Inzinerine Ekonomika-Engineering Economics, **2026, 37(2), 168–181**

Natural Resource Efficiency: The Role of Financial Development, Recycling and Eco-Innovation in ASEAN

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https://doi.org/10.5755/j01.ee.37.2.42034

Rising concerns over environmental degradation that have been intensified with a global focus on efficient management of natural resources. Within this context, factors such as financial development (DD) and eco-innovation (EI) have been received increasingly with scholarly attention. This research aims to examine the impact of FD and EI on natural resource efficiency (NRE) within ASEAN economies, while integration of artificial intelligence (AI), urbanization (URB), and economic growth (GDPG) as additional determinants. With utilization of secondary data, the analysis employs the Method of Moments Quantile Regression (MMQR) for generating robust and distribution-sensitive estimates. The empirical outcomes shows that FD positively contributes to NRE, whereas EI shows no significant relationship. Moreover, recycling activity (RECY) shows a negative and statistically significant relationship with NRE. Within this contrast AI, GDPG, and URB are found to have significant and positive relationship on NRE. The research has advanced the current body of knowledge by applying a rigorous methodological approach and integration of emerging variables relevant to sustainable resource management. Additionally, this offers significant practical implications for government, regulatory bodies and policy makers seeking to enhance natural resource efficiency across ASEAN region.

Keywords: *Natural Resource Efficiency; Financial Development; Eco-Innovation; ASEAN; QARDL.*

Introduction

Efficient management of natural resources has now become an increased crucial priority across the globe, specifically as nations encounter the escalating sustainability challenges, demographic pressures, and intensifying environmental degradation. Within this global context, the Association of South Asian Nations (ASEAN) stands out as a region of strategic significance due to its rising economic expansion, rich ecological diversity, and dynamic socio-economic development trajectory. Composed of 10 countries at different levels of economic transformation, ASEAN embodies both opportunity and vulnerability in pursuit of sustainable development. Hartley and Medlock III (2017) in their study explained that two ASEAN economies remain heavily reliant on agriculture as main contributor of GDP, while others including Vietnam, Indonesia, Thailand, Malaysia, and the Philippines have undergone considerable for industrial restructuring and economic modernization. For pats decades, ASEAN countries that have collectively experienced notable economic progress, with appropriate 6% rise in GDP from 2000 to 2007 preceding to global financial crisis (Nawaz, Azam, & Bhatti, 2019). As per the classification of world bank, Indonesia, Vietnam, Thailand, and the Philippines all fall within middle-income category, whereas Malaysia contributes towards leading the region within terms of per capita income and development performance (Rees, 2017).

However, these economic advancements, the rising pace of industrialization, population growth and urban expansion has been placed unprecedented pressure on ASEAN ‘s natural resource base, that includes forests, water bodies, soil systems, and marine ecosystems which plays indispensable roles for supporting livelihoods and regional economic activity. Maon environmental systems such as Mekong River Basin and Lake Toba have sustained historically local communities, also increasing consumption demands and development pressures that have contributed towards extensive environmental challenges which include air pollution, eco system degradation, water contamination, and depletion of natural resources (Khan *et al.*, 2019; Zhao *et al.*, 2024). These all challenges highlight the current requirement which necessitates the enhancement of natural resource efficiency (NRE), a critical dimension for sustainable development which seeks to optimize the use of natural resource by using minimal environmental harm. The requirement for improved NRE is additionally underscored with the fact that ASEAN countries face deep socio-economic disparities and uneven resource distribution, which makes sustainable management strategies critical for long-term regional stability.

An important but often dimension of natural resource management includes crucial role of indigenous communities. These communities possess deep-rooted ecological knowledge systems, spiritual and cultural practices, and long-standing stewardship responsibilities that contributes more towards sustainable resource governance. Thus, their contributions would remain insufficiently integrated in formal environmental and economic governance frameworks. Reytar and Veit (2019) have noted that

indigenous communities globally manage among 50 % and 65 % of world's area of land, that not is not only comprises of 10% of this land but also formally recognized under legal ownership with an additional 8% being acknowledged under management rights. The evidence consistently shows that deforestation rates in indigenous managed territories are lower often by half compared to lands without recognized legally indigenous stewardship (Rights and Resources Initiative, 2015). Insights highlight requirement for ASEAN policy makers for moving beyond traditional economic models and incorporating indigenous resource governance practices for strengthening natural resource efficiency and long-term ecological resilience. However, indigenous stewardship financial development (FD) has been recognized as major driver to influence natural resource efficiency. Well-functioning financial system plays a major role for directing capital allocation, shaping decisions for investment, and supporting technological advancement. Xu and Tan (2020) in their study have argued that financial development could enhance natural resource efficiency with channeling of resources in sectors with higher productivity growth and by promotion of investment in cleaner production technologies, which results in more sustainable allocation of limited natural resources. The mechanism such as credit provision, efficient financial intermediation and market-based incentives, FD would fosters an environment that would support industrial restructuring and environmentally efficient production process. Recycling (RECY) also shows another basic component of sustainable resource management, specifically within a broader framework of circular economy. Recycling also reduces the extraction of virgin raw materials, that decreases generation of waste, mitigation of environmental degradation, also supporting conservation of resources. The empirical data shows that its environmental significance for example recycling of one tone of office papers could save approximately 27,300 liters of water, 18 trees, 2.28 cubic meters of landfill space and about 2450 liters of oil (Lamma, 2021). Within the context of ASEAN countries where generation of waste is increasing rapidly due to urbanization and industrial growth, which strengthen recycling systems significant for improving natural resource efficiency and reduction of ecological strain.

