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Unveiling the Nexus: Energy Innovation, Fintech, Environmental Taxes, and Natural Resources

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Abstract: This study explores the intricate interplay between economic development and environmental well-being within the East Asian context. Despite the region's robust economic performance, it grapples with significant environmental challenges, including pollution, waste management issues, and deforestation. Our investigation focuses on assessing the impact of energy innovation, financial technology (Fintech) revenue, environmentally related taxes, and natural resource rents on environmental sustainability. Employing cointegration and autoregressive distributed lag (ARDL) estimation methodologies, our analysis indicates that energy innovation, environmentally related taxes, and Fintech revenue positively and significantly influence environmental sustainability. However, natural resource rents exhibit a negative effect. Furthermore, we observe bidirectional causality between environmental sustainability and both energy innovation and Fintech revenue, suggesting a mutually reinforcing relationship. Conversely, the relationship between environmental sustainability and GDP growth, natural resource rents, and environmentally related taxes appears unidirectional. These findings underscore the necessity of adopting a holistic approach. East Asian nations should adeptly manage their natural resource endowments, harness Fintech for sustainable initiatives, and sustain investments in clean energy innovation. By embracing these strategies, East Asia can chart a course towards a sustainable future, simultaneously propelling economic progress and fostering a healthier global environment.

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Introduction

In the contemporary epoch, our global society witnesses the advent of advanced technology, pervasive industrialization, and rapid urban expansion, bestowing upon its denizens an array of advantages, thereby yielding a superior standard of living and augmented income in contrast to preceding generations. The transformative currents of modernization, encompassing urban growth and technological progress, not only streamline daily existence but also stimulate economic advancement, propelling lifestyles to unprecedented echelons. Within this tide of modernization and economic affluence, an escalating concern emerges—the compelling exigency for environmental conservation. This concern reverberates across the entire globe, compelling all stakeholders to acknowledge the inevitability of addressing environmental sustainability (ES) to preserve the fragile ecological equilibrium of our planet. Although the notion of ES is not novel, its origins harken back to the concept of appropriate technology and the burgeoning environmental consciousness of the 1970s, as delineated by Pearce and Vanegas (2002).

The delineation of environmental sustainability poses a persistent challenge, characterized by diverse conceptualizations. Nevertheless, its fundamental essence centres on safeguarding the environment against pollution, the exhaustion of energy and renewable resources, and the degradation of natural resources. A multitude of factors shape environmental sustainability, as elucidated by Syed and Tollamadugu (2019). The evolution of European environmental policy frameworks (Jordan, 1999), the establishment of transnational agreements concerning environmental matters, and the United Nations' advocacy for global environmental preservation (Cichowski, 1998) underscore the widespread recognition and dedication to addressing environmental issues on both national and international scales.

The persistent and escalating alterations in climate, exemplified by phenomena like global warming, ice melt, and sea level rise (Dervash et al., 2023), command the focus and apprehension of environmental advocates and scientific communities, underscoring the vital necessity for planetary preservation. Notwithstanding policy dialogues and regulatory initiatives at both domestic and international tiers, the ongoing degradation of the environment and exacerbation of global warming pose a pivotal inquiry: Do individuals possess genuine awareness of environmental sustainability beyond the confines of economic progress?

Amidst enduring environmental adversities, this poignant inquiry assumes salience. Despite the observance of remarkable global economic strides, a conspicuous disparity persists concerning substantive advancements in environmental conservation. The dichotomous relationship between economic progression and environmental custodianship underscores the imperative for a paradigmatic shift. Nations are called upon not merely to prosper economically but also to prioritize and significantly augment their dedication to environmental safeguarding (Rehman et al., 2021). Navigating this delicate equilibrium, the world finds itself at a juncture of progress, summoning forth innovative resolutions and a collective awareness that situates environmental sustainability at the apex of global concerns.

In today's intricate tapestry of progress, fuelled by advanced technology and urbanization, we enjoy unprecedented affluence and lifestyle advancements. However, this march of progress raises concerns about its toll on ecological resilience. As we embrace industrialization and economic growth, we must ask: how can we ensure this progress doesn't irreversibly harm our environment? (Ziolo et al., 2020).

The introductory remarks lay the groundwork for a nuanced investigation into the interconnection between progressive development and ecological resilience, elucidating the obstacles and prospects arising when the engines of advancement align with the necessity of safeguarding our planet. Undertaking a thorough examination of this intricate relationship, our focus turns to eight East Asian nations. These countries, characterized by dense populations and dynamic economies, offer a compelling focal point for our inquiry. The chosen dataset encompasses the period from 2011 to 2021, capturing a decade of significant advancements at the intersection of economic advancement and environmental preservation.

East Asia, celebrated for its vibrant economic expansion and technological innovations (Mohamed et al., 2022), furnishes a fertile terrain for our inquiry. The selected nations, propelled by a zeal for progressive advancement, have undergone substantial metamorphoses across diverse domains, spanning industry to urban development. As we navigate the intricacies of their trajectories, our aim is to elucidate the intricate interplay between economic advancement and environmental imperatives.

The high population density characteristic of these East Asian nations introduces an added stratum of intricacy to our analysis. With burgeoning populace, the requisites for resources and energy have escalated, presenting both challenges and avenues for sustainable methodologies (Christopher, 2019). As these nations negotiate the delicate equilibrium between economic advancement and ecological conservation, our objective is to elucidate discernible trends, trajectories, and innovative practices that have surfaced over the preceding decade. Our scrutiny encompasses a pivotal timeframe, spanning from 2011 to 2021, affording us the opportunity to encapsulate the evolution of policies, endeavours, and societal perceptions regarding environmental sustainability. This temporal purview facilitates the identification of change patterns and the evaluation of the repercussions of progressive development on ecological robustness.

