality in continuous wavelet transform

The continuous wavelet transform for the Granger causality developed by Olayeni (2016) is employed, which extends the CWT-based correlation measure by Rua (2013). It can be written as

$$G_{Y\to X}(s,\tau)=\frac{\xi\left\{s^{-1}|\Re\left(W_{XY}^m(s,\tau)\right)I_{Y\to X}(s,\tau)|\right\}}{\xi\left\{s^{-1}\sqrt{|W_X^m(s,\tau)|^2}\right\}\xi\left\{s^{-1}\sqrt{|W_Y^m(s,\tau)|^2}\right\}} \quad (5)$$

where $W_Y^m(s,\tau)$, $W_X^m(s,\tau)$ and $W_{XY}^m(s,\tau)$ are the wavelet transformations and $I_{Y\to X}(s,\tau)$ as the indicator function which is defined as

$$I_{Y\to X}(s,\tau)=\begin{cases}1, & if\ \phi_{XY}(s,\tau)\in(0,\pi/2)\cup(-\pi,-\pi/2)\\ 0, & otherwise\end{cases} \quad (6)$$

It is clear that the big difference between the wavelet correlation and the CWT-Granger causality measure is the inclusion of the causal information through the indicator function $I_{Y\to X}(s,\tau)$.

Data

The data used in the current study consist of the annual observation of biomass energy consumption (BIO) which is collected from the Global Material Flows Database. The human development index (HDI) is gained from the database of United Nations Human Development Reports. The biomass energy is measured as tons per capita. In order to empirically examine the biomass energy-human development relationship, we use quarterly times data over the period of 1990Q1-2017Q4 for BRICS countries. The annual data for this paper was transformed into quarterly frequency utilizing the quadratic match-sum approach. This method performs amendments for seasonal deviations since the data is transformed from low to high frequency by dropping the point-to-point data deviation (Haseeb et al. 2020; Hung, 2020). More importantly, this adopted approach has perfectly captured the required larger frequency of data without undermining the real essence of related variables and tallies with past studies Shahbaz et al. (2016), Sharif et al. (2019), Sharif et al. (2020), and Shahbaz et al. (2018). Using quarterly data in empirical research has two merits: first, it raises the degree of freedom, and second, it raises the statistical power of estimation. This results in the estimated wavelet technique may be robust. Table 1 documents the summary statistics, demonstrating the mean value, maximum, minimum, skewness, kurtosis, Jarque-Bera, and standard deviation of the natural logarithm of various variables for an individual country.

It is clear from Table 1 that the average values for HDI in BRICS countries are negative, which fluctuates from -2.03 to -1.67. Biomass energy use has positive values for Brazil and Russia throughout the study, while India, China, South Africa have positive values. The biomass energy consumption has a larger mean than the human development index. Measured by standard deviation, biomass energy is more volatile than human development. In addition,

Table 1. Descriptive statistics of the return series

Variable	Mean	Median	Maximum	Minimum	Std. Dev	Skewness	Kurtosis	Jarque-Bera
Brazil								
Biomass Energy	0.679953	0.59017	1.137983	0.329191	0.238037	0.363656	1.688333	10.49745***
Human Development	-1.754797	-1.74554	-1.65843	-1.88034	0.065125	-0.32753	2.116636	5.644023***
Russia								
Biomass Energy	0.082526	0.098076	0.441978	-0.33722	0.212065	-0.03326	2.06099	4.135435***
Human Development	-1.67421	-1.68314	-1.58166	-1.74319	0.052592	0.263917	1.701059	9.173999***
India								
Biomass Energy	-0.79766	-0.78952	-0.72425	-0.88647	0.043622	-0.50153	2.412534	6.305839***
Human Development	-2.03441	-2.03674	-1.81809	-2.24115	0.125262	0.010734	1.723464	7.606689***
China								
Biomass Energy	-0.62238	-0.66551	-0.23414	-0.99785	0.217195	0.178658	1.865013	6.607391***
Human Development	-1.85203	-1.84992	-1.66953	-2.08013	0.127558	-0.15686	1.707314	8.25746***
South Africa								
Biomass Energy	-0.18607	-0.19147	-0.01408	-0.35033	0.075625	0.306437	2.553228	2.684357***
Human Development	-1.82803	-1.83361	-1.73528	-1.88331	0.041123	0.790952	2.72794	12.02338***

Notes: *** represents the 1% significance level.

the findings of the Jarque-Bera test are significant at the 1% level, which confirms that biomass energy consumption and human development are not normally distributed for all countries under consideration. More accurately, the entire quarterly data exhibit asymmetry and leptokurtic distribution as indicated by skewness and kurtosis coefficients.