Eco-innovation (EI) has similarly been emerged as a significant factor for promoting efficiency of resources and fostering environmentally sustainable economic growth. Haila and Rundquist (2011) in their study discussed that eco-innovation extends beyond the environmental benefits for the generation of significant economic values for the enhancement of productivity, reduction of emissions, and encouragement of adoption of green technologies. Moreover, Szutowski, Szulczewska-Remi, and Ratajczak (2017) focused more on eco-innovation plays a transition from linear models of production towards more resource-efficient systems. With an increased significance of green technologies in global markets, eco-innovation presents a crucial pathway for ASEAN countries striving for improving natural resource efficiency.

Despite, the significance of these factors, there is a substantial gap that persists the empirical literature. However, previous studies have determined financial development, eco-innovation, and recycling separately, limited attention which has been paid for their combined impact on natural resource efficiency within multi-country ASEAN context. Most existing studies focus on either single countries or advanced economies, leaving considerable uncertainty regarding how these determinants operate within a diverse and rapidly developing region such as ASEAN. Additionally, the role of artificial intelligence (AI) a transformative technology that enhances environmental monitoring, predictive analytics, waste management, and resource optimization has been insufficiently explored in empirical studies related to NRE. The methodological approaches employed in previous research also reveal gaps, as few studies utilize advanced econometric techniques such as the Method of Moments Quantile Regression (MMQR), which allows for more robust estimation and captures heterogeneity across different levels of resource efficiency. Furthermore, despite growing recognition of Indigenous governance globally, empirical studies examining Indigenous community involvement in resource efficiency within ASEAN remain scarce, representing a critical omission in existing scholarship.

These identified gaps provide a strong rationale for conducting a comprehensive empirical investigation into the determinants of natural resource efficiency across ASEAN countries. By integrating factors such as financial development, eco-innovation, recycling, artificial intelligence, urbanization, and economic growth, this study aims to generate a holistic understanding of the economic, technological, social, and environmental drivers of natural resource efficiency. Such insights are essential for policymakers and regulatory institutions seeking to design effective strategies that not only support environmental sustainability but also promote equitable economic development across the region. Given ASEAN's increasing vulnerability to climate change, biodiversity loss, and resource scarcity, evidence-based recommendations are vital for guiding sustainable resource governance, strengthening policy frameworks, and encouraging technological adoption.

Accordingly, the aim of this study is to investigate the key determinants of natural resource efficiency within ASEAN using advanced econometric modelling. The study seeks to examine the relationship between financial development and natural resource efficiency, evaluate the influence of eco-innovation, and assess the role of recycling in improving resource efficiency. It further aims to analyze how artificial intelligence contributes to enhancing resource optimization, while also exploring the broader effects of urbanization and economic growth. Through this comprehensive analysis, the study intends to offer valuable policy recommendations that support sustainable development and strengthen natural resource governance across ASEAN nations.

Literature Review

Association of Southeast Asian Nations (ASEAN) is regional intergovernmental organization consisting of ten member states Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam each of them have been characterized by different socio-economic structures, political systems and environmental landscapes (Stubbs, 2019). Being established with primary objectives, regional stability, economic integration, and collaborative development, ASEAN has been

evolved in a crucial actor for global political and economic affairs. ASEAN accommodates one of fastest growing-populations globally and continues to undergo being accelerated towards industrialization and urbanization. The demographic and structural shifts places mounting pressure on ecosystems, thereby making the efficient management of natural resources as a critical and increasingly immediate area of governance for member states (Yıldırım *et al.*, 2025; Lestari & Soewarno 2024; Bartuseviciene *et al.*, 2025). ASEAN's resource and environmental profile is being marked by exceptional biodiversity, abundant reserves for forest, extensive river system, fertile agriculture land, and globally significant marine ecosystems. However, Indonesia, Malaysia, and the Philippines are among the world's megadiverse countries, possessing a substantial share of global species richness (Zafarullah, & Mehnaz, 2025). Thus, countries like Cambodia. Loas rely mostly on hydro power and forest resources, whereas Thailand and Vietnam shows a mix of agricultural productivity, industrial activity, and coastal resource dependence (Chunta, 2025). The ecological diversity is offering major economic opportunities, that also presents significant challenges for sustainability of natural resource efficiency (NRE) which is across the region, specifically within the context pf rapid economic growth, expansion of populations and increase in urbanization (Qamruzzaman, 2025).