The initiation of this research endeavour stemmed from a compelling imperative to bridge extant lacunae in understanding the interrelation between progressive development and ecological efficacy. Despite various inquiries into this intricate interplay, a discernible void persists in comprehensively appraising the influence of financial metrics on ecological robustness. Acknowledging this gap in scholarly discourse, our study endeavours to address this lacuna and furnish valuable insights to the ongoing dialogue concerning sustainable advancement. Additionally, the paucity of investigations employing diverse progressive development indicators to scrutinize their enduring impacts on individual nations accentuated the indispensability of our inquiry. The scarcity of comprehensive assessments spurred our intellectual curiosity and propelled our exploration into this multifaceted interaction, with the aim of offering a more nuanced perspective on the challenges and prospects engendered by economic advancement within the realm of environmental sustainability.

The inclusion of variables such as energy innovation, environmental taxes, and fintech revenue was a deliberate decision, motivated by the recognition that these factors wield significant yet frequently undervalued influence over the environmental terrain. The distinctive configuration of our study represents a conscientious endeavour not only to broaden scholarly comprehension of these correlations but also to furnish actionable insights for policymakers and stakeholders grappling with the intricate equilibrium between economic advancement and environmental guardianship. Through this research endeavour, we aspire to make substantive contributions to the ongoing global dialogue on sustainable development and to delineate a pathway for nurturing a symbiotic relationship between progressive development and ecological durability.

Literature Review

The endeavour to achieve environmental sustainability within the context of economic development has garnered escalating scrutiny within academic inquiry and policymaking spheres. Scholars have delved into a spectrum of factors shaping environmental sustainability, encompassing economic metrics, technological advancements, financial modalities, and practices pertaining to natural resource management.

The GDP Growth Rate has emerged as a central focus in environmental sustainability research owing to its linkage with economic activity and resource utilization. Numerous investigations have scrutinized the association between GDP growth and environmental degradation, underlining the imperative to disassociate economic expansion from environmental repercussions. Ahmad et al. (2020) conducted an inquiry utilizing cointegration tests to explore the enduring correlation among ecological footprint, natural resource endowments, technological advancements, and economic growth. Their findings unveiled that the abundance of natural resources and economic proliferation contribute to the escalation of the ecological footprint over time. Nevertheless, technological innovations act as a mitigating force against the environmental degradation engendered by this process. Furthermore, their analysis provided support for the Environmental Kuznets Curve hypothesis, indicating an inverse relationship between economic growth and ecological footprint when considering the quadratic effect. Moreover, in a recent investigation, Xu (2023) examined the interplay between financial globalization, economic growth, and environmental sustainability. Their study identified the existence of an Environmental Kuznets Curve (EKC) concerning the ecological footprint and economic growth, particularly within the context of financial globalization and population density.

Energy innovation stands as a pivotal catalyst for environmental sustainability, facilitating the transition toward cleaner energy sources and heightened energy efficiency. Scholarly investigations underscore the importance of directing investments toward renewable energy technologies and embracing energy-efficient practices, which contribute significantly to climate change mitigation by curtailing greenhouse gas emissions. Furthermore, advancements in clean energy technologies not only bolster environmental objectives but also spur economic expansion and fortify environmental resilience. Studies by Guo et al. (2021) and Suki et al. (2022) elucidate the interconnectedness among CO2 emissions, green innovation, renewable energy integration, and energy sector investment. Their findings underscore the urgency of transitioning toward sustainable energy sources to effectively combat environmental degradation. Moreover, the utilization of renewable energy is recognized as pivotal in mitigating environmental harm, while technological innovation assumes a critical role in abating carbon emissions and minimizing ecological footprints.

The emergence of Financial Technology (Fintech) introduces fresh avenues for advancing sustainable finance and investment, providing platforms such as green bonds, crowdfunding mechanisms, and digital payment systems to direct capital toward environmentally beneficial endeavours. Scholarly inquiry underscores the pivotal role of regulatory frameworks and policy incentives in leveraging Fintech to address environmental concerns and promote sustainable development. Udeagha and Muchapondwa (2022) delves into the synergistic interplay between GFN and Fintech in propelling the transition toward carbon neutrality, particularly within BRICS economies. Drawing support from the EKC hypothesis, their findings underscore the positive impacts of GFN, Fintech, and ENI on environmental sustainability. Furthermore, bidirectional causality is noted between CO2 emissions and GFN, Fintech, indicating the intertwined nature of financial mechanisms and environmental outcomes. Additionally, Liu et al. (2024) illuminate the role of Fintech, natural resources, and urbanization in China's pursuit of environmental sustainability, revealing the potential of Fintech to facilitate initiatives for green growth.

Efficient management of Natural Resource Rent assumes paramount importance in safeguarding environmental sustainability, particularly in regions abundant with resources susceptible to challenges delineated by the Resource Curse Hypothesis, which encompasses economic volatility, governance deficiencies, and environmental degradation. Scholars advocate for policies that advocate for sustainable resource extraction practices, equitably distribute revenues, and invest in alternative livelihoods to ameliorate adverse environmental impacts. Investigations conducted by Recep and Ozcan (2020b) delve into these intricate dynamics. Muhammad Zahid et al. (2022) scrutinize China's natural resource rents, discerning that while they bolster environmental sustainability, they may concurrently impede economic growth. Conversely, Recep et al. (2020b) underscore the significance of efficient natural resource utilization and heightened integration of renewable energy to realize sustainable development goals.

ERT are pivotal in shaping environmental policy by encouraging sustainable practices and addressing externalities. Recep et al. (2020a) investigated the impact of ERT on CO2 emissions, finding a non-linear relationship, particularly in the context of globalization, where higher ERT levels correlate with reduced emissions. They also observed a positive contribution from environmental-related technologies and patents, especially in more globalized settings. In a related study, Muhammad Zahid et al. (2022) examined the heterogeneous effects of environmental taxes on environmental footprints in OECD economies. Their analysis emphasizes the need for stringent monitoring of environmental regulations, particularly regarding energy usage policies and cleaner production objectives. These findings highlight the significance of ERT as a policy tool for curbing environmental degradation and fostering sustainable development.

