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The Role of Technological Innovation, Natural Resources, and Economic Growth in Fostering Environmental Sustainability: A Case Study of Thailand

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ABSTRACT: Thailand, an emerging economy, is seeing a rise in greenhouse gas emissions and environmental strain due to its significant dependence on non-renewable energy sources. In this sense, a nation's strategic utilization of technical innovation and resource management become essential requirements. Thus, using the EKC paradigm, this study investigates the relationship between ecological footprint, economic growth, natural resources, and technological innovation. To ensure reliable results, the study used co-integration, FMOLS, DOLS, and OLS approaches. The empirical result validates the existence of the EKC hypothesis, which states that sustained economic expansion causes environmental quality to first fall before improving over time with a doubling of per capita income. Moreover, it was discovered that the natural resource coefficients did not exhibit statistical significance in any of the equations, highlighting their theoretical value. On the other hand, technical advancements had a major detrimental effect that eventually reduced the ecological footprint It emphasizes how important environmental conservation is. In order to accomplish significant environmental improvement, the report suggests focusing more on innovation-driven initiatives and improving the management of natural resources.

Keywords: Ecological footprint, Economic Development, Technological Innovation, FMOLS, DOLSrted U.

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1. Introduction

The degree of human well-being and global socioeconomic growth have both increased dramatically in recent decades, which has increased the tremendous energy demand for fossil fuels. When broken down by income level, fossil fuels still account for 80% of total energy output, despite numerous nations' significant efforts to enhance renewable energy production, consumption, efficiency, and conservation (Al-Mulali et al., 2015). The average GDP contribution of emerging economies, where about 59% of the world's population resided, was 40%.

Furthermore, robust economic growth was observed in most of these economies (2020). These countries have maintained $550 million in foreign exchange while making major contributions to the global economy. 2019 saw the IMF (2019). These change economies saw a usual yearly growth rate of 4.65 percent during the previous 40 years, rising from 3821 billion USD in 1984 to 23,488 billion USD (in constant USD 2010) in 2016 Li and Lin (2019). The basic claim that economic growth allows nations to eliminate poverty through equitable income distribution, raise citizens' standards of living through the development of infrastructural facilities, and create jobs is supported by economic literature (Muhammad et al., 2022). But there are also negative aspects of growth, such as environmental deterioration when economies prioritize artificial well-being over the environment (Yousaf et al., 2021). The current and upcoming generations of above-ground and underwater species will be significantly impacted by the unwarranted surge in economic expansion in response to this calamity. At 400 parts per million, the amount of greenhouse gases (GHGs) comparable to carbon dioxide (GCD) released into the atmosphere is thought to have reached a tipping point[1] globally. Lüthi et al., (2008). According to UNEP (2018), climate change is the worst environmental concern the world has ever faced. Many developing nations are endowed with natural resources that contribute to the creation of new job possibilities (Shaikh et al., 2023); yet, by disposing of massive amounts of solid and industrial waste into soil and water, they have lowered the quality of their environment and increased air pollution (Ali et al., 2021). Moreover, most industrialized and growing nations are confronted with significant issues due to environmental degradation. Studies in environmental economics reveal a conflicting relationship between economic growth and environmental quality, demonstrating an inverted U-shaped correlation between economic growth and environmental factors such as greenhouse gasses (Dinda, 2004; Stern, 2004; Zafar et al., 2019).

The Environmental Kuznets curve hypothesis suggests that individuals in early economic development often disregard environmental protection and exploit natural resources for income. However, as time goes on, individuals begin to demand more from their lives and a clean, green environment; hence, they begin to allocate a portion of their income to environmental conservation (Kuznets, 1971; Grossman & Krueger, 1995). There has been a prolonged debate regarding the country's ecological footprint (EF) and natural resource availability (Johnsson et al., 2019). According to Danish et al. (2019), the rapid extraction and use of natural resources speeds up the EF process, which helps to explain

[1] According to scientific study, tipping points might cause significant ecosystems like the Amazon rainforest and Arctic tundra to undergo permanent alterations... These ecosystems are nearing thresholds of dramatic change that could have significant consequences. Additionally, the retreat of mountain glaciers is a cause for concern, as it could result in reduced water supply in the driest months, with effects that could last for generations.

why industrialization is associated with faster economic growth. The EF, on the other hand, tracks how human activity affects the environment in terms of built-up land, deforestation brought on by physical output manufacturing and forest cultivation for human needs, land used for crop production, human activity along coastal areas, land used for animal grazing, and carbon emissions footprint. The Ecological Footprint (EF) is a comprehensive measure utilized to evaluate the impact of activities initiated by residents on environmental quality, as supported by several studies (Ahmed et al., 2020; Yousaf et al., 2018; Ozcan et al., 2018). Industrialized economies predominantly depend on non-renewable energy sources such as coal, oil, and gas, which have a substantial role in global pollution (Tugcu et al., 2012).