The richness in natural resource endowments, ASEAN face several environmental pressures, which includes deforestation, degradation of land, scarcity of water, marine pollution and unsustainable agricultural practices (Chakraborty & Dey, 2024; Chen *et al.*, 2024). These challenges have been further compounded with climate change influencing, such rising sea levels, intensified patterns of monsoon and increased frequency of extreme weather events, that disproportionately affect resource-dependent communities and vulnerable eco-systems (Dudgeon & Strayer, 2025, Suciati & Indrawati, 2024; Du & Wang, 2025). The diversity and complexity of ASEAN's ecological system demanding context-specific strategies being informed by empirical evidence which captures distinct development pathways of every member country. The existing literature remains limited within terms of comprehensive multi-country analyses which determine a holistic set of determinants as financial development, eco-innovation, institutional quality, urban planning and financial development pathways for every member country analyses which determines a holistic set of determinants such as eco-innovation, recycling, artificial intelligence (AI), economic growth, and urbanization and financial development within single analytical framework. This gap has highlighted the importance of conducting an integrated literature review for synthesizing present knowledge and identifying crucial factors which shape NRE across ASEAN region.

Natural Resource Efficiency in ASEAN

ASEAN region has possessed an outstanding diverse and rich basis for natural resources, that plays a significant role for supporting national economies and broader regional development. Area is characterized by an extensive forest systems specifically tropical and equatorial rainforests which host some of world's highest level of bio-diversity. These forests are contributing significantly for environmentally stable support carbon sequestration, regulation of hydrological cycles, and maintaining of ecological balance (Ramirez, Lecciones, & Capina, 2019; Skare *et al.*, 2024; Lu *et al.*, 2025). Additionally, the terrestrial ecosystems, ASEAN countries are being endowed with wider marine resources, that includes coral reefs, coastal zones and deep-sea eco-systems. These resources would sustain major fisheries which provide livelihood opportunities supporting food security and stimulation of tourism-driven development, making them an essential source of economic growth for different member states. Mineral resources have also consisted of major component of region's natural wealth. Countries like Indonesia, Malaysia, and Vietnam have significant reserves of coal, oil, natural gas, and metallic minerals that are most essential for domestic and industrial growth for export earnings. Trade and extraction of these resources contributing significantly for government revenues and foreign inflows (Nawaz *et al.*, 2019). With these sectors agriculture remains deeply embedded in socio-economic issues of ASEAN economies. Hoang (2020), agriculture serves as primary source of employment and income for a larger share of population, specifically in rural areas, with key agricultural outputs that include rice, rubber, palm oil and a variety of tropical fruits. In this there is not only support for livelihood but also contributing towards regional food security and export competitiveness. From this abundance, there is an efficient management of natural resources in ASEAN country faces several challenges critically.

Importance of Enhancing Resources Efficiency

With an enhancement of resource efficiency it is crucially significant for ASEAN countries, that is supports long-term sustainability by ensuring that natural, mineral, and energy resources as used in a manner which fulfills current societal needs while safeguarding their availability for future generations (Sheldon, 2018). As ASEAN economies continue to experience rapid industrialization and urbanization, the strategic use of resources becomes significant not only for environmental protection but also for the maintenance of economic stability. From economic perspective, improvement of resource efficiency enhances productivity which reduces production costs, and increase regional competitiveness. Firms that are adopting resource-efficient technologies such as automation, digital manufacturing, and circular production systems could reduce waste, enhance the performance of energy, and strengthen their position in global value chains. Recent studies show that resource efficiency is directly associated to innovation-driven economic growth, specifically through green technologies and eco-industrial systems (Meng & Wang, 2025). ASEAN's manufacturing and energy-intensive sectors, practicing to stimulate new business opportunities and supporting job creation, also by contributing towards inclusive development and reduced unemployment. The environmental benefits are equally important, Ayoungman et al. (2025), in their study discuss that higher resource efficiency reduces the intensity of resource extraction, minimization of waste generation, and lowering the overall ecological footprint. This has been critical for ASEAN countries facing rising pressures from

deforestation, marine degradation, and air pollution, integrating renewable energy sources such as solar, hydropower and biomass and adoption of low-carbon technologies which could help mitigating climate change by reducing green-house gas emissions and improvement of eco-system resilience (IEA, 2022). These would be aligned with regional commitments under Paris Agreement and ASEAN's own framework of sustainability.