Empirical results

Continuous Wavelet Transform (CWT)

Figure 1 reports the continuous wavelet transform power spectrum results for human development index (HDI) and biomass energy consumption (BIO) in BRICS countries. The horizontal (x-axis) and vertical axis (y-axis) present time and frequency, respectively. The CWT has been utilized to depict the variance in both time and frequency. The bold line in a light shade shows the cone of influence, which determines the region impacted by the edge effects. Specifically, the color code for the power spectrum ranges from blue (low power) to yellow (high power). Put differently, the yellow (blue) colored region indicates strong (weak) reaction power to shocks.

As shown in Figure 1, the yellow area mostly occurs at high scales (lower frequency). Biomass energy and human development of BRICS countries experience significant volatility at the 5% significance level. The intensity levels eventually rise from blue to yellow; the yellow area indicates that the variations of BIO and HDI in BRICS are very high. On the other hand, blue areas show fluctuations between BIO and HDI to external shocks such as the global financial crisis. For most BIO, their co-movement is centered around 2007 according to the value of the power spectrum indicated by color, and they exist in different cycle areas, which are primary centered in the low-frequency area. The variations in 2007 could be due to the influence of pollical and policy events. However, HDI in BRICS countries exhibited low volatility in all scales and frequencies, implying that the global financial crisis, European debt crisis, and Russian financial crisis has no impact on HDI in the BRICS countries.

Overall, with the findings of CWT of biomass energy and human development index for BRICS countries, we can see a similar pattern for HDI in different time and frequencies, while BIO shows more volatility in the long run.

The cross-wavelet transform (XWT) can experience typical high power between HDI-BIO pairs in Figure 2. In a similar fashion, XWT is analogous to CWT plots in Figure 1. The XWT shows the domestic covariance between HDI and BIO at various scales and periods. The yellow (blue) colors demonstrate high (low) power, the yellow (warmer) colors suggest that the two variables have high joint power. Besides, arrows show the direction of relevance and a lead-lag correlation. If the arrow points right (left), the pair has a positive (negative) relationship. Arrows pointing up and the right suggest HDI leading, and those down and to the right show, HDI lagging, whilst these down and to the left represent HDI leading. The XWT uncovers that the interdependence between BIO and HDI is significant at low and medium frequencies, indicating that the two variables have the same variation in the long run, except in South Africa. Put it another way, the covariance of HDI and BIO showed significant yellow noise around 2007, which suggests that a strong relationship exists among the pairs. At the same time, for the combinations including South Africa, India, and Russia, the relationship on the scales of 8-16 and 16-32 around