1.2 Environment Degradation in Thailand

When compared to other developed ASEAN nations, Thailand's CO2 emissions skyrocketed, raising questions about the country's trajectory toward sustainable development. In addition, this nation is now classified as an upper-middle-income nation within the ASEAN (Phrakhruopatnontakitti et al., 2019). This nation is the fifth-largest carbon dioxide emitter in Pacific and East Asia (World Bank, 2016), and it actively participates in the ASEAN bloc. The energy and transportation industries are acknowledged as the principal and most noteworthy origins of carbon dioxide emissions because of their substantial dependence on fossil fuels and alternative energy sources. If Thailand does not transition to sustainable energy sources, the World Bank (2016) projects that in 2050, these two sectors would account for over 76% of global greenhouse gas emissions. In addition, the World Bank gave the Thai government a grant of USD 3 million to help with environmental protection. Figure 1 displays the trend of CO2 emissions by sector. Thailand's energy consumption has grown over the past three decades in tandem with the country's economic expansion (IIP, 2013). The average annual increase in energy usage is between 4 and 5%. Consequently, carbon dioxide emissions from the electricity producing industry have been rising steadily over the years. In the meantime, the second-biggest contributor continued to be the transportation sector. Thailand's tourism sector, accounting for 20% of GDP in 2018, welcomed 38 million foreign visitors. Post-crisis, the industrial sector's CO2 share increased, but the energy and transportation sectors fell. ASEAN nations continue to be top CO2 emitters (Fossil 2021; Zhang et al., 2019). However, inadequate infrastructure and logistics around the world, together with the vast amounts of fossil fuel that transportation activities consume, release more carbon into the atmosphere, seriously impairing environmental quality (Chen & Haynes, 2015; Khan et al., 2017). Fuel CO2 emissions, coming in at number 21 in the world NEAA (2017). Similar to this, a rise in economic activity in 2015 led to a 4% increase in Thailand's energy usage (Kyophilavong et al., 2015). Because the industrial sector relied heavily on the usage of oil in the early 1990s, Figure 2 illustrates how CO2 emissions from this sector were a major source of oil consumption. However, compared to oil and gas, energy consumption—such as coal—tends to increase the percentage of CO2 emissions, making them the largest contributors to CO2 emissions. There is an asymmetry in the CO2 share of oil and coal use between 1987 and 2019 worldwide NEAA (2017). Above these are the emissions brought on by gas use, whose proportion has been rising over time and lowering the quality of the environment. Later in the 1970s, anthropogenic activities such as the consumption of cereal crops, the reclamation of land after forests were cleared for lumber, excessive grazing, Overfishing and urbanization have surpassed the planet's biological potential, with 80% of the global population living in countries with inadequate environmental regulations (GFN, 2020). The global ecological footprint increased from 2.7 gha per person in 1970 to 2.77 gha per person in 2017. The per capita bio-capacity was 2.69 gha and 1.69 gha in the respective years. Lorente et al. (2018) suggest that countries rich in natural resources might mitigate environmental damage by shifting from fossil fuel use to renewable energy sources and decreasing reliance on obsolete energy imports.

According to Saum et al. (2018), sustainable administration practices combined with relentless development in the consumption and production of residual mineral deposits could slow down the ongoing depletion of natural resources. This would allow resources to be replenished and redeveloped in response to human needs. Among the main drivers of environmental deterioration are human activities such as mining, agriculture, and deforestation Sarkodie (2018). Similar to this, Asia's ecological footprint saw a mass shortfall in the late 1960s, rising from 0 to 1.68 gha per person. To balance the earth's ecological footprint (EF) and bio-capacity (GFN) (2017), this significant gap calls for 1.68 gha. Following 1992, when it reached 0.78 to balance the earth in 2017, the ecological footprint (EF) and bio-capacity necessary in Southeast Asian countries began to degrade. The growing trend of CO2 emissions starting in Thailand in 1986 was one of the primary causes of this gap. Following 1986, other Southeast Asian nations like Malaysia experienced increases in real GDP per capita and the ecological footprint (EF) vs bio-capacity gap (Figure 3). Over the past 57 years, Thailand's bio-capacity per capita has decreased by 28%, while the country's ecological footprint (EF) per capita has expanded by over 211%. The growing imbalance between environmental degradation and human activities suggests that humanity may owe the world anything, as the globe is too large and needs more resources than it can replenish.

Aside from that, the only thing this report discusses is how technology advancements have protected Thailand's environment from degradation. The globe is heading toward a novel approach to invention. In a similar vein, the Thai government has made major strides in innovation and cutting-edge technology to lower CO2 emissions while making effective use of available natural resources. The idea of improving human happiness and national sustainable development is intimately related to the economical utilization of a natural resource to meet needs without negatively impacting present or future generations. The only thing that can prevent the overall CO2 emissions from rising is faster technological advancement. The advancement of technological discoveries has been aided by growing economies, as evidenced by the rise in patent applications from 110 thousand to 1740 thousand. thousand during the period from 1980 to 2016 World Bank (2020). However, the ASEAN nations advanced technologically enough, as evidenced by a rise in registered patent applications of more than three thousand percent in the same time frame. Over the last five years, Thailand's average number of registered patents has accounted for 20 percent of all patents, making it the third largest country among ASEAN members in terms of the number of filed patent applications. According to Song et al. (2019), the technological revolution might have contributed to sustainable growth without wasting natural resources if it had received national focus and prominence. Additionally, the problem of shortage combined with population increase has constrained mineral reserves. Considering continued technology advancement, these problems could be resolved globally without endangering the environment. According to Bekun et al. (2019), it might be possible to advance technologies by transforming conventional patterns. These patterns might include recycling manufactured goods, using environmentally friendly products and substitutes, and adopting creative policies that restrict hazardous chemicals. All of these measures would promote sustainable economic development and lessen environmental degradation. As a result, technical improvement. The current research examines how economic growth and technical progress have influenced Thailand's ecological footprint, with a specific focus on the industrial sector's utilization of mineral resources and technological advancements between 1980 and 2017. It addresses a notable deficiency in the literature concerning sustainable development and environmental preservation.