Role of Indigenous Communities

Indigenous communities have valuable traditional knowledge regarding natural resources and they are ware of natural resource management in diverse fields of agriculture, forestry, fishing etc. These are often related to the respect for nature and provide insights regarding resilience to environmental change. The traditional knowledge is present in the form of agriculture practices, traditional fishing methods etc. (Mulalap *et al.,* 2020). Community based management refers to the collective efforts in the management of natural resources by local community and the application of their knowledge and methods in achieving sustainability. The community takes the ownership of their decisions and take those decisions that are helpful for sustainable practices and align them with needs of the local people (Murray, Agyare, Dearden, & Rollins, 2019; Lulaj & Mekaniwati, 2025; Xie *et al.,* 2025). There are diverse indigenous communities in ASEAN region that are rich with cultural traditions and they are connected with land and resources. For instance in Indonesia the Dayak communities have implemented certain practices for agroforestry and they use traditional agricultural methods for farming and conserve forest (Leo, Supriatna, Mizuno, & Margules, 2022; Nicoletti & Appolloni, 2024; Khatami *et al.,* 2024). Similarly in Malaysia, the Orang Asli community have developed tourism practices that are a source of livelihood for people and also preserve culture of the area (SF & VC, 2019).

Financial Development and Resource Efficiency

Financial development plays crucial role in the promotion of resource efficiency by investing in sustainable practices and these practices involve several activities that reduce resource utilization and its impact on the environment that ultimately provide benefits for the society as well as the environment. According to He, Liu, Zhong, Wang, and Xia (2019), sustainable practices involve investments for renewable energy resources and use of efficient technologies that help in mitigate the risk. Similarly the waste management systems are also initiated in order to manage the resources efficiently and promote sustainability. The financial institutions also play strong role in managing the funds for resource efficiency like banks and other institutions grant loans to businesses and organizations for sustainable practices and in managing their resources (Hermes, Lensink, & Meesters, 2018). In this way the financial bodies also play their part in environmental sustainability and climate change and at the same time generate returns for investors. The resource management projects require large investments in the form of infrastructures, technology, and equipment that are used for management of resources that are sometimes not in the range of small businesses. According to Saud, Chen, and Haseeb (2020), certain financial development programs can be initiated like micro finance programs in which the funds are provided in order to reduce the gap and to make it accessible for the population. In addition to these traditional financial mechanisms, technology-oriented financing has emerged as a critical driver for enhancing natural resource efficiency, particularly in dynamic and rapidly developing regions such as ASEAN. The rise of artificial intelligence (AI), the Internet of Things (IoT), cloud computing, and other advanced digital tools has reshaped the financial sector by improving business architecture, operational systems, service models, and the nature of financial products offered to industries (Liu *et al.,* 2021). These technologies enable financial institutions to better assess environmental risks, monitor resource consumption patterns, and design targeted green financing solutions that support eco-efficient practices across sectors. Cloud computing, for example, reduces operational costs and enhances transparency and data accessibility, thereby allowing banks and financial markets to implement sustainable financial products more effectively and at larger scales (Khan *et al.,* 2026) .

Recycling Initiatives

Recycling involves transforming discarded and unnecessary items into useful materials by applying modern technologies and techniques (Geissdoerfer *et al.,* 2017). It includes the collection, sorting, and treatment of used products to recover valuable resources, which are then processed into recycled materials for new production cycles (Beitzen-Heineke *et al.,* 2017). As global sustainability trends rise, manufacturers are increasingly responsible for recovering, reusing, recycling, and safely disposing of products after use (Pham *et al.,* 2024).

Recycling practices differ from region to region in terms of infrastructure, technology and the awareness among the public. Many regions have very well structured recycling structures that is equipped with robust collection and have processing facilities while some projects are not fully equipped and have limited resources (Kojima, 2020). The recycled materials in ASEAN region include plastic, paper, glass; metals etc. and these recycling initiatives involve both the formal as well as the informal mechanism. The informal mechanism involves the picking of waste material from households and business centers etc. whereas the formal involves all the process and procedures need to involve in recycling of waste (Ferronato, Portillo, Lizarazu, & Torretta, 2021). There are certain challenges for recycling initiatives like contamination of waste material through harmful material can result in reducing its quality that can be used for recycling process. Similarly the infrastructure that is not equipped with essential structures and systems and do not possess storing capacity of waste can be challenging as it can reduce the effectiveness of recycling initiatives. Moreover the lack of awareness among people can impact the programs and the changes in demand for recycled products can affect its processing (Bui, Tseng, Tseng, & Lim, 2022).

Eco-Innovation

Eco-innovation is the process of development of new products and processes and designs such business models that address the environmental challenges and helps in the promotion of sustainability. It is essential for achieving sustainable development as it guides the industries and businesses to reduce the impact on the environment and increase their efficiency that can leads them towards economic growth (García-Granero, Piedra-Muñoz, & Galdeano-Gomez, 2018). The innovative processes include the environmental considerations in order to have positive impact on the environment as well as the impact on society. According to García-Granero et al. (2018), eco-innovation in agriculture sector involves the development of such practices that help in promoting sustainability through farming methods and reduce the use of chemicals. Similarly the development of clean energy technologies like solar and wind energy as well as the construction of industries in which the design and construction is done using environmental friendly innovative technologies (Kanda, Hjelm, Clausen, & Bienkowska, 2018). Eco-innovation has significant impact on resource efficiency by reducing the waste generation and resource consumption that help in the promotion of sustainable use of natural resources. These innovative technologies help in improving production processes and reduce its impact on the environment (Kanda *et al.,* 2018). Hence eco-innovation plays crucial role in enhancing the use of resources and adopt processes that align with the sustainable practices.