In summary, the amalgamation of literature highlights the nuanced complexity inherent in environmental sustainability, influenced by a spectrum of economic and technological determinants. The examined studies elucidate the intricate interplays among GDP growth rate, energy innovation, natural resource rent, environmentally related taxes, fintech revenue, and the overarching aspiration of attaining environmental sustainability. While GDP growth frequently aligns with escalated resource consumption and environmental degradation, strategic measures and innovations, such as energy innovation and environmentally related taxes, present avenues for decoupling economic expansion from ecological harm. Moreover, astute management of natural resource rent and the utilization of fintech revenue offer prospects for fostering sustainable resource utilization and financing environmentally beneficial endeavours. These findings underscore the imperative of comprehensive approaches that integrate economic advancement, technological ingenuity, and environmental policy to propel environmental sustainability objectives and cultivate resilient, eco-conscious societies.

Theoretical Framework

Environmental Sustainability

Environmental sustainability stands as a paramount objective in the realm of global development, aspiring to safeguard natural resources, biodiversity, and ecosystems for posterity. The attainment of environmental sustainability mandates a comprehensive framework that harmonizes economic progress with ecological conservation and societal welfare. Consequently, comprehending the determinants shaping environmental sustainability assumes pivotal significance for informed policy formulation and strategic decision-making processes.

Independent Variables

1. Energy Innovation: Energy innovation assumes a pivotal role in facilitating the transition toward a sustainable energy paradigm. Through the cultivation and integration of clean energy technologies, energy innovation holds the capacity to diminish greenhouse gas emissions, alleviate the impacts of climate change, and fortify energy resilience. An examination of the repercussions of energy innovation on environmental sustainability offers valuable insights into the efficacy of technological interventions in confronting environmental imperatives and advancing sustainable energy modalities.
2. Natural Resource Rent: Natural resource rent, acquired through the extraction and utilization of natural resources, bears significance for environmental sustainability. While resource extraction can fuel economic expansion and progress, it may concurrently engender environmental deterioration, habitat depletion, and ecological disarray. Hence, scrutinizing the nexus between natural resource rent and environmental sustainability assumes critical importance in comprehending the environmental ramifications of economies reliant on resources and delineating approaches for sustainable resource governance.
3. Fintech Revenue: Fintech revenue, stemming from innovative financial technologies and services, holds promise in shaping sustainable finance and investment practices. Assessing its role in environmental sustainability can elucidate how financial innovation fosters green financing, climate resilience, and sustainable development initiatives.
4. Environmentally Related Taxes: Environmentally related taxes serve as policy instruments crafted to internalize the environmental externalities associated with economic undertakings and cultivate environmentally sustainable conduct. By levying taxes on pollution, carbon emissions, and resource extraction, these fiscal measures seek to motivate enterprises and consumers toward the adoption of cleaner technologies and methodologies. Evaluating the influence of environmentally related taxes on environmental sustainability offers valuable insights into the efficacy of fiscal interventions in confronting environmental hurdles and facilitating the shift toward a low-carbon, resource-efficient economic framework.
5. GDP Growth Rate: The GDP growth rate quantifies the percentage variation in the value of goods and services generated by a nation's economy within a defined timeframe. While GDP growth signifies economic enlargement and productivity, it does not inherently account for environmental ramifications or societal welfare. However, elevated GDP growth rates have been linked with increased resource exploitation, environmental degradation, and expansion of ecological footprints. Therefore, scrutinizing the relationship between GDP growth rate and environmental sustainability is imperative for understanding the environmental implications of economic expansion and identifying strategies to disentangle economic progress from environmental degradation.

Need for Analysis in the Context of Environmental Sustainability

Examining energy innovation, natural resource rent, fintech revenue, environmentally related taxes, and GDP growth rate in the context of environmental sustainability holds significant importance for several reasons:

1. Understanding the drivers of environmental change: Through scrutinizing the impact of these variables on environmental outcomes, policymakers and researchers can pinpoint the primary drivers of environmental change and prioritize interventions to tackle them.
2. Informing sustainable development strategies: Examining the interconnection between economic activities and environmental sustainability offers significant insights into the trade-offs and synergies among economic growth, environmental preservation, and social welfare. Such analysis informs the formulation of sustainable development strategies and policies aimed at fostering inclusive and environmentally sustainable growth.
3. Identifying policy levers for environmental improvement: Through discerning the factors that exert positive or negative impacts on environmental sustainability, policymakers can craft tailored policies and incentives to stimulate sustainable practices and alleviate environmental hazards. This may encompass advocating for clean energy technologies, instituting green taxation frameworks, nurturing sustainable finance endeavours, and embedding environmental considerations into economic decision-making frameworks.
4. Enhancing resilience to environmental challenges: In light of mounting environmental challenges like climate change and biodiversity loss, grasping the link between economic factors and environmental sustainability is pivotal for enhancing resilience and adaptive capacity. By fostering sustainable resource management, curbing pollution, and investing in green technologies, nations can bolster their resilience to environmental risks, ensuring the welfare of current and future generations.

Hypotheses

Given the imperative for analysis within the framework of environmental sustainability, the study posits the following hypotheses:

H1: Energy innovation positively influences environmental sustainability.

H2: Natural resource rent exhibits a mixed or negative effect on environmental sustainability.

H3: Fintech revenue contributes to environmental sustainability.

H4: Environmentally related taxes have a positive impact on environmental sustainability.