2. Literature review

Research on the impact of excessive natural resource use on economic growth and the issues of depletion and climate change due to pollution has been extensive (Sun et al., 2022; Yousaf et al., 2021. These comprised an extensive field that garnered substantial attention about sustainable development and environmental preservation. Because of how climate change affects food insecurity and sustained economic development in the modern world, environmental degradation poses a serious threat to human survival (Khan et al., 2020). Thus, natural resources and environmental degradation are not given enough thought or attention by different stakeholders and governments. The ecological footprint of environmental degradation has received a great deal of attention recently, according to a variety of study sources.

There is a connection between the ecological footprint and real economic growth through various pathways, whether direct or indirect. Nonetheless, similar findings were reached by studies that looked at these relationships with either linear or non-linear economic growth. Ahmed et al. (2023) studied how energy transition, country risk, economic growth, and natural resource utilization affect the environmental sustainability of E-7 countries.Economic growth and cleaner energy transition minimize environmental deterioration, but natural resource consumption and national risk increase it, according to ecological footprint measures of sustainability. Khan et al. (2023) analyzed the relationships among natural resources, renewable energy usage, economic growth, and carbon dioxide emissions in 35 BRI member nations from 1985 to 2019. Asici & Acar (2015) discovered that economic expansion has a positive impact on the usage of renewable energy, however carbon dioxide and natural resources have a negative impact on it. The study, conducted across 116 countries, revealed a U-shaped correlation between rising per capita income and individual ecological footprint, emphasizing the link between economic advancement and environmental impacts.

Ulucak & Bilgili's 2018 study reexamined EKC phenomena using income groups from 1961 to 2013, confirming the hypothesis's validity across all countries. The relationship between Thailand's technological innovation, ecological impact, and economic growth was examined by Norton et al. (2021). An analysis of data from 1990 to 2018 revealed that ecological footprint negatively affects economic growth, although technical innovation and economic growth had a favorable correlation.

The authors suggest that to reduce Thailand's environmental impact, policymakers should prioritize sustainable economic development and technological innovation. The EKC hypothesis was examined in the European Union (EU) between 1980 and 2013 by Destek et al. (2018). Their empirical investigation showed a U-shaped reversal in the correlation between GDP growth and ecological effect as time progressed. Other research has refuted the U-shaped correlation between environmental deterioration. Uddin et al. (2017) demonstrated a direct relationship between ecological footprints and economic development by analyzing data from the top 27 CO2-generating countries from 1991 to 2012.Using data from 1961 to 2013, Ozcan et al. (2018) found no evidence to support the EKC hypothesis on Turkey's ecological footprint and economic development. The study discovered a feedback loop and a strong positive correlation between ecological effect and economic growth. The utilization of technologies to support economic expansion over time or the dynamic behavior of national environmental policies may determine whether a U-shaped relationship exists between environmental deterioration and economic growth. Many developed and developing countries still struggle with several issues related to long-term growth and environmental quality.

Between 2004 and 2012, Cho and Sohn (2018) studied in several industrialized nations, such as France, Germany, the UK, and Italy. The panel study investigated the relationship between green patent applications and carbon emissions. Their empirical findings show that the use of green technology may consistently and considerably reduce carbon emissions. Shahbaz et al. (2018) investigated the connections between France's 1995–2016 CO2 emissions, foreign investment, energy innovation, and financial development. The findings indicate that while the foreign population increases CO2 emissions in France, energy innovation and financial development greatly cut CO2 emissions and contribute to improving environmental quality. There is little doubt that this approach can provide economies of scale without sacrificing environmental quality. In the framework of the Chinese economy, Ahmed et al.'s most recent study (2020) looked at the formal routes and connections between the use of natural resources, the urbanization process, and the development of ecologically imprinted human capital. The empirical results of the study, which covered the years 1970 to 2016, showed that rising urbanization, economic growth, and the renting of natural resources are all contributing factors to the ecological footprint's expansion. The authors also show how human population growth slows down environmental degradation, both independently and in conjunction with urbanization. Considering the previously mentioned,

Ahmed et al. (2020a) also looked into how, between 1984 and 2016, the world's twenty-tw emerging countries—including. The study reveals a consistent, long-term link between Thailand's ecological footprint, technological innovation, natural resource usage, and economic growth. The primary findings have shown that environmental degradation can be stopped both now and in the future by utilizing state-of-the-art technologies.

Overuse of natural resources leads to increases in both economic growth and environmental impact. Zafar et al. (2019) examined how the USA's ecological footprint changed between 1970 and 2015 in relation to natural resources, human capital, and foreign direct investment. According to the study's findings, FDI, natural resources, and human capital all contribute to a reduction in ecological impact. Additionally, a one-way causal relationship between natural resources and ecological footprint was found by the study.

In the context of Asian nations, the ongoing process of ecological footprint, environmental quality, and correlation with economic growth are all significant factors to take into account. Danish et al. (2020) examined the primary factors—economic development, urbanization, use of renewable energy sources, and availability of natural resources—that affected the ecological footprint in the BRICS countries between 1992 and 2016. They discovered negative correlations between the usage of renewable energy sources, urbanization, and ecological footprint in addition to an inverted U-shaped association between economic growth and ecological footprint. Similar research was conducted in 28 OECD nations by Alvarez-Herranz et al. (2017) to examine the impact of energy technologies on greenhouse gas emissions from 1990 to 2014. According to their findings, environmental deterioration and waste can be efficiently reduced by technical advancements in the energy sector.