Integration of Indigenous Knowledge, Financial Development, Recycling, and Eco-Innovation

Indigenous knowledge involves such practices that sometime involve traditional practices in order to manage resources and use this knowledge with financial development institutions in order to increase the effectiveness of project and promote resource efficiency. Financial institutions can support these communities by providing funds for the development of infrastructure and the technology which helps the community to preserve and use the knowledge they have in order to improve the quality of living (Middleton, 2023). Climate financing remains limited and risky, as it is difficult to determine an efficient price for climate actions in real socioeconomic environments (Monasterolo *et al.,* 2019). These constraints increase economic and climate-related financial risks (Zhao et al., 2022; Chenet *et al.,* 2021), while global climate funds are still insufficient to meet adaptation needs (Manuamorn *et al.,* 2020). Strengthening financial literacy and climate-finance education is therefore essential to support adaptation policies and improve financial well-being (Yao *et al.,* 2015; Scandurra *et al.,* 2020). Within the context of integrating indigenous knowledge, financial development, recycling, and eco-innovation, effective climate finance enables communities and industries to adopt sustainable practices, utilize local ecological wisdom, and promote circular-economy solutions (Lulaj, & Mekaniwati, 2025).

Similarly the communities also possess knowledge related to waste reduction and reuse and recycling of waste as they have deep understanding of land and resources. This link enhances the efficiency and effectiveness of waste management. There exist certain modern techniques for the management of waste like composting etc. Moreover the indigenous knowledge can transform eco-innovation by providing insights regarding sustainable practices and use of latest techniques for biodiversity conservation and it helps in creativity as well as develops resilience in development of sustainable technologies (Vassallo, Banerjee, & Prabhu, 2023). The eco-innovation practices use indigenous knowledge in order to identify solutions and address environmental challenges by keeping in consideration the rights and values of culture. According to Zimmerman et al. (2020), the kayapo indigenous people in Brazil have implemented the management system for natural resource that use the indigenous knowledge, financial development, and eco-innovation in achieving the goal.

Challenges and Opportunities for Integration

There are certain challenges for the integration as there are many factors that can provide resistance for initiatives including cultural differences and the knowledge may not be fully recognized by people or it is not given due importance by the government, financial institutions and the industries due to their limitations for integration of such knowledge in decision making programs. The barriers are also present regarding financial resources that limits the investment opportunities and the regulations and frameworks designed by the government also hinders the integration in development agenda (Weiskopf *et al.,* 2020). Although there are some opportunities that can help in achieving the objective like the collaboration of indigenous communities with government and agencies, industries etc. in order to implement the initiatives. Similarly designing such policies that support the knowledge and create opportunities for integrating this perspective can enhance the outcome. Moreover the support should be provided to small and local businesses who are working for the betterment of environment and sustainability which at the same time promotes eco-innovation and recycling initiatives. By addressing these challenges and unlocking the opportunities, ASEAN region can integrate indigenous knowledge, financial development, recycling, and eco-innovation in order to promote sustainability.

Variable Description and Methodology Specification

Variable Description

This research investigation uses a panel data analysis to provide insights into the nexus among natural resource efficiency, financial development and eco-innovation in two ASEAN countries named Singapore and Malaysia. The variables used in the data are presented in the table below. Different sources were used to extract the required data. Annual data from the year 2000 to 2021 was obtained from the sources mentioned in the table.

Table 1

Variable Description, Measurement and Source

Variable	Abbreviation	Description & measurement	Type	Source
Natural Resource Efficiency	NRE	Sum of economic output producers per unit of material consumed	Response	OECD
Eco-Innovation	EI	Share of patents on environmental technologies in total patents (%)	Predictor	OECD
Financial Development	FD	Domestic credit to private sector (% of GDP)	Predictor	WDI
Economic development	ED	Gross domestic product Growth (annual percentage)	Control	WDI
Urbanization	URB	Share of urban population in total population (%)	Control	WDI

"Note: OECD = Organization for Economic Cooperation and Development, WDI= World Development Indicators, IMF= International Monetary Fund"

Model Construction

The functional form of the relationship is described below:

$$NRE_{it} = f\,(\,RECY_{it}\;,\;EI_{it}\,,FD_{it}\,,\;AI_{it}\,,EG_{it}\,,URB_{it}\,) \quad (1)$$