H5: GDP Growth rate positively influences Environmental Sustainability Index

Model Design

Our study aligns with the previously outlined theoretical framework, encompassing Energy Innovation, Fintech Revenue, Natural Resource Rent, Environmentally Related Taxes, and GDP Growth Rate. Through the integration of these variables, our objective is to assess their combined influence on the Environmental Sustainability Index. Recognizing the importance of economic indicators in addressing climate change, the GDP Growth Rate is incorporated into our model. The overarching representation of our model is encapsulated by the following equation:

$$ESI = \beta_0 + \beta_1 \cdot GDPGrowth + \beta_2 \cdot NaturalResourceRent + \beta_3 \cdot EnergyInnovation + \beta_4 \cdot TaxPercentageGDP + \beta_5 \cdot FintechRevenue + \epsilon$$

Where:

1. *ESI* is the Environmental Sustainability Index,
2. *βo* is the intercept,
3. β_1 to β_5 are the coefficients for the respective variables,
4. € represents the error term in the model.
5. This equation symbolizes the intricate interrelation among economic, technological, and environmental elements, furnishing a comprehensive framework for our analysis, grounded in the proposed hypotheses and theoretical underpinnings.

In our panel data analysis, the cross-sectional units are designated by i, representing discrete entities or regions, while t signifies the temporal aspect of the panel, delineating the chronological sequence of observations. Within this framework, we formulate the following four models to thoroughly investigate the relationships delineated in our research hypotheses.

Model-1: Economic Growth and Natural Resource Rent (NRR)

Environmental Sustainability Index is modelled as a function of GDP Growth rate and Natural Resource rent.

Equation:

$$ESI_{it} = a_{it} + \beta 1 GDP\ Growth\ rate_{it} + \beta 2 Natural\ Resource\ rent_{it} + \mu_{it}$$

Model-2: Introducing Energy Innovation

Energy Innovation is incorporated as a predictor variable into Model-1.

Equation:

$$ESI_{it} = a_{it} + \beta_1 GDP\ Growth\ rate_{it} + \beta_2 Natural\ Resource\ rent_{it} + \beta_3 Energy\ Innovation_{it} + \mu_{it}$$

Model-3: Introducing Environmentally Related Taxes

Environmentally related taxes as a percentage of GDP are introduced into Model-2.

Equation:

$$ESI_{it} = a_{it} + \beta_1 GDP\ Growth\ rate_{it} + \beta_2 Natural\ Resource\ rent_{it} + \beta_3 Energy\ Innovation_{it} + \beta_4 Environmentally\ related\ taxes_{it} + \mu_{it}$$

Model-4: Adding Fintech Revenue

Fintech Revenue (% of GDP) is included in Model-3.

Equation:

$$ESI_{it} = a_{it} + \beta_1 GDP\ Growth\ rate_{it} + \beta_2 Natural\ Resource\ rent_{it} + \beta_3 Energy\ Innovation_{it} + \beta_4 Environmentally\ related\ taxes_{it} + \beta_5 Fintech\ Revenue_{it} + \mu_{it}$$

Table 1: Measurement and Source of the Selected Variables.

Variables	Measurement	Source
Environmentally Sustainability	Greenhouse Gases Emissions (metric tons per capita)	OECD Stats
GDP Growth Rate	GDP Growth (annual %)	WDI
Energy Innovation	% of all Technologies	OECD Stats
Natural Resource Rent	% of GDP	WDI
Environmentally Related Taxes	% of GDP	OECD Stats
Fintech Revenue	% Contribution in Total fintech market	Statista.com

Statistical Modelling

Panel OLS Estimates

In our endeavour to comprehend the complex interplay between financial indicators and environmental sustainability across various national settings, our study adopts a rigorous econometric methodology: the Panel Ordinary Least Squares (OLS) estimator. Acknowledging the diverse nature of the data spanning multiple countries, the Panel OLS estimator is deemed a suitable approach. Unlike conventional OLS, which presupposes uniformity across observations, Panel OLS accommodates both cross-sectional and time-series fluctuations, providing a robust means to analyse datasets characterized by inherent heterogeneity.

Building upon seminal contributions by esteemed researchers such as Kao and Chiang (2001); Pedroni (2001), and Phillips and Moon (2000), we utilize the following panel data regression equation:

$$Y_{it} = \alpha + \beta_1 X_{1it} + \beta_2 X_{2it} + \beta_3 X_{3it} + \cdots + \beta_k X_{kit} + \epsilon_{it}$$

In this equation

1. Y_{it} represents the dependent variable at time *t* for entity *i*.
2. $X_{1it}, X_{2it}, X_{3it}, \ldots, X_{kit}$ denote the various independent variables for entity *i* at time t.
3. *a* is the intercept term representing the average effect across entities.
4. $\beta_1, \beta_2, \ldots, \beta_k$ are the coefficients to be estimated for each independent variable.
5. ϵ_{it} represents the error term, capturing the unobserved factors affecting Y_{it} at time t for entity *i*.

Cointegration Test

The second phase of econometric methodologies entails performing the Johansen Cointegration Test, which serves as a fundamental instrument for evaluating long-term relationships among variables within a system. Diverging from conventional correlation and regression analyses, cointegration analysis scrutinizes the integration characteristics of multiple time series variables, particularly when they exhibit non-stationarity and potentially share integration of the same order.

The Johansen Cointegration Test, pioneered by Søren Johansen, enables researchers to ascertain whether a group of variables possess common stochastic trends, indicative of enduring, long-term relationships. This assessment holds particular utility in time series analysis, where variables may demonstrate trends and manifest interdependencies across time periods.