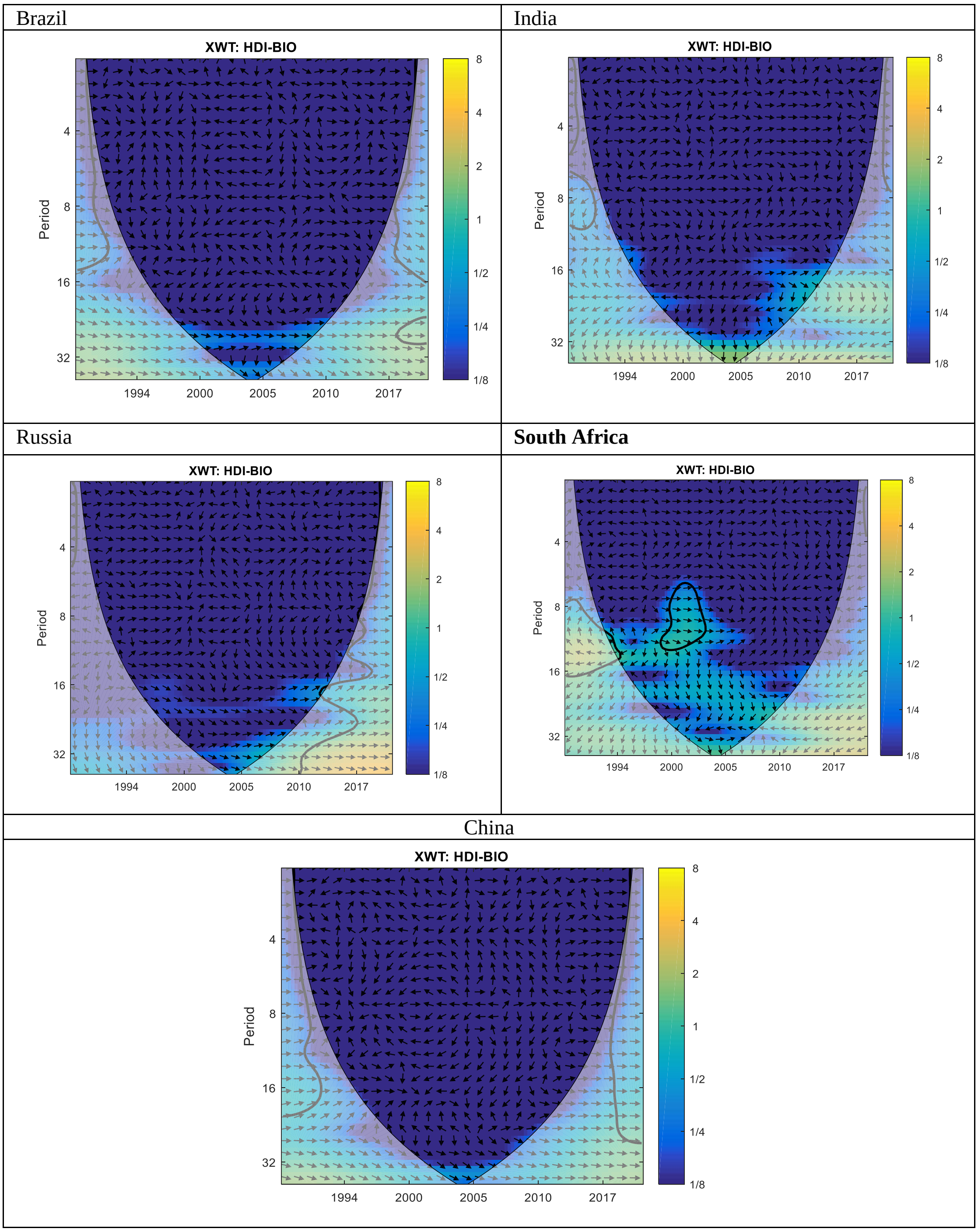


Figure 2. Cross-wavelet transform for BIO and HDI in BRICS countries

2008 is stronger. Furthermore, phase differences reveal that intercorrelation between HDI and BIO was not homogeneous across time and frequencies, as indicated by arrows that point up, down, right, and left across various time and scales. As a result, the findings show that the variation of examined variables in BRICS countries exhibits fundamental changes during the sample period studied.

Wavelet Coherence (WTC)

The results of wavelet coherence are reported in Figure 3. The WCT detects the regions where the two-time series co-move in the time and frequency domain. Plots of wavelet coherence are the same as those of continuous XWT and CWT, indicated in Figures 1 and 2. The x-axis shows the period, while the y-axis represents the frequency elements, which are transformed to quarterly, and a color code indicates the degree of fluctuation between the pairs. The warmer (yellow) areas suggest that the two variables have strong connections, while cooler (blue) areas suggest that two variables are less dependent. In particular, WTC clearly illustrates zones through time scales where each pair is remarkably dependent or

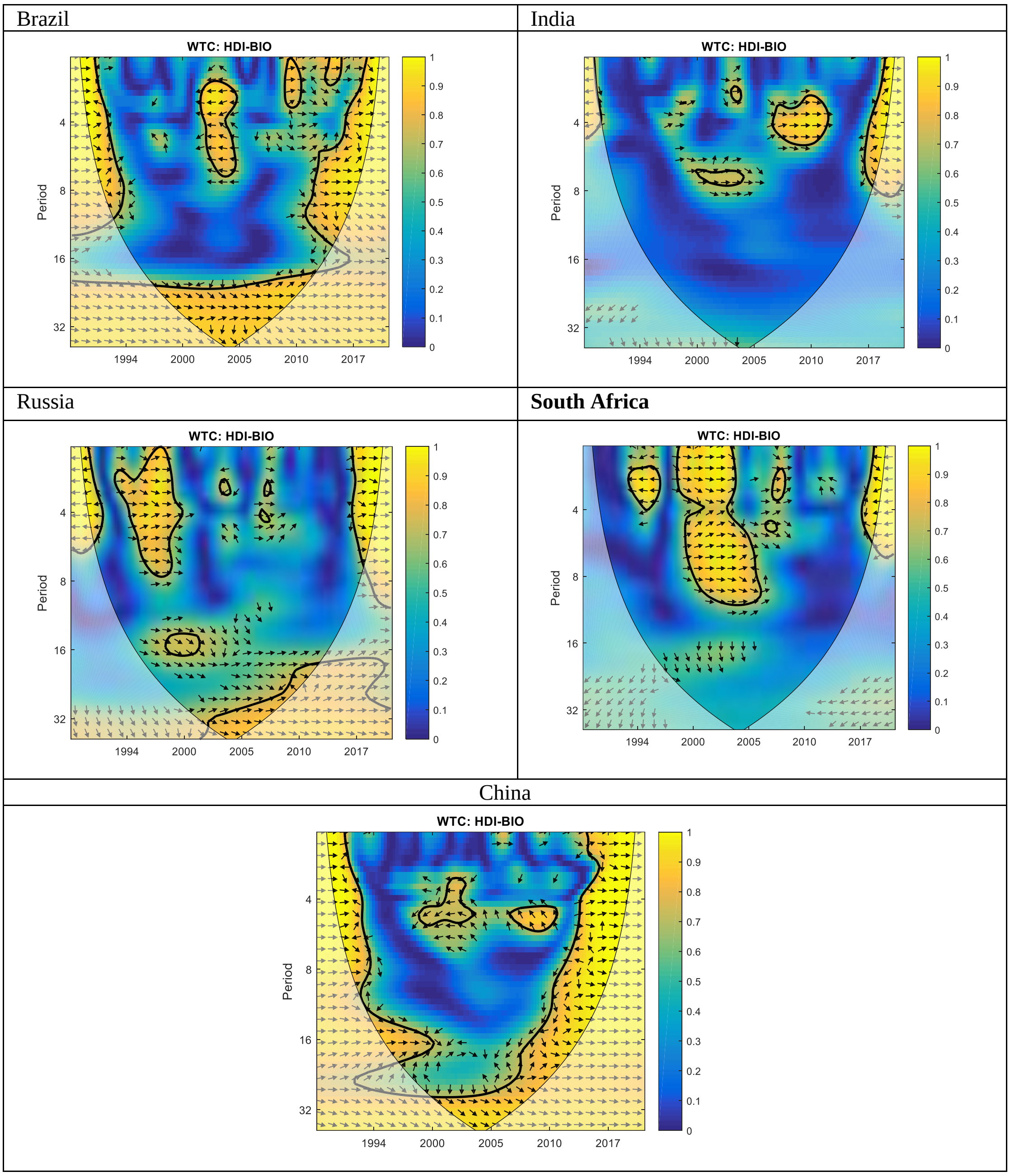
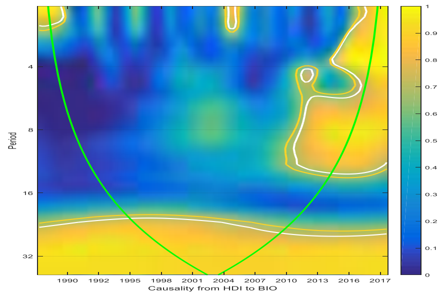