The investigation of the associations is carried out through the empirical model below:

$$NRE_t = \alpha_0 + \alpha_1\, EI_{it} \;+\; \alpha_2\, RECY_{it}\;\; \alpha_3\, FD_{it} \;+\; \alpha_4\, EG_{it} \;+\; \alpha_5\, AI_{it} + \alpha_6\, URB_{it} \;+\; \varepsilon_{it} \quad (2)$$

The coefficients to be estimated are presented by the α; while, the error term is ε. The above equation is then used in the next section for the estimation

Econometric Approach

CSD Testing

In the realm of panel data analysis, CSD has become prevalent due to globalization, economic integration, and reduced trade restrictions. Ignoring the potential for cross-sectional dependence and assuming independence between cross-sections can result in biased, inconsistent, and inaccurate results. To overcome this problem, the CSD test proposed by Pesaran (2004) has been widely used to determine the presence or absence of CSD. This test utilizes a standard equation, as shown in equation (4):

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right) \sim N(0,1) i,j \quad (3)$$

Where, CD represents test statistic, T denotes the time dimension, N denotes cross-sectional dimension, and $\hat{\rho}_{ij}$ is the estimated cross-sectional correlation between units i and j (Pesaran, 2004).

Stationarity or Unit Root Tests

Conventional first-generation tests may fail when slope heterogeneity and CSD issues exist (Hanif & Nawaz, 2024). Therefore, to explore the stationarity properties of data series in the occurrence of slope heterogeneity and CSD, Cross-sectional Im, Pesaran, and Shin (CIPS) and Cross-sectional Augmented Dickey-Fuller (CADF) tests are utilized which are proposed by (Pesaran, 2007).

The cross-sectional average required for the CIPS estimate is shown in equation (8).

$$\text{CIPS}= \frac{1}{N}\sum_{i=1}^{N} CADF_i \quad (4)$$

Where, $CADF_i$ is the augmented Dickey-Fuller test statistic for the ith cross sectional unit. Additionally, the statistics of CADF test is given as follows:

$$\Delta y_{it} = \alpha_i + \delta_i^* y_{it-1} + \gamma_0 \bar{y}_{t-1} + \sum_{j=0}^{\gamma}\alpha_{j+1}\overline{\Delta y}_{t-j} \;+\; \sum_{k=1}^{\gamma} c_k \Delta y_{it-k} + \varepsilon_{it} \quad (5)$$

Method of Moments Quantile Regression (MMQR) Approach

To analyze the models empirically, we apply MMQR technique proposed by (Machado & Silva, 2019). There is frequent use of the quantile regression techniques when the effect of the independent variables is different across the conditional distribution of the outcome or dependent variable. These varying impacts of the explanatory variables are not captured by the conventional mean regressions such OLS estimation technique, because these techniques mainly aim to examine the effect of the explanatory variables on the conditional means or averages of the outcome or dependent variables. As a result, the mean regression approaches consider the average or mean value of the conditional distribution and disregard the effect of independent variables on the entire range of the values of the dependent variable. Therefore, as compared to the mean regression methods, the MMQR method gives more robust findings as it deals with the issue of distributional heterogeneity and estimates the impact of independent variables across the conditional distribution of the dependent variable. Moreover, in contrast to other quantile regression methods, this method also captures the heterogeneous conditional covariance effects on the dependent variable by considering the individual effects that affect the entire distribution (Sobirov et al., 2024).

The conditional quantile of a variable $(\tau|Xit)$ is expressed as follows:

$$Y_{it} = \alpha_i X'_{it}\beta + (\delta_{it} + Z'_{it}\gamma) + \varepsilon_{it} \quad (6)$$

Where, probability greater than 1 is $(\delta_{it} + Z'_{it}\gamma)$, and γ, α, β and δ are the estimated parameters. Fixed effects (i) show fixed effects whereas Z denotes the k-vector of the identified factor of X, which undergoes several adjustable changes with I factor, is given as follows:

$$Z_l = Z_l(X), l = l\ldots\text{.k} \quad (7)$$

In above equation, X shows fixed effect independent of time, while ε_{it} shows the error term distributed among individuals or cross sectional units and across time. We

normalize this error term to fulfill the moment condition without imposing a limit as follows:

$$Q_y\left(\frac{\tau}{X_{it}}\right) = \left(\alpha_i + \delta_i q(\tau)\right) + X_{it}\beta + Z'_{it}\gamma q(\tau) \quad (8)$$

Where, X_{it} denote explanatory variables in the equation which are TO, WGM, NRERU, I4.0 and SSC in the present study.

Findings and Results

First of all, Table 2 displays the basic characteristics of variables under consideration. First of all, the mean value is observed to be the highest for RECY and NRE has the minimum value of mean. The highest value of standard deviation is observed for RECY and the lowest value of standard deviation is observed for NRE variables. Data range i.e., minimum and maximum values is also given in summary/descriptive statistics. Furthermore, according to the finding of Jarque-Bera Test (J-B) test, some of the data series do not follow any normal distribution as indicated from highly significant statistics.