The Johansen Cointegration Test entails the estimation of a vector error correction model (VECM), which represents a multivariate expansion of the error correction model (ECM). The VECM configuration is delineated as employed by Gianfreda et al. (2023) and Adedoyin et al. (2020):

$$\Delta Y_t = \Pi Y_{t-1} + \Gamma_1 \Delta Y_{t-1} + \Gamma_2 \Delta Y_{t-2} + \cdots + \Gamma_{p-1} \Delta Y_{t-(p-1)} + \epsilon_t$$

Where:

1. Y_t is a $K \times 1$ vector of non-stationary variables at time t,
2. ΔY_t represents the first difference of Y_t,
3. Π is a matrix of coefficients capturing the long-term equilibrium relationships among the variables,
4. Γ_i are matrices of coefficients capturing the short-term dynamics,
5. p is the lag order of the model,
6. ε_t is a vector of error terms.

The Johansen Cointegration Test evaluates the rank of the matrix Π to ascertain the quantity of cointegrating relationships among the variables. This examination entails computing trace and eigenvalue statistics and contrasting them with critical values to establish the existence of cointegration.

Cross-Sectionally Augmented Autoregressive Distributed Lags (CS-ARDL)

In our analysis of panel data, we utilize the CS-ARDL model to investigate the dynamic interrelationships within our dataset. The CS-ARDL model, tailored for panel data, offers a robust framework for examining both short-term and long-term dynamics across cross-sectional units.

This model incorporates autoregressive and distributed lag structures, accommodating potential cross-sectional dependencies and elucidating how variables evolve over time within each cross-sectional unit. Its utility is particularly evident when analysing heterogeneous panel datasets, as it captures diverse individual behaviours and responses to changes in the independent variables (Chudik & Pesaran, 2015; Yao et al., 2019).

The CS-ARDL model can be expressed as follows:

$$Y_{it} = \alpha + \beta_1 X_{it} + \gamma \bar{X}_t + \sum_{j=1}^{p} \delta_j Y_{it-j} + \sum_{j=1}^{q} \emptyset_j X_{it-j} + \sum_{j=1}^{r} \psi_j \bar{X}_{t-j} + \epsilon_{it}$$

Where:

1. Y_{it} represents the dependent variable for entity i at time t.
2. X_{it} denotes the matrix of independent variables for entity i at time t.
3. $\bar{X}$ denotes the cross-sectional average of the independent variables at time t.
4. α represents the intercept capturing the average effect across entities.
5. B_1 signifies the coefficients corresponding to the individual variables.
6. γ represents the coefficients corresponding to the cross-sectional averages of the variables.
7. δ_j, ϕ_j and ψ_j denote the coefficients of the lagged dependent and independent variables, and the lagged cross-sectional averages, respectively.
8. p, q and r represent the order of autoregressive and distributed lag terms.
9. ε_{it} is the error term.

Utilizing the CS-ARDL model, our objective is to elucidate the intricate dynamics inherent in our panel dataset, encompassing both temporal and cross-sectional dimensions. This methodology facilitates a comprehensive comprehension of how distinct units react to diverse factors over time. The CS-ARDL model serves as a valuable tool for unveiling lagged effects, thereby uncovering the complex interactions among variables across heterogeneous entities in our panel dataset.

Granger Causality Test

The bidirectional Granger causality test is a vital analytical tool for exploring causal relationships between variables in a dataset. It determines whether a causal link exists between two variables and identifies the direction of causality. By examining temporal precedence, the test identifies potential cause-and-effect relationships, offering insights into system dynamics. This test is grounded in the concept of Granger causality, which posits that if variable X Granger-causes variable Y, past values of X should contain information aiding in predicting Y beyond past values of Y alone (Nicholson et al., 2017; Shojaie & Fox, 2022). Mathematically, this is represented by the following equation.

$$Y_{it} = \alpha + \sum_{j=1}^{p} \beta_j Y_{i,t-j} + \sum_{k=1}^{q} \gamma_k X_{i,t-k} + \delta X_{it} + \epsilon_{it}$$

In this Equation

1. Y_{it} is the dependent variable for individual i at time t,
2. X_{it} is the independent variable of interest,
3. α is the intercept term,
4. B_j and γ_k are the coefficients to be estimated for lagged values of Y and X respectively,
5. p and q are the maximum lag orders for Y and X variables,
6. δ is the coefficient for the contemporaneous effect of X on Y,
7. ε_{it} is the error term

Estimating this equation allows us to evaluate whether past values of X offer additional explanatory power for Y beyond what past values of Y already explain, and vice versa.

Empirical Results & Discussion

In this section, we present the outcomes, analyses, and discussions of our findings. Upon examining the correlation matrix (Figure 1), significant associations emerge between key variables central to our study of environmental sustainability. Notably, the ESI displays a moderate positive correlation with environmentally related taxes as a percentage of GDP (r = 0.542) and a weak positive correlation with Fintech Revenue (r = 0.194). Conversely, ESI shows negative correlations with GDP Growth rate (r = -0.269), Natural Resource rent (r = -0.544), and Energy Innovation (r = -0.190) (Ullah et al., 2021). Previous studies by Mohsin et al. (2021) and Garcia and Orsato (2020) have also employed correlation matrices to investigate relationships between economic and environmental variables. These correlations illuminate the intricate interplay among economic activities, environmental policies, and technological advancements in shaping environmental sustainability outcomes. Nevertheless, further analysis is warranted to ascertain the causal mechanisms underlying these correlations and their implications for policy and practice.