Mensah et al.'s 2018 study investigated the relationship between economic development, technological progress, and CO2 emissions in 28 OECD countries from 1990 to 2014. Technological advancements lowered CO2 emissions and had a favorable impact on environmental preservation, however, the EKC hypothesis was not validated. Destek and Sinha (2020) observed an inverted U-shaped correlation between economic growth and ecological footprint in 24 OECD nations from 1980 to 2014 when examining the EKC hypothesis.

Uddin et al. (2019) employed the Environmental Kuznets Curve (EKC) theory to examine the correlation between ecological footprint and economic growth in fourteen South Asian and ASEAN member countries. The EKC phenomenon has been empirically verified in several Asian nations, such as Malaysia, Pakistan, Nepal, and India. Using provincial panel data from 1985 to 2005, Sun et al. (2008) inspected the effect of technical invention on CO2 production in China in a different study. Conferring to the study's outcomes, less environmental degradation resulted from more technical innovation, especially in Asia's Eastern region where technological advancements were more widespread. Contrary to these findings, a study conducted in Pakistan by Hassan et al. (2019) discovered that between 1970 and 2014, resource extraction and economic expansion had a positive and noteworthy impression on the ecological footprint. These findings imply that an overreliance on natural resources may have detrimental repercussions on the environment. Energy consumption rises in tandem with economic expansion, but using too much coal and oil-based energy is bad for the environment. In the context of ASEAN nations, Azam et al. (2015) looked into the connection between energy use and economic expansion. (As an illustration, consider the Philippines, Singapore, Malaysia, Thailand, and Indonesia). The years 1980–2012 are covered by the empirical study. The results demonstrate that energy use positively and significantly affects economic growth over the long run. Using panel data from 1994 to 2014, Azam and Khan (2017) investigated how environmental deterioration in Thailand, Malaysia, and Indonesia was impacted by economic growth, corruption, poverty, and health. The findings demonstrated that although spending on health care has a detrimental impact on the environment, economic growth has a favorable impact on environmental deterioration. While this is going on, corruption has minimal impact on environmental degradation in Thailand and Indonesia, but it has a significant positive impact in Malaysia. Consistent with this data, Azam et al. (2018) examined variables that were highly correlated with CO2 emissions, including energy use, per capita income, and tourist arrivals in Thailand, Malaysia, and Singapore from 1990 to 2014. Using the panel FMOLS estimation technique, they discovered that, with the exception of Thailand and Singapore, where a substantial and negative link was established, tourism activities significantly and positively boosted environmental waste in Malaysia. Few empirical studies, when taken into consideration, contradict one another. The inconsistent results may be attributed to varying governmental policies and the unique features of every nation or location. Actually, the creation of effective environmental protection laws that combat climate change without stifling economic expansion is greatly aided by technology progress. Furthermore, since CO2 emissions are the only indicator of environmental deterioration, the body of research on climate change is inadequate. Thailand's environmental state is not evaluated using ecological footprint, natural resource value, economic growth, technological advancement, or contemporary literature summaries. The study employs the Environmental Kuznets Curve (EKC) framework to examine the effects of technological innovation, economic growth, and natural resource utilization on the ecological footprint across both short and long time periods.

3. Theoretical and Conceptual Framework

Simon Kuznets proposed the environmental deterioration and economic growth hypothesis in the 1950s and 1960s; this theory is now referred to as the EKC hypothesis. Up until this day, Kuznets' hypothesis has served as the standard model for calculating the correlation between ecological quality and economic development. This research is predicated on the EKC theory as well. We also take into account innovations in technology and natural resources. Grossman and Krueger (1995; 1991) discuss the impact of technical innovation, composition, and size on environmental degradation in this area. The composition effect and structural changes in the economy are related. The manufacturing sector's structural transition from agricultural to manufacturing increases pollution and deteriorates the environment, which further moves the economy away from manufacturing and toward services. The economics helps them to safeguard the environment in this process. Sarkodie & Destek (2019) secondly, the impact of scale pertains to the growth in output level while maintaining ongoing advancements in technology and economic structure. Because of this, the economy as a whole expands in the early stages and worsens environmental quality since increased output necessitates increased inputs (crude materials), which in turn raises economic movement and creates more left-over and pollution (Ulucak et al., 2020). Additionally, a third network that emphasizes the sophisticated and clean technology shift in the economy is the third technical effect. This helps the production process become more efficient and productive. In essence, it addresses several issues at once to stop environmental deterioration. Seker & Dogan (2016). The modernization hypothesis of ecology, which Huber (2000) introduced, is likewise predicated on an advanced industrialized civilization that addresses environmental problems. Huber asserts that there is an endless supply of renewable resources on earth for human use. Rapid production, thus, depletes natural resources and harms the environment due to inefficient management, which in turn affects ecological sustainability for the sake of economic expansion (Bekun et al., 2019). According to both theory and production practice, there are also direct impacts of environmental degradation on the rate of economic growth overall and the extraction of natural resources (Schnaiberg, 1980; Schnaiberg & Gould, 2000). But our study's breadth and technical effects most closely match the ecological modernization idea. Thailand's ecological footprint and environmental sustainability are so missing, with the primary causes being technological innovation, natural resource development, and economic expansion.