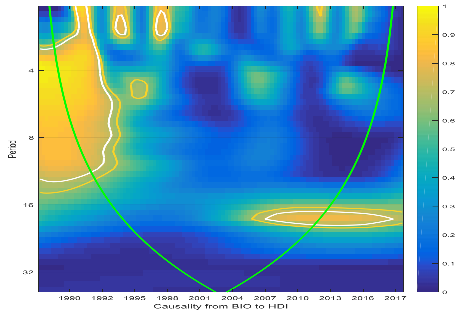
Figure 3. Wavelet coherence for BIO and HDI in BRICS countries
Notes: The vertical axis is the frequency element while the horizontal axis is the time period; the thick black contour illustrates a significant area at the 5% level, and the curved black line represents a cone of influence. The color code for power ranges from blue (low) to yellow (high). Areas inside the black contour plotted in the warmer color present a significant strong relationship. The phase difference between the two variables is shown by arrows. The arrows pointing right and left and up and down imply the direction of correlation and lead-lag correlation.

otherwise, corresponding to the domestic nexus ranging from 0 to 1. Using the phase differences, WTC has similar findings on the causality of the variables where the XWT and CWT uncover structural changes and variations. The arrow pointing in different directions suggests the interdependence and lead-lag nexus between HDI and BIO in BRICS countries.

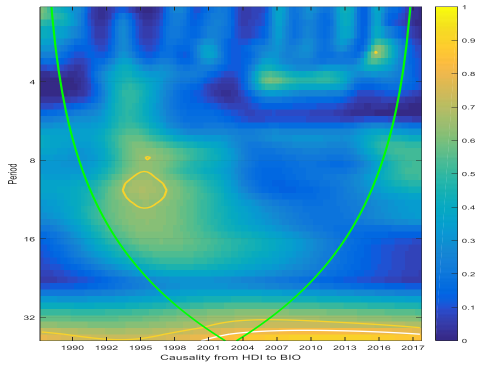
Wavelet coherences unveil a correlation between human development and biomass energy consumption in the BRICS countries, while wavelet phase difference identifies the interactive linkages of series by observing lead-lag interdependence at different time and frequencies. Arrows presenting phase differences suggest the direction of the relationship and causal associations. Precisely, right and left arrows demonstrate that the pairs are in-phase and out-phase, respectively. The in-phase wavelet phase difference shows that the HDI and BIO move jointly in a similar direction, while the out-phase suggests that the pairs co-move in opposite directions through time and frequency bands. Put differently, an in-