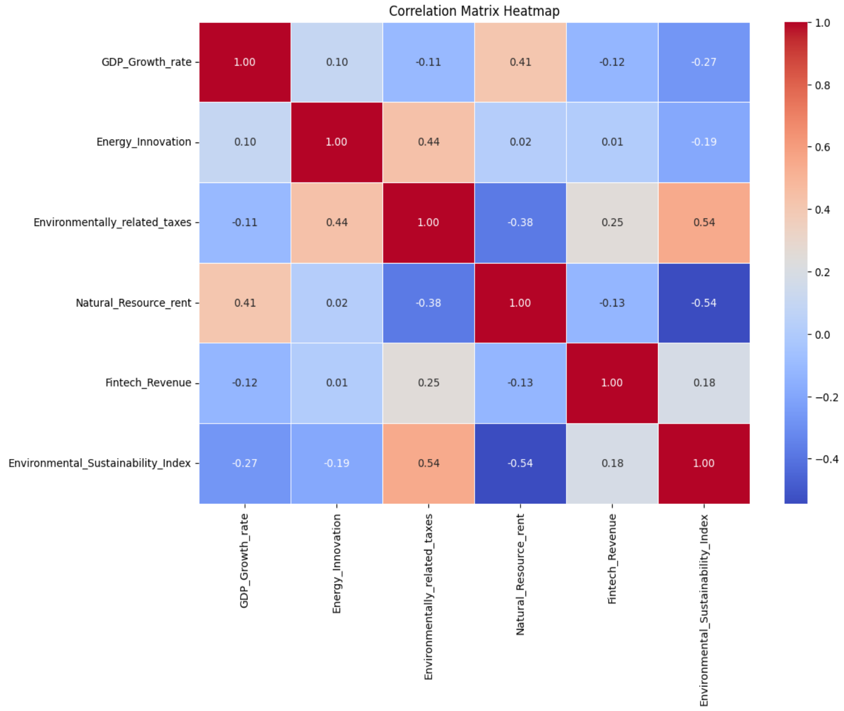

Figure 1: Correlation Matrix.

To address the non-stationarity of the dataset, a robust panel data analysis was conducted using the PanelOLS estimator, as examined by Phillips and Sul (2007). The results, summarized below, elucidate the intricate relationship between financial indices and environmental sustainability across the selected eight countries. The overall model demonstrates an R-squared value of 0.4149, indicating considerable explanatory power. Notably, the between-group variation (R-squared Between) is 0.1017, suggesting that a significant portion of the environmental sustainability index's variance is attributable to inter-country disparities. Additionally, the F-test for Poolability yields a highly significant result (P-value: 0.0000), providing compelling evidence to reject the null hypothesis of no poolability. This implies that the panel as a whole does not exhibit unit roots, and there are common trends that can be considered stationary.
The estimated coefficients pertaining to GDP Growth Rate, Natural Resource Rent, Energy Innovation, Environmentally Related Taxes, and Fintech Revenue provide valuable insights into their respective impacts. Notably, the significant negative effect of -0.1295 observed for Natural Resource Rent suggests a potential adverse influence on environmental sustainability (Ullah et al., 2021). Similarly, the negative coefficient of -0.1812 for Fintech Revenue also denotes a substantial and statistically significant adverse impact on environmental sustainability. Conversely, although the coefficient for GDP Growth Rate is positive (0.0230), it fails to reach statistical significance at the conventional level. Similarly, while the coefficient for Energy Innovation is negative (-0.0246), it is not statistically significant. This indicates that while these variables may exert some influence on environmental sustainability, their effects lack robustness. The incorporation of entity effects further underscores the necessity of considering individual country variations in assessing the broader environmental impact of financial indices. These findings emphasize the need for a nuanced understanding of the diverse and interconnected nature of environmental sustainability within the examined countries.

Table 2: PanelOLS Estimation Summary.

Dependent Variable	Environmental Sustainability Index	
R-squared	0.4149	
Estimator Cov. Estimator	PanelOLS Unadjusted	
Parameter Estimates		
Parameter	Coefficient	P-Value
Intercept	6.9649	0.0000
GDP Growth Rate	0.0230	0.2568
Natural Resource Rent	-0.1295	0.0001
Energy Innovation	-0.0246	0.1735
Environmentally Related Taxes	0.9548	0.0002
Fintech Revenue	-0.1812	0.0124
F-Test for Poolability		
F-Statistics	560.34	
P-Value	0.0000	
Distribution	F (7,75)	
Included Effects	Entity	

Drawing from these results, our aim was to investigate the enduring relationships and potential cointegration among the chosen financial indices and the environmental sustainability index within the eight countries.

Acknowledging the intricate interplay among these variables, we employed the Johansen Cointegration Test to scrutinize the presence of stable, long-term relationships among the variables in the system. This analytical tool is particularly adept at assessing whether the designated predictors, including GDP Growth rate, Natural Resource rent, Energy Innovation, environmentally related taxes, and Fintech Revenue, manifest significant associations with the Environmental Sustainability Index.

Table 3: Cointegration Test.

Models	Trace Statistics (Critical Values)	Eigen Statistics (Critical Values)
Model - 1	40.8566 (18.89, 21.13, 25.87)	27.1579 (18.89, 21.13, 25.87)
Model - 2	63.5887 (25.12, 27.59, 32.72)	36.9762 (25.12, 27.59, 32.72)
Model - 3	89.3953 (31.24, 33.88, 39.37)	48.6982 (31.24, 33.88, 39.37)
Model - 4	149.6361 (37.28, 40.08, 45.87)	73.9547 (37.28, 40.08, 45.87)

The critical values of the Trace Statistics and Eigen Statistics at significance levels of 1%, 5%, and 10%, as elucidated in Table 3, serve as benchmarks. In this context, the test outcomes reveal that the trace statistics across all models notably surpass the critical values, indicating the presence of cointegration relationships (Farooq et al., 2021; Johansen, 1991). Similarly, the eigen statistics consistently exceed the critical values, further substantiating these findings. Interpreting these results within the broader context of cointegration, it suggests that the included variables do not merely represent chance occurrences or short-term associations. Instead, they demonstrate robust, stable, and long-term relationships with the Environmental Sustainability Index. This observation aligns with the theoretical framework, highlighting the significance of economic, technological, and policy-related factors in shaping environmental sustainability outcomes. The cointegration findings, as delineated in Table 2, reinforce the notion that the selected variables significantly contribute to the Environmental Sustainability Index. This empirical evidence fortifies the theoretical foundations of the study, affirming the interconnectedness between economic indicators, technological innovation, policy measures, and environmental well-being.