4. Empirical framework

Verifying the order of integration for each of the pertinent variables is the first stage in the methodical process to ascertain whether a long-term link exists. For estimate, a collection of theoretically consistent variables is chosen. When converted to a logarithm, the ecological footprint function looks like this.

$$LnEF_t = \beta_0 + \beta_1 LnGDPPC_t + \beta_1 LnGDPPC_t^2 + \beta_2 LnNR_t + \beta_3\ LnPT_t + \epsilon_t \quad (4.1)$$

where LnEFt, which is obtained from the worldwide Footprint Network, stands for the log ecological footprint per capita in a worldwide hectare. It tracks how much land is used for grazing and development, how much is consumed for forestry, agriculture, and fisheries, and how much CO2 emissions are produced by human activity. Alternatively, the log GDP per capita (or gross domestic product per person) squared at time t is indicated by 〖LnGDPPC〗_t and 〖LnGDPPC〗_t^2. LnNRt is the log natural resource as a percentage of GDP, LnPTt is the number of patent applications submitted by Thai nationals and foreigners, and ̍t is thought to be a white noise error term. Data for these variables were sourced from the WDI between 1980 and 2020.

4.1 Unit Root Test

Because empirical approaches frequently fail, it is crucial to verify if the variables are stationary if a time series variable continues to be non-stationary. The ADF (Augmented Dickey-Fuller) test is used for this, and its explanation is provided in 4.2.

$$\Delta \boldsymbol{E_t} = \boldsymbol{\beta_0} + \boldsymbol{\beta_1 E_{t-1}} + \sum_{k=1}^{n} \boldsymbol{d_k}\, \Delta \boldsymbol{E_{tk}} + \boldsymbol{\varepsilon_t} \quad (\mathbf{4.2})$$

In the formula above, Et is a time series variable. White noise is represented by the error term εt, while the first difference operator is shown by Δ

4.2 Co-integration testing

The following formula was used to link long-term and the independent variables and the EF was investigated using the:

$$\boldsymbol{E_t} = \boldsymbol{\delta} + \boldsymbol{B_t E_{t-1}} + \cdots + \boldsymbol{B_a E_{t-z}} + \boldsymbol{\varepsilon_t} \qquad (\mathbf{4.3})$$

Et is a variable with p x 1 dimensions that is integrated at order I (1) in equation above. Thus, vector auto-regressive equation is given as follows:

$$\Delta \boldsymbol{E_t} = \boldsymbol{\delta} + \Phi\, \boldsymbol{E_{t-1}} + \sum_{i=1}^{z-1} \Gamma_i\, \Delta \boldsymbol{E_{t-1}} + \boldsymbol{\varepsilon_t} \quad (\mathbf{4.4})$$

Where $\Phi = \sum_{i=1}^{z} \boldsymbol{B_i} - \boldsymbol{I}$ **and** $\Gamma_i = -\sum_{j=i+1}^{z} \boldsymbol{B_j}$

While using the Eigen and trace statistics, we detect presence or absence of a long-run link is ascertained using the

4.3 Dynamic Ordinary Least Square Regression with Full Modification

We employed the dynamic and Fully Modified Ordinary Least Squares Method (henceforth, DOLS & FMOLS) econometric methodologies in this work to ascertain if EF, GDPPC, NR, and PT have a long-run relationship. Philips and Hansen (1990) created FMOLS technology initially. When it comes to reliable empirical data, this method performs better than alternative methods for estimating a combination of I (1) series in a single co-integrating equation. It helps when the sample size is small. The model takes into account a co-integrating equation, which is covered in Section 4.5, and an n+1 dimensional (Yt, Xt) time series vector process.

$$Y_t = \beta_0 X_t + \alpha_1 D_{1t} + u_{1t} \quad 4.5$$

where D_t=D_1t, D_2t are the deterministic trends and X_t is the stochastic regressors of N variables governed by the system of equations as illustrated in 4.5.1.

$$\boldsymbol{X_t} = \boldsymbol{\lambda_{21} D_{1t}} + \boldsymbol{\lambda_{22} D_{2t}} + \boldsymbol{\epsilon_{1t}} \quad \mathbf{4.5.1}$$

And $\Delta\boldsymbol{\epsilon_{2t}} = \boldsymbol{u_{2t}}$

Asymptotically unbiased and totally efficient is the estimator powered by FMOLS. On the other hand, Stock and Watson (1993) and Saikkonen (1992) provided support for a simple method of constructing an asymptotically efficient feedback-free estimator for a co-integrating system. By adding q-lags and p-leads of 〖ΔX〗_t to the co-integrating regression, they suggested a DOLS method that creates a residual co-integrating equation. It is perpendicular to equation 4.6's historical record of stochastic regresor advancements

$$Y_t = \beta_0 X_t + \alpha_0 D_{1t} \sum_{q=-q}^{p} \emptyset \, \Delta X_{t+1} + v_{1t} \quad 4.6$$

Less-squares estimates of λ=β_0,α_0 are based on the assumption that the long-run correlation between v_1t and v_2t is fully absorbed by combining the q-lags and p-leads of the differenced regressors. Equation 4.6's asymptotic distribution is the same as equation 4.5's.

FMOLS and DOLS are highly effective in addressing endogeneity among independent variables and serial correlation in equations, according to Danish et al., 2019. The main difference between the DOLS and FMOLS methods is that the latter use a non-parametric approach, while the former use a parametric approach with the lags and leads effect of independent variables to control endogeneity and autocorrelation (Kao & Chiang, 2000; Kumar & Smyth, 2007; Danish et al., 2019). In contrast, the DOLS is favored in parametric investigations since it offers a reliable and effective empirical investigation, even for small samples (Rukhsana & Shahbaz, 2008; Dogan & Seker, 2016a; Danish et al., 2019). According to Azam et al. (2018), Wald tests using asymptotic f-statistics or Chi-square statistical inferences support estimating co-integration from DOLS and FMOLS.