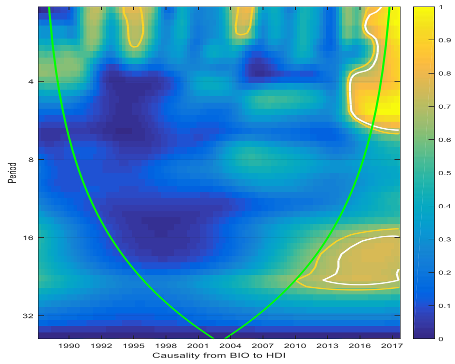
Brazil



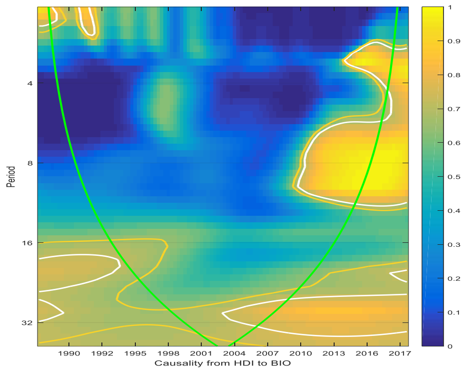


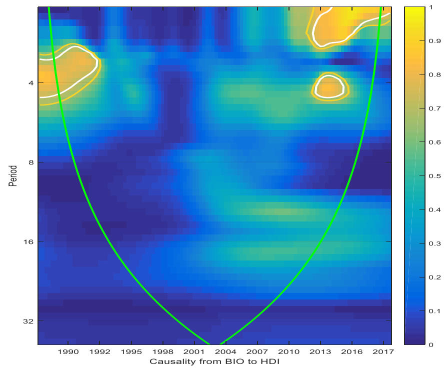
Russia



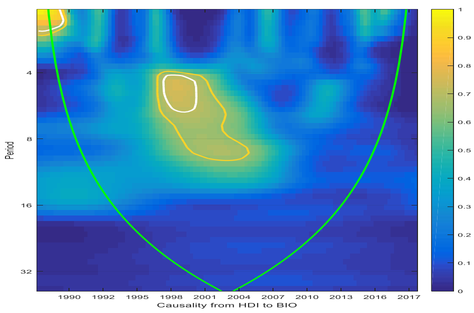


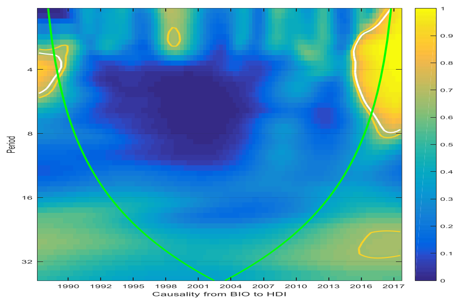
China





South Africa





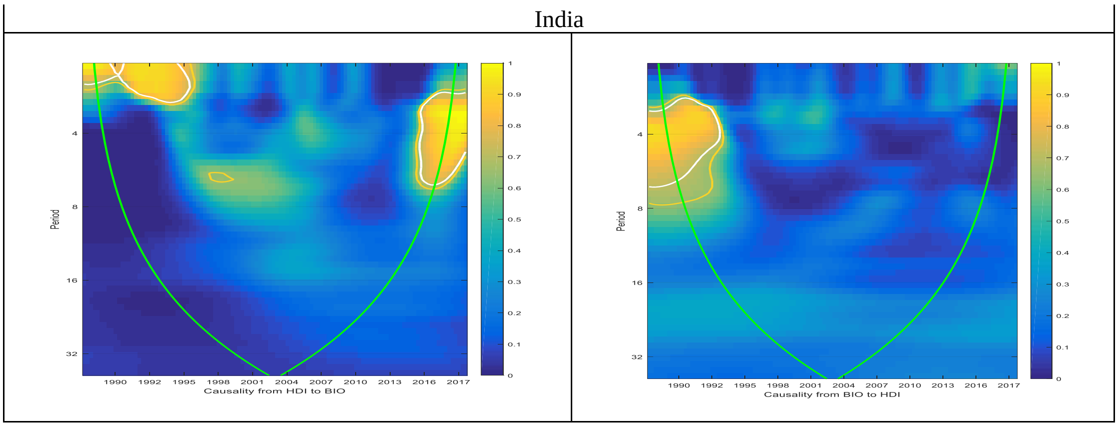


Figure 4. Wavelet based causality from HDI to BIO and BIO to HDI
Note: white and yellow contour indicate statistical significance at 5% and 10% level, respectively. The bold green contour presents the cone of influence that delimits the area not impacted by edge effects. The significance levels are calculated based on the 1000 Markov bootstrapped series.

phase difference indicates a positive correlation, and an out-phase difference shows a negative relationship between HDI and BIO in the BRICS countries. The right up or left down arrows indicate that HDI, as the dependent variable, is leading, and the right and down and left and up arrows suggest that BIO, as an independent variable, is leading.