Table 4: CS-ARDL Estimation Summary.

Dependent Variable	Environmental Sustainability Index	
R-squared	0.727	
Estimator	PanelOLS	
Cov. Estimator:	Driscoll-Kraay	
	Parameter Estimates	
Parameter	Coefficient	P-value
Lag GDP Growth Rate	0.2391	0.0718
Lag Natural Resource Rent	-0.1495	0.0004
Lag Energy Innovation	0.3245	0.0002
Lag Environmentally Related Taxes	2.4692	0.0000
Lag Fintech Revenue	0.0374	0.0001

Based on our CS-ARDL estimation results detailed in Table 4, it becomes evident that continuous investment in technological progress is not only advantageous but also imperative for attaining environmental sustainability objectives. The positive and statistically significant coefficient (0.3245) attributed to lagged Energy Innovation (significant at the 1% level) underscores the lasting influence of past innovations on shaping the present state of environmental well-being. This underscores the critical necessity for ongoing technological advancements that promote cleaner and more sustainable practices. For instance, a study by Li and Ge (2023) yielded similar findings, highlighting the pivotal role of energy innovation in realizing sustainable development objectives. These outcomes resonate with our own, emphasizing the significance of prioritizing investments in technological innovation to advance environmental sustainability (Liu et al., 2022).

Our results highlight the positive and significant impact of environmentally related taxes on the environmental sustainability index, with a coefficient of 2.4692 (significant at the 1% level). This underscores the effectiveness of fiscal measures in mitigating environmental degradation. Additionally, findings from Recep et al. (2020a) align with our study, suggesting that environmentally related taxes reduce CO_2 emissions, particularly at higher levels of globalization.

Furthermore, our findings underscore the contribution of the financial sector, particularly Fintech Revenue, to environmental objectives. The coefficient (0.0374) linked to lagged Fintech Revenue highlights its potential impact on promoting environmental sustainability (significant at the 1% level). This suggests that leveraging big data insights and machine learning within the Fintech sector can facilitate the transition towards eco-friendly practices. This resonates with the broader global trend towards sustainable finance, where financial technologies play a pivotal role in advancing environmental well-being (Saqib et al., 2023). Additionally, Chueca Vergara and Ferruz Agudo (2021) suggest that Fintech can enhance overall sustainability in financial businesses by promoting green finance.

Moreover, our findings indicate that augmenting natural resource rent (NRR) could serve as a strategic measure to mitigate environmental resource consumption. The negative coefficient of -0.1495 associated with lagged Natural Resource Rent suggests that higher rents correspond to reduced environmental impact (significant at the 1% level). This underscores the potential efficacy of economic mechanisms, such as increased NRR, in guiding nations towards more sustainable resource utilization practices. In East Asian nations, where rapid economic expansion often drives heightened exploitation of natural resources, effective resource management is imperative for achieving environmental sustainability goals. Given the region's heavy reliance on industries like mining, forestry, and agriculture, sustainable resource management is critical to forestall overexploitation, habitat degradation, and pollution. Through the implementation of policies fostering sustainable resource extraction, conservation, and restoration, East Asian countries can mitigate environmental deterioration and safeguard their natural ecosystems for future generations. Our CS-ARDL estimation not only elucidates temporal dynamics but also underscores the essential role of ongoing technological investment, strategic tax policies, financial innovations, and resource management strategies in achieving lasting environmental sustainability (Toda & Yamamoto, 1995). Furthermore, research by Szymczyk et al. (2021) suggests that with effective governance, natural resource rent can diminish greenhouse gas emissions in South Asian nations, further affirming the potential of economic mechanisms in alleviating environmental impact.

Table 5: Granger Causality Test.

	GDP Growth Rate	Natural Resource Rent	Energy Innovation	Environmentally Related Taxes	Fintech Revenue
Estimator	PanelOLS	PanelOLS	PanelOLS	PanelOLS	PanelOLS
Cov. Est.	unadjusted	unadjusted	Unadjusted	unadjusted	unadjusted
R-Squared	0.439	0.4356	0.4519	0.4355	0.4327
R-Squared (Within)	0.439	0.4356	0.4519	0.4355	0.4327
R-Squared (Between)	0.8802	0.883	0.9216	0.8694	0.8741
R-Squared (Overall)	0.8794	0.8822	0.9207	0.8685	0.8732
F-Statistic	11.738	11.575	12.367	11.57	11.441
P-Value (F-stat)	0.0002	0.0002	0.0001	0.0002	0.0002
L.GDP Growth Rate	0.0109 (0.5835)				
L. Environmental Sustainability	0.651 (4.8424)	0.652 (4.8424)	0.6923 (4.9298)	0.6638 (4.6214)	0.6453 (4.7429)
L. Natural Resource Rent		0.0424 (0.3940)			
L. Energy Innovation			0.0262 (2.0265)		
L. Environmentally Related Taxes				-0.2181 (-0.3867)	
L. Fintech Revenue					0.1254 (2.0587)
Effects	Entity	Entity	Entity	Entity	Entity

The value in parentheses is the associated t-statistic for the coefficient estimate. It measures the significance of the coefficient estimate