Table 2

Findings of Descriptive Statistics

Variables	Mean	Std. Dev	Minimum value	Maximum value	J-B Stat
NRE	4.291	3.314	1.16	10.21	5.736**
EI	8.302	2.803	2.752	14.273	0.3784
RECY	24560	15747	318861.9	4825700	3.359
FD	22.5	12.845	1.000	44	2.123
AI	2.681	5.5165	0.000	27.660	217.6***
EG	4.7460	3.6333	-5.456	14.519	4.482
URB	85.324	15.233	61.977	100	6.020**

Before the associations between the variable are evaluated, the cross-sectional dependence (CSDS) test is carried out. The assessment of CSD is necessary to provide efficient findings. Interdependency can result due to a number of factors. For instance, economic dependence, unanticipated shocks, changes in oil prices, shocks in demands and other latent factors can lead to CSD. Table 3 demonstrates the results for CSD. At a 1% significance level, the null hypothesis of no CSD is tested against alternative hypothesis. The standard rule for CSD test is rejection of null hypothesis when the p-value is below the level of 0.05 whereas the null hypothesis cannot be rejected when the p-value is greater than 0.05. Consequently, Table 3 shows p-value for all the tests is less than 0.05 for most of the variables, suggesting that the assumption of cross-sectional independence is rejected.

Table 3

Findings of Cross-Sectional Dependence Test

Variables	**CD-test**	**P-value**
NRE	1.237	0.216
EI	2.847**	0.004
RECY	3.538***	0.000
FD	-0.491	0.624
AI	-0.169	0.866
EG	3.475**	0.001
URB	0.000	1.000

Where, *** & ** show 1 and 5% level of significance, respectively.

The findings of unit root tests are given in Table 4. The statistical significance of the outcomes of CADF and CIPS tests affirm the mixed order of integration among series because some data series are level stationary and some are stationary at first difference.

Table 4

Findings of Unit Root Tests

Variables	**CADF Test**		**CIPS Test**	
	Level	**1st difference**	**Level**	**1st difference**
NRE	-1.898	-3.579**	-1.696	-3.663***
RECY	3.839	3.342**	0.121	-5.079***
EI	-3.140**	-------	-3.500***	---------
FD	-1.787	-3.803**	-1.994	-4.779***
AI	-2.687**	--------	-3.893***	---------
EG	-1.249	-3.033**	-1.662	-3.105***
URB	2.610***	---------	2.610***	---------

Where, *** & ** show 1 and 5% level of significance, respectively.

For the long-run estimation, the study considers MMQR estimation approach. In Table 5, the analysis is presented with 9 quantiles. The findings have provided evidence for the association between EI, FD, RECY, AI, EG, URB and NRE. The outcomes indicate that the coefficients differ across quantile values which suggest that the impact of the predictors on NRE varies at different points in the distribution of the variable. First of all, RECY is found to impact NRE significantly and negatively over 0.5 to 0.9 quantiles. Although this finding is contradictory to expectations, they can be justified on the basis of the fact that some recycling methods use massive amount of water and energy which ultimately reduces NRE overall (De Sa & Korinek, 2021). The finding that RECY has negative impact on NRE is in line with (Andre & Cerda, 2006) and (Van Ewijk, Stegemann, & Ekins, 2018).

Second, the results showed a positive impact of EI on NRE at all quantiles. Nonetheless, EI was not significantly associated with NRE. This positive impact of EI on NRE is in line with the studies of Miao, Fang, Sun, and Luo (2017) and (X. Li, Ma, Ruman, Iqbal, & Strielkowski, 2024). However, the insignificant impact shows that although EI has great potential to encourage NRE, its integration faces several difficulties to translate the innovative ideas into efficient use of resources. This insignificant effect is in line with García-Granero et al. (2018) and Kanda et al. (2018). This highlights the need for the strategic policies that help to fill this gap among the effective resource management and innovation practices.

Next, the findings show the impact of FD on NRE. FD is found to be positively associated with NRE at extreme high (0.8 and 0.9) quantiles only. With p-values less than 0.01, the association between FD and NRE is viewed as statistically significant. The positive impact of FD on NRE which is also in line with existing studies, such as He et al. (2019) discusses that an important role to encourage sustainability is played by financial institutions via renewable energy investments and initiatives for waste management. This positive relation among financial institutions and natural resource efficiency highlights the major role played by financial institutions towards the sustainable development. This also aligns with the perspective of Saud et al. (2020), who highlights the role of FD to support the initiatives of environmental sustainability via projects of resource management. Moreover, not only financial support is provided by financial institutions, but they also contribute towards the enhancement of resource efficiency via implementation of sustainable activities by industries and businesses. In similar context, the findings reveal that there is potential in initiatives of financial development and it provides contribution towards the implementation of eco-innovation activities as outlined by García-Granero et al. (2018) and Kanda et al. (2018). This multidimensional role played by financial institutions leads to sustainable resource management initiatives and encouraging economic growth in ASEAN countries.