The plot pair of wavelet coherence suggests that human development and biomass energy consumption exhibit significant connectedness over time and frequency domains in the BRICS countries. The pair (HDI-BIO) coherence rises at lower and medium bands (0-4 months and 4-8 months). Co-movement of human development and biomass energy illustrate high coherence in Brazil, Russia, China, and South Africa, but in India, the connection between these variables is low.

The findings of wavelet coherence for Brazil determined four yellow-colored areas for 1990-1994, 2004-2007, 2008-2010, and 2014-2016, suggesting significant and positive co-movement between HDI and BIO variables. For 1990-1994 and 2014-2016, we find high levels of co-evolution between the two variables for the 1-4-quarter and 16-32 quarter scales, and arrows are pointed upward, indicating that the two variables are in phase with that human development as a leading variable. This implies that HDI precedes an increase in BIO in Brazil. By contrast, between 2004 and 2007, we observe that two variables are out of phase since the arrows are clearly pointed upward and to the left with HDI as part of BIO serving as the lagging carriable. Apparently, there exists a causal association between human development and biomass energy use in Brazil at different time and frequencies.

In Russia, China, and South Africa, wavelet coherence, human development, and biomass energy consumption are correlated at all times and across low, medium, and high frequencies. Specifically, there is a strong relationship between HDI and BIO in China during the sample period. We note the existence of a large yellow-colored region for the 2000-2010 period, showing a positive and significant interaction between the HDI and BIO for the 0-4 and 6-32 quarter frequencies, where most of the arrows are right side downward direction which suggest that both variables revealing cyclic effect that HDI has a positive causal impact on BIO in these nations. However, in China, the arrows point leftward and downward in one area in 4-8 quarter scales over the period 200-2005, suggesting that HDI negatively influences BIO in this country. Overall, the findings of wavelet coherence between BIO and HDI in Russia, Brazil, China, and South Africa confirm that both time series have a bidirectional relationship during the periods of 1994-2000 and 2010-2016 but 2005-2008, we found a unidirectional causal association between human development and biomass energy use.

According to Figure 3, we find a low level of co-movements between HDI and BIO in India. There are several areas with high wavelet coherence in 1-4 quarters and 4-8 quarter scales, corresponding to 2000-2010. The majority of the arrows point rightward and downward, indicating that HDI and BIO are positively correlated, and HDI leads BIO in the medium run. Nevertheless, we find no causal association between HDI and BIO in the long and very long run for the case of India. Generally, the outcome confirms that a positive nexus between human development and biomass energy use in the medium term, where HID is leading the biomass energy consumption in India.

Overall, we find a positive and significant association between the two variables for the short, medium, and long-run periods. More importantly, we also unveil a lead-lag interaction in different time and frequency domains between human development and biomass energy use in the BRICS countries.

Figure 4 depicts the findings of the CWT-based Granger causality developed by Olayeni (2016) between human development and biomass energy consumption in the BRICS countries. Casual associations are demonstrated based on contour graphs since there are three dimensions involved: time, fre-