4.4 Short Run Analysis (ECM)

The ecological footprint function now allows for the testing of short-term correlations between variables. Equation 4.7 illustrates how an error correcting mechanism (ECM) is used to achieve this.

$$\begin{aligned}\Delta lnEF_t &= \Phi_0 + \Phi_1 \sum_{i=1}^{p} \Delta\, lnGDPPC_t + \Phi_2 \sum_{i=1}^{p} \Delta\, lnGDPPC_t^2 \\ &+ \Phi_3 \sum_{i=1}^{p} \Delta\, lnNR_t + \Phi_4 \sum_{i=1}^{p} \Delta\, lnNR_{t-1} \\ &+ \Phi_5 \sum_{i=1}^{p} \Delta\, lnPT_t + \Phi_6 \sum_{i=1}^{p} \Delta\, lnPT_{t-1} + \Phi_7 \mathrm{EC}_{t-1} \\ &+ \varepsilon_t \qquad (4.7)\end{aligned}$$

The variables on the right side of the equation match those in the long run function, with two exceptions. The dependent variable in the equation is the initial change in ecological footprint, as shown by the symbol 〖ΔlnEF〗_t. First, the variables are used in the first differenced form, denoted by Δ, together with their initial lag. The model includes the initial lag of the error correction term, T7, which represents the long-run model change in reaction to a short-run shock.

4.5 Causality Analysis

Granger's (1969) paradigm is used to verify that there is a causal relationship between the variables. In the form of a causal link, short-run causality aids in determining the direction of the variable. Assuming that Yt represents the ecological footprint per person over time and Xt represents per capita GDP, natural resources, and technological innovation. This paradigm states that the forecast accuracy of Yt for Xt variables increases if a real uni-directional relationship (X granger cause Y) is found by taking only previous Yt values into consideration. Granger causality scenarios with p-lagged ordering might be uni- or bi-directional.

$$\begin{aligned}Y_t = \Upsilon_0 + \sum_{i=1}^{n} \vartheta_i \, Y_{t-1} + \cdots \vartheta_p \, Y_{t-p} + \sum_{i=1}^{n} \mathrm{p} \, X_{t-1} \\ + \cdots \mathrm{p}_q X_{t-q} + \varepsilon_t \quad (4.8)\end{aligned}$$

$$X_t = \Upsilon_0 + \sum_{i=1}^{n} \vartheta_i \, X_{t-1} + \cdots \vartheta_p \, X_{t-p} + \sum_{i=1}^{n} \mathrm{p} \, Y_{t-1} + \cdots \mathrm{p}_q Y_{t-q} + \mathrm{u}_t \quad (4.9)$$

F-statistics can be used to establish whether there is uni- or bi-directional Granger causality between the ecological footprint and the independent factors. Granger causality only examines cause-and-effect relationships with constant combinations, hence it may not always demonstrate real causality. Maziarz (2015). if a shared process with distinct legs drives both the independent Xt and dependent Yt variables. If one rejects Granger causality as the null hypothesis, then changing one variable won't change the others.

5. Empirical Results

Augmented Dickey-Fuller (ADF-test) statistics are the most efficient means of observing the integration of dependent and independent variables. The results are shown in Table 1. Since every variable in the model is confirmed to be stationary at the starting difference, we may go on to the next phase of the model 4.1 analysis. Using Johansen and Juselius (1990), the co-integration between the variables in question is explicitly tested. Section 4.3 reports the model as well as the results of Johansen and Juselius's (1990) methodology.

Variables	Level		Difference	
	C	C & T	C	C & T
LNEF	-1.24	-1.38	-5.81*	-5.929*
LNGDPPC	-1.44	-1.90	-3.37**	-3.530***
LNGDPPC²	-1.26	-2.00	-3.54**	-3.632**
LNNR	-1.36	-2.33	-6.40*	-6.270*
LNPT	-2.61	-2.34	-5.97*	-6.196*

Authors estimate: that *, * & *** shows significance at 1, 5 & and 10 percent. Note: C shows constant, and T shows determinist trend

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5.1 Johansen and Juselius Co-integration

The results obtained by Johansen and Juselius (1990) are displayed in Table 2. The trace and maximum Eigenvalue statistics are used to ascertain whether the equation has a long-run connection. As shown, the likelihood that there isn't a co-integrating vector is ruled out by both the trace and the Eigenvalue statistics. Since none of the other theories could be ruled out, the equation must contain a single co-integrating vector. Put another way, there is a connection between Thailand's natural resource wealth, EF, rising per capita income, and technological progress. The outcomes support the ecological footprint per person equation's long-term correlations among its variables. Analyzing the magnitude of the variables in equation 4.1 and determining whether or not their coefficients have the expected direction is equally significant. The next section discusses and presents the estimation of long-run coefficients.

No Equation	Trace Values	Critical Value	Eigen Values	Critical Value
NONE *	84.38*	69.82	39.65*	33.88
AT MOST 1	44.73	47.86	24.54	27.58
AT MOST 2	20.19	29.80	15.81	21.13
AT MOST 3	4.38	15.49	3.26	14.26
AT MOST 4	1.11	3.84	1.11	3.84

*, * & *** shows significance at 1, 5 & 10 percent.