The Granger causality tests conducted for each predictor variable concerning environmental sustainability yield valuable insights into relationship dynamics essential for policy formulation and decision-making. These tests provide a structured approach to determine the direction and intensity of causality between economic factors and environmental outcomes. For instance, the results outlined in Table 5 indicate unidirectional relationships between GDP growth rates, natural resource rent, and environmentally related taxes with environmental sustainability, suggesting that fluctuations in these economic variables may impact environmental outcomes (Udemba et al., 2022). Conversely, bidirectional relationships are observed between energy innovation, fintech revenue, and environmental sustainability, signifying a mutual influence where advancements in energy technologies and financial innovations can both affect and respond to environmental sustainability efforts (Afjal et al., 2023). Moreover, Taskin et al. (2022) extracted empirical evidence from time-varying tests revealing a bidirectional relationship between energy efficiency and environmental and financial variables, particularly during significant episodes like the recent pandemic-induced economic downturn. These findings underscore the importance of comprehending the intricate interactions between energy efficiency, environmental sustainability, and financial variables, especially amidst economic crises. Such insights are critical for guiding policy interventions aimed at promoting sustainable development and resilience amidst global challenges. Additionally, the positive coefficient for lagged environmental sustainability suggests that past environmental conditions may influence current tax policies targeting environmental preservation, highlighting the interdependence between environmental conditions and fiscal measures. Similarly, the positive coefficient for lagged environmental sustainability suggests a potential impact of past environmental conditions on current fintech revenue, indicating the relevance of historical environmental factors in shaping contemporary financial technology trends. Furthermore, our analysis reveals statistically significant models overall, as evidenced by the low p-values in the F-statistic tests. Additionally, R-squared (Between) values elucidate the variability in environmental sustainability across different countries, offering crucial insights into diverse sustainability contexts.

Conclusion

In conclusion, our CS-ARDL estimation highlights the significant impact of prior innovations, environmentally related taxes, and fintech revenue on environmental sustainability. The positive coefficients associated with lagged Energy Innovation and Fintech Revenue underscore their potential to positively influence current environmental conditions. Conversely, the negative coefficient for lagged Natural Resource Rent suggests a potential conflict between resource extraction and environmental welfare. These findings underscore the importance of promoting innovation and implementing effective policy measures to achieve sustainable development objectives.

Strategic Policy Considerations

The insights presented are pivotal for devising strategic initiatives to accomplish environmental sustainability objectives in East Asia. These findings elucidate the intricate relationship between economic variables and environmental concerns, underscoring the necessity for concerted actions. In light of our study's results, the following policy suggestions are put forth.

Positive and Significant Impact of Energy Innovation (1% Level)

Policy Recommendation: Promote investment in renewable energy and sustainable tech, inspired by East Asian leaders like China and Japan. Offer subsidies, tax breaks, and research funding to spur innovation in clean energy, mirroring successful strategies. Improve energy infrastructure and efficiency in nations like Vietnam and Indonesia, while diversifying energy sources in South Korea and Japan. Encourage collaboration between government, industry, and research for faster adoption of eco-friendly practices, advancing East Asia's environmental goals (Akdag & Yıldırım, 2020). This holistic strategy, informed by regional experiences, will drive environmental sustainability in the region.

Positive and Significant Impact of Environmentally Related Taxes (1% Level)

Policy Recommendation: Drawing from the tax strategies of East Asian nations, the implementation of environmental taxation policies is advised to internalize external environmental costs (Sami et al., 2022). Following models from China, South Korea, and Thailand, levying taxes on carbon emissions, pollution, and resource extraction can stimulate eco-friendly behaviour among businesses and consumers. Transparent tax administration and directing revenues toward environmental preservation and mitigation efforts are vital for successful execution. Nonetheless, the efficacy of such taxes may fluctuate, demanding a delicate equilibrium between environmental imperatives and economic considerations.

Potential of Fintech Revenue in Fostering Environmental Sustainability (1% Level)

Policy Recommendation: East Asian nations should leverage Fintech for sustainable finance, emphasizing regulatory structures integrating ESG factors into financial decisions (Muganyi et al., 2021). Promoting green financial instruments like green bonds can effectively direct funds to eco-friendly endeavours. Although some countries are testing fintech for environmental initiatives, heavy reliance on fintech revenue for large-scale projects isn't the current priority.

Negative Impact of Natural Resource Rent on Environmental Sustainability (1% Level)

Policy Recommendation: East Asian nations should enact stringent regulations governing natural resource industries to mitigate environmental impacts and ensure sustainable resource management (Safdar et al., 2022). Diversifying economic sectors beyond extractive industries, investing in renewable energy, and promoting eco-tourism can enhance economic resilience. While China invests heavily in clean energy, Malaysia, Vietnam, and Thailand address deforestation and pollution concerns. South Korea prioritizes clean technology development. Despite progress, challenges persist, requiring a comprehensive approach. Continued investment in innovation, responsible resource management, and effective policy implementation are imperative for a sustainable future in East Asia.

Limitations of the Study

While this study yields valuable insights into the determinants of environmental sustainability in East Asia, it acknowledges several limitations warranting attention in future research endeavours. Firstly, the analysis spans from 2011 to 2021, offering a substantial temporal perspective, yet a more extended timeframe would afford a comprehensive view of environmental trends and economic fluctuations. Moreover, the regional focus on East Asia may limit the generalizability of findings to areas with distinct economic and environmental landscapes. Additionally, environmental sustainability encompasses a multifaceted array of issues beyond the study's scope, such as biodiversity loss and climate change. The research design primarily examines contemporaneous relationships between variables, potentially neglecting the long-term environmental ramifications of economic policies. Lastly, the model may not fully account for the influence of unobserved variables that could impact environmental sustainability. Future investigations can address these limitations by leveraging more detailed datasets with broader coverage, conducting comparative analyses across diverse regions, expanding the range of environmental indicators considered, employing dynamic modelling approaches to capture the enduring effects of economic policies, and integrating qualitative inquiries to delve into the social and political dimensions shaping environmental outcomes in East Asia. By delineating these limitations and outlining avenues for future inquiry, this study endeavours to contribute to a more nuanced understanding of the trajectory toward sustainable development in East Asia.

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