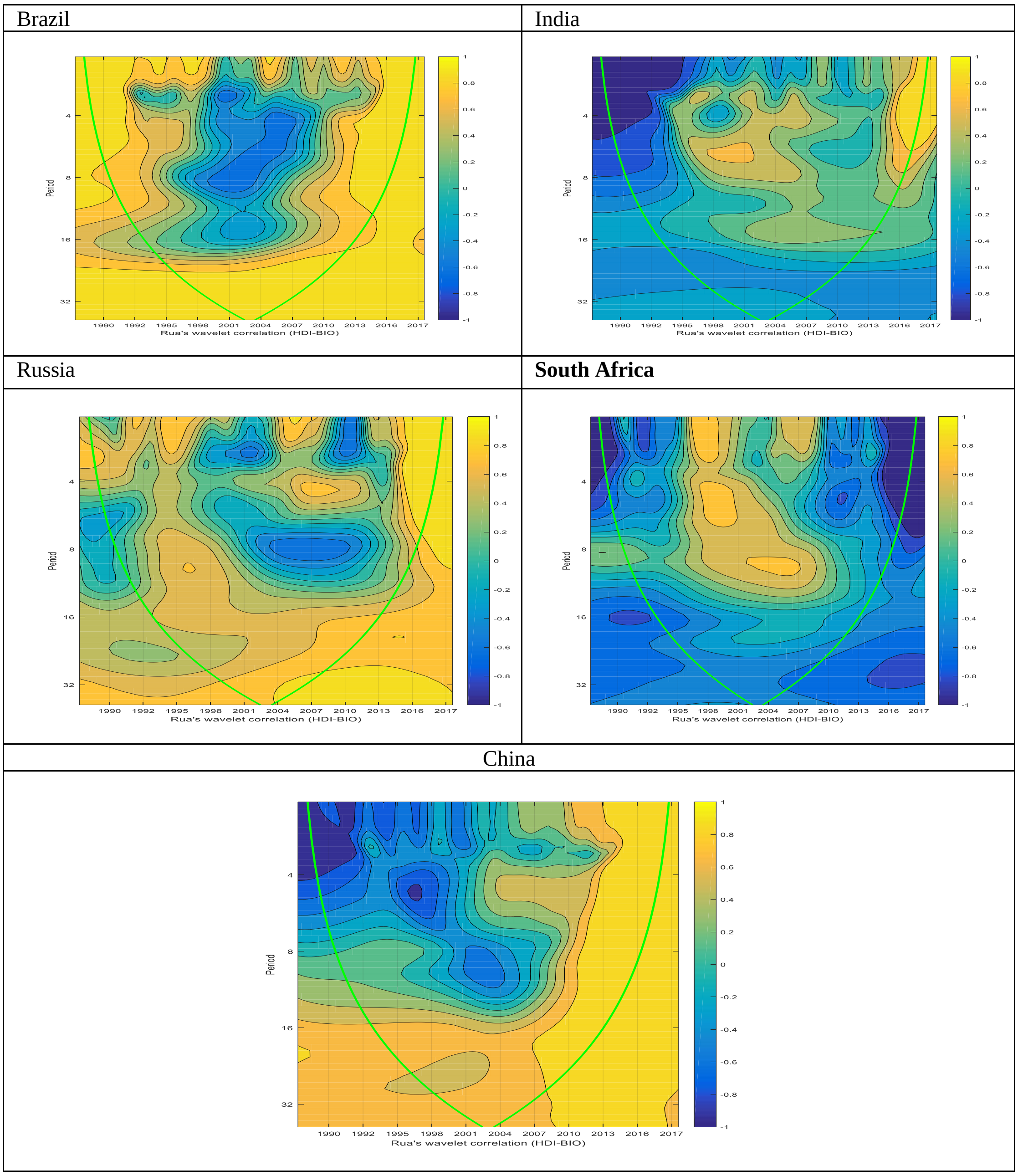


Figure 5. Wavelet-based correlations (Rua, 2013)
Notes: Blue (yellow) shows negative (positive) correlations.

quency, and magnitude of the causal nexus. The horizontal axis shows the period spanning the entire sample period, while the vertical axis measures frequency, which is expressed in quarters ranging from the highest frequency of 4 quarters to the lowest frequency of 32 quarters. The magnitude of causal associations between the two variables is uncovered by a color code ranging from blue (lack of causal relation) to yellow (strong causal association). White and yellow contours describe the significance level of the CWT-based Granger causality at the 5% and 10%. The bold green line is the cone of impact, which delimitates the island not impacted by edge effects.

In Figure 4, we concentrate on three frequencies between human development and biomass energy used in the BRICS countries, such as the 0-4 quarter scale, which reflects the short term, 4-8 quarter scale, which is associated with the medium term, and 8-16 and 16-32 quarter scales, which related to the long term. These frequencies are selected to evaluate whether the long-term, medium-term, and short-term nexus between HDI and BIO are different or similar. It is clear from Figure 4 that the pairs reveal the near-total persistence of significant causal associations between HDI and BIO at all time scales and frequencies in China, Brazil, Russia, and South Africa, but the absence of a significant causal relationship at the lowest frequencies (from 16-32 quarters approximately) over the sample period for the two examined variables in India.

Interestingly, in China and Brazil, the co-movement between human development and biomass energy use experienced an increasing trend, particularly after the global financial crisis of 2008. This causal relationship also attained its peak in the low and medium frequencies during the period shown. Moreover, in South Africa, a strong bidirectional effect between the two variables is found from 1990 to 1995 and from 2015 to 2017 on 0-4 quarter scales. Nevertheless, this causal effect has become a little bit weak in the low frequency in India. The causality findings reveal that HDI impacts BIO variables in India. Overall, the causal effects from human development to biomass energy consumption in the BRICS countries are more pronounced than in the opposite direction, especially at low and medium frequencies. Hence, an increase in biomass energy usage is accompanied by an increase in human development. This finding is consistent with Wang et al. (2018) for Pakistan, Wang (2019) and Wang et al. (2020) for BRICS countries.