5.2 Long-run coefficients

It has previously been demonstrated that every variable in the ecological footprint equation is co-integrated, hence estimating the long-run coefficients using the OLS is sufficient. However, both fully modified ordinary least squares and dynamic ordinary least squares are used to estimate long-run elasticity coefficients. The coefficients computed with the three previously described approaches are shown in Table 3. The most significant factor influencing ecological footprint per capita, as shown by the long-run coefficients by OLS, was income per capita (lnGDPPC).

The average rise in ecological footprint is between 4 and 5 percent for every 1% increase in income per capita. The Kuznets (EKC) hypothesis is supported in the case of Thailand by the quadratic relationship of squared income per capita (lnGDPPC2). There is a 0.29% decrease in ecological footprint per head for every 1% rise in squared income per head. In each of the equations listed in Table 3, the statistical coefficients of per capita income and squared income per head were determined to be statistically significant. According to Danish et al. (2020), Ahmed et al. (2020), Ulucak & Bilgili (2018), and As¸ici and Acar (2015), this complements the findings of the previous investigations.

Despite this, the ecological footprint equation showed a negligible but theoretically meaningful link with the coefficients of technological innovation and natural resources. The primary cause may be because the OLS equation contains endogeneity and autocorrelation. The findings from FMOLS and DOLS, with the exception of the statistical significance of technical innovation, are thus found to be comparable to those from OLS. The DOLS data provide more evidence in favor of the hypothesis that income per capita positively impacted the ecological footprint early in economic growth but that this contribution declined with per capita income. The ecological footprint per person was shown to be significantly impacted negatively by technological innovation, while the impact of the coefficient of natural resources (LnNR) was found to be negligible. The ecological footprint per person decreases by 0.05% for every 1% improvement in technological innovation (lnPT). The magnitude is far less than that of the usual predictors, which are income and square income per head. According to our empirical findings, earlier studies by (Uddin et al., 2019; Ahmed et al., 2020a; Khan et al., 2020; Destek & Sinha, 2020) have found similar outcomes.

The Durban Watson statistics value in the OLS estimation example is too low; nevertheless, to enhance, the coefficients are estimated using the covariance approach and the HAC standard errors. Adjusted R2 is significantly better with DOLS with a single lag and lead impact than it is with the conventional OLS and FMOLS estimate process. In the meantime, "Wald-test" statistics, which are conventional in the model's situation, have a significant influence.

Authors estimate Note: DOLS contains 1, 2 lead, and lags in equations.

	OLS			Fully Modified OLS			Dynamic OLS		
Variables: LNEF	Coeffs	t-stats	Prob	Coeffs	t-stats	Prob	Coeffs	t-stats	Prob
lnGDPPC	4.26	3.85	0.00	4.88	5.22	0.00	5.39	5.65	0.00
lnGDPPC2	-0.22	-3.30	0.00	-0.26	-4.59	0.00	-0.29	-4.95	0.00
lnNR	0.01	0.52	0.61	0.01	0.56	0.58	0.01	-0.06	0.95
lnPT	-0.04	-2.04	0.03	-0.04	-3.22	0.01	-0.05	-1.95	0.07
C	-19.13	-4.34	0.00	-21.56	-5.79	0.00	-23.40	-6.24	0.00
Adj R2	0.976			0.977			0.987		
D.W	1.171			1.319			2.080		
Wald (F-Test)	374.85			451.50			171.23		
Jarque-Bera	1.7656			1.0784			4.5839		

5.3 Short-run coefficient

Considering Thailand's natural resources, economic growth per capita, ecological effect per person, and technological innovation in light of short-term trends. The results are shown in Table 4. The findings show that there are negligible short-term effects on the ecological footprint of income, natural resources, and squared income per head. In the context of China and Pakistan, the other time-series investigations by Danish et al. (2020), Ahmed et al. (2020a), Hassan et al. (2019), panel studies, and Zafar et al. (2019) found noteworthy and beneficial contributions. But in this sense, the ecological footprint is significantly improved by technology advancements. Not to add,The fair short-run convergence of Thailand towards the long-run equilibrium is demonstrated by the coefficient value of 0.68 of the ECMt-1. The empirical evidence may indicate that at the first stages of development, income per capita may contribute to the enhancement of human activities in the degrading environment; but, as time goes on, technological innovation reduces environmental degradation while simultaneously increasing income per capita. Environmental deterioration is accelerated in the short term by technological advancement through trial and error. which, given time, might eventually be retrieved.

5.4 Diagnostics test

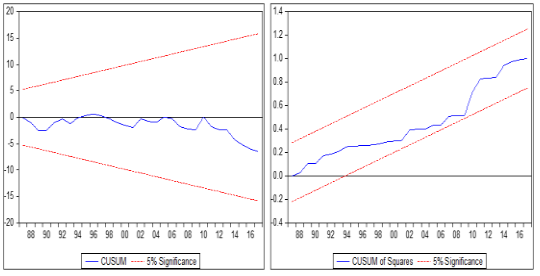
The stability of the model is tested using the cusum and cusum2 squared residuals. At the 5% level of significance, Figure 4 shows that residuals lie under both the upper and lower bound, indicating that the coefficient is quite stable. As a result, it is determined that the model's proven stable coefficients have no structural fractures.