Rua's (2013) measure of CWT correlation is given in Figure 5. This approach is conducted to check the validity of the above results of the causal associations between human development and biomass energy use in the BRICS countries. These plots illustrate a positive relationship between the two variables and generally confirm the findings in WTC and in the causal effects as described in Figures 3 and 4. It is evident that both variables have high positive connectedness during 1990-1998 and 2008-2016 at different quarter bands of scales (low, medium, and high frequency) in cases of Brazil, China, South Africa, and Russia. Nevertheless, such correlation is existent for the whole sample period at high and low frequencies. Besides, there is a weak relationship between these variables at medium frequency, which suggests the neutrality hypothesis during the periods in these countries. By contrast, In India, a high negative correlation appears between 2010 and 2016 on the 16-32 quarter scale, as indicated by regions of blue color. These results demonstrate that there seem to be significant causal associations between human development and biomass energy use in the BRICS countries, as visualized in Figures 3, 4, and 5. These outcomes aligns with the findings of Dias et al. (2016), Wang et al. (2018) and Khan et al. (2019).

In general, the primary novelty of our empirical outcomes lies in their capacity to depict the causal associations between human development and biomass energy consumption in the BRICS countries. Our results offer fresh insight into the strength and direction of causal connections between the two variables in the time and frequency domains. More accurately, we employ the recent wavelet-based Granger causality test of Olayeni (2016) to determine the particular frequencies and time periods where the casual connectedness is more intense and identifying the prevailing causality direction. As a result, the present paper results may be seen as a supplement to the empirical evidence on the human development-biomass energy relationship provided by the present literature. Further, our findings also extend the results of Khan et al. (2019), Reiter and Steensma (2010), Shahbaz et al. (2016), Aydin et al. (2019), Sinha and Sen (2016) and Wang et al. (2020) with the estimates of reaction of the relationship of biomass energy consumption to human development. They argue a significant interaction between biomass energy consumption to human development.

Concluding remarks and policy implications

The essence of the study is whether biomass energy consumption has any causal effect on the human development index in the BRICS countries in the time-frequency space. Nevertheless, past studies have neither evaluated this connection in a non-linear approach nor considered this nexus in terms of both time and frequency. The in-depth analysis is done by applying the wavelet framework using quarterly data for the 1990-2017 time period. Specifically, the wavelet coherency method of Rua (2013) and the wavelet-Granger causality test of Olayeni (2016) are utilized to quantify the strength and direction of causal relationships through time and across various frequencies simultaneously.

The empirical findings uncover that the causal linkages between human development and biomass energy consumption in the BRICS countries are not homogeneous in different time and frequency scales. We also discover the strong relationship between the -two variables in China, Russia, Brazil, and South Africa after the global financial crisis 2008 at low and medium frequencies, while this connection is somewhat low in India over the sample period. More importantly, the remarkable causality is mostly concentrated at a lower time horizon (between 1 and 16 quarter scales). The possible explanation for this is that the higher frequency element of the nexus receives much attention from people due to their closer association with environmental issues, hence enhancing the spillover of uncertainty between human development and biomass energy use in the medium term. On the other hand, the causal associations between both indices at longer horizons turn out to be quite limited, suggesting that little attention is paid to the transitory long-run relationship in the two indicators. Further, the low and medium casual relationships running from human development to biomass energy are more pronounced than in the opposite direction, which unveils that the human development index of the BRICS countries embodies vital information about the low and medium evolution of biomass energy consumption.

Policy lessons drawn from the preceding depend not only on the causal association between biomass energy consumption and human development but also on the direction and magnitude of the influences. Empirical findings suggest that human development in the BRICS countries is associated with increased biomass energy consumption. This implies that it is necessary to decline energy intensity of output via the adoption of energy-efficient technologies and seek alternative clean energy sources to reduce CO_2 emissions associated with biomass energy usage to enhance growth. Put differently, governments need to employ the resources of renewable energy to reduce the energy crisis in the BRICS countries. BRICS governments can achieve their millennium growth purposes to reduce severe poverty and hunger and secure the objective of achieving environmental sustainability by resolving energy crises.

Overall, biomass energy usage benefits the human quality of life, so policies to increase biomass energy usage in the energy consumption should be conducted. BRICS nations should raise awareness about biomass energy and encourage biomass energy production and consumption. Put it another way, development of the biomass energy infrastructure and encouragement of biomass energy consumption are significant energy policy tools because they enhance human welfare while also being impacted by it. There are direct and indirect influences between biomass energy consumption and human development. If energy needs are gained from biomass energy sources, energy dependence on fossil fuels from these nations will decrease, which enables sustainable economic growth and development.

Since this study estimates the biomass energy-human development nexus in BRICS countries and at different time and frequency domains, future studies could investigate this relationship in other regions. Future studies could explore energy output-human development linkages for other renewable energy apart from biomass or biomass sources on global warming and economic growth in detail.

Declarations

1. Availability of supporting data. Please contact author for data and program codes requests. R and Matlab are used to organize data.
2. Competing interests. The authors declare that they have no competing intrests.
3. Funding. The author received no financial support for the research, authorship and/or publication of this article.
4. Authors' contributions. NTH conceived of the study, carried out drafting the manuscript.

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