5.5 Causality analysis

To confirm that the variables have a causal link, Granger's (1969) paradigm is employed. Table 5 demonstrations the results of the Granger causality test. Significant unidirectional causalities from LNGDPPC, LNGDPPC2, and LNPT to LNEF, respectively, are demonstrated by the results. On other side, natural assets and technological innovation are caused by the (LNGDPPC) income per capita granger and (LNNR) natural resources.

Null Hypothesis	Conclusion	F-statistic	P-value
Causal Effect of LNGDPPC To LNEF	Yes	3.54	0.03
Causal Effect of LnEF To LnGDPPC	No	1.22	0.32
Causal Effect of LnGDPPC2 To LnEF	Yes	3.20	0.04
Causal Effect of LnEF To LnGDPPC2	No	0.97	0.42
Causal Effect of LnNR To LnEF	No	0.87	0.47
Causal Effect of LnEF To LnNR	No	0.58	0.63
Causal Effect of LnPT To LnEF	No	2.98	0.05
Causal Effect of LnEF To LnPT	Yes	1.80	0.17
Causal Effect of LnGDPPC2 To LnGDPPC	Yes	2.36	0.09
Causal Effect of LnGDPPC To LnGDPPC2	No	2.30	0.10
Causal Effect of LnNR To LnGDPPC	No	1.24	0.31
Causal Effect of LnGDPPC To LnNR	Yes	4.33	0.01
Causal Effect of LnPT To LnGDPPC	No	1.79	0.17
Causal Effect of LnGDPPC To LnPT	Yes	2.34	0.09
Causal Effect of LnNR To LnGDPPC2	No	1.24	0.31
Causal Effect of LnGDPPC2 To LnNR	Yes	4.05	0.02
Causal Effect of LnPT To LnGDPPCc2	No	1.85	0.16
Causal Effect of LnGDPPC2 To LnPT	No	2.32	0.10
Causal Effect of LnPT To LnNR	No	0.91	0.45
Causal Effect of LnNR To LnPT	No	2.23	0.11

Dependent variable: Δ (LNEF)	Coefficient	Std. Error	T-statistics	P-value
C	-0.02	0.01	-1.82	0.08
Δ(LNGDPPC)	-3.48	2.55	-1.37	0.18
Δ(LNGDPPC2)	0.27	0.16	1.72	0.10
Δ(lnNR)	0.04	0.03	1.37	0.18
Δ(lnPT)	0.05	0.02	2.23	0.03
ECMT-1	-0.68	0.14	-5.03	0.00
Adj R2	0.6958			
F-statistic	17.47			
D.W stats	2.31			



Authors estimate:

6. Conclusion

Despite considerable growth, rise in industrialization, socio-economic development, and human welfare, the significant increase in demand for non-renewable energy is seen dominating source worldwide. On the other side, many developing and developed countries put enough effort into increasing renewable sources of energy for their production, consumption, conservation of energy, and efficiency, but failed to transform completely fossil fuel energy into environmentally friendly energy; that is still a dominating source of environmental degradation. In a comparable way, Thailand is a major polluter of the environment and one of the top emitters of greenhouse gases into the atmosphere due to its growing economy. By 2050, it's predicted that Thailand's growing reliance on non-renewable energy sources will increase greenhouse gas emissions in the atmosphere by 76%. Moreover, the significant increase in human activities based on ecological footprint rose almost 211 percent compared to bio-capacity which rose only 28 percent over the last 57 years. The sustained rise in imbalances between human activities and environmental protection is an alarming worse situation waiting for future generations. To bring environmental sustainability, technological innovation is a must and necessary to reduce the waste of natural resources through recycling, substituting, and environmentally suitable products, restricting hazardous chemicals from polluting the environment, and adopting innovative policies that will lead to sustainable economic growth and lessen environmental flagging. Therefore, an investigation into the effects of economic evolution, resource development, and technological advancement is conducted in order to determine Thailand's ecological footprint (EF). within the 1980-2020 time-series covering period

When working with time-dimension analysis, the ADF-unit root test statistics are employed. The results demonstrated that mineral reserves, income per person, environmental effect per person, and technological innovation are all stationary at the first difference (1). This made it possible for us to investigate the historical relationship between ecological harm and series. This was accomplished by applying the Johanson co-integration technique, which demonstrated the existence of a sustained link between the independent regressors under study and the ecological footprint. All three econometric models—FMOLS, DOLS, and ordinary least squares—use the long-run coefficient and connection. The primary objective of the study is also accomplished, as demonstrated by the empirical results. The findings provide credence to the EKC hypothesis in Thailand, which postulates that environmental quality will eventually decline as a result of economic expansion in the early phases of development and then gradually improve as per capita income doubles.

Furthermore, it was discovered that the natural resource coefficients in every equation retained their theoretical significance despite being statistically insignificant. But technological advancement has a negative impact that is strong enough to reduce the ecological footprint per person by 0.05 percent in the end. This influence is notably smaller than that of the usual variables, namely income and square income per head. According to the coefficient of ECM, the system will self-correct by about 0.67% in a given year if there is a divergence from the long-term environmental quality equilibrium.

7. Policy recommendations

The study additionally presents some recommendations for tools for policy making. Thailand's economy should first embrace a policy centered on renewable energy sources and outlaw any current non-renewable energy sources that produce pollution beyond the ISO-mandated threshold. Second, the government ought to support funding for R&D initiatives aimed at fostering innovation and technology, and collaborate with developed countries to establish legislation pertaining to electricity vehicles. Third, in order to conserve the environment, the government should plant trees, raise public awareness of environmental issues, and forbid deforestation. Fourth, aid for education and development should come from the global community.

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