Regarding control variables, AI has significant and positive impact on NRE at all quantile levels (0.1 to 0.9), suggesting that AI promotes NRE. This finding is counterintuitive as AI has massive potential to optimize waste recycling and management operations and activities. Similarly, AI significantly result in effectiveness and efficiency of resource management (Jones, Harris, Febriansah, Adiwijaya, & Hikam, 2024). From previous studies, the findings of Jones et al. (2024) and (J. Li, Ma, Qu, & Wang, 2023).

Likewise, the association between EG and NRE is positive. Nonetheless, the p-values exceeded 0.05 only at 0.4 to 0.9 quantiles. Therefore, the association is statistically significant only at these quantiles. The positive association between EG and NRE is supported by the earlier studies of and Steinberger and Krausmann (2011). This finding supports that rise in EG income level encourages technological advancement which increases resource productivity and NRE. Similarly, the relationship between URB and NRE is positive and significant at all quantiles, in line with the studies of Liu, Lu, Xian, and Ouyang (2023) and (Yang & Liu, 2014).

Table 5

Results of MMQR Estimation

Series	Location	Scale	Quantiles								
ASEAN Countries			**1st**	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**	**8th**	**9th**
RECY	-0.677*	-0.327	0.091	-0.100	-0.467	-0.612	-0.648*	-0.730**	-0.914**	-1.045***	-1.148***
	(0.060)	(0.164)	(0.981)	(0.889)	(0.321)	(0.132)	(0.094)	(0.032)	(0.002)	(0.000)	(0.000)
EI	1.511	-0.681	2.959	2.711	1.948	1.646	1.571	1.401	1.018	0.746	0.531
	(0.124)	(0.290)	(0.170)	(0.163)	(0.129)	(0.133)	(0.132)	(0.130)	(0.209)	(0.341)	(0.521)
FD	0.016	0.0260	-0.038	-0.029	-0.0002	0.011	0.014	0.020	0.035	0.045**	0.053**
	(0.519)	(0.118)	(0.494)	(0.566)	(0.993)	(0.699)	(0.610)	(0.393)	(0.101)	(0.025)	(0.011)
AI	0.125**	-0.027	0.184*	0.174*	0.143**	0.130**	0.127**	0.121**	0.105**	0.094*	0.085**
	(0.011)	(0.391)	(0.086)	(0.071)	(0.025)	(0.016)	(0.013)	(0.009)	(0.009)	(0.016)	(0.039)
EG	0.174**	-0.008	0.193	0.190	0.180	0.176*	0.175*	0.173**	0.168**	0.164**	0.161**
	(0.047)	(0.876)	(0.308)	(0.264)	(0.116)	(0.065)	(0.055)	(0.036)	(0.017)	(0.019)	(0.031)
URB	0.191***	0.038**	0.109	0.123**	0.166***	0.184***	0.188***	0.1981***	0.2199***	0.235***	0.247***
	(0.000)	(0.052)	(0.118)	(0.051)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

*Where, ***, ** and * represent significance at 1, 5 and 10 %, respectively.*

Conclusion and Recommendations

The primary objective of the present study is to estimate the role of FD, EI and RECY in NRE in two ASEAN countries named Malaysia and Singapore over 2000 to 2021 period. To analyze this objective empirically, we relied on MMQR estimation approach. The outcomes of the regression established that financial development enhances, whereas recycling reduces natural resource efficiency in ASEAN countries. In contrast, eco-innovations are not found to significantly impact NRE in selected countries over all quantiles. This exploration regarding the efficiency of natural resources in ASEAN countries discloses significant insights related to determinants impacting the practices of resource management in the region. The findings outline the natural resource efficiency's persistence over a period of time and the potential role played by financial development to encourage initiatives that are sustainable. These findings offer significant knowledge to the stakeholders and policymakers that are looking to improve the resource efficiency and encourage sustainable development in ASEAN countries.

The current study has practical implications and they offer knowledge to stakeholders and policymakers that are part of natural resource management in ASEAN countries. Firstly, identifying the significance regarding the persistence in practices of resource management recommends the requirement for continuity and long-term planning in the implementation of policies. Policymakers must give preference to approaches that encourage sustained efficiency of resources over the period of time to attain the advantages for environment that are long lasting. In addition, potential positive influence of financial development highlights the significance of promoting collaboration among agencies of environment and the financial institutions to make a network of investments towards initiatives for sustainability. This outlines the significance to implement financial resources to attain development of infrastructure and innovation in the resource management. However, considering the insignificant role of eco-innovations in the management of sustainable resources highlight the significance of implementing traditional practices into the efforts for modern conservation. Policymakers must look to involve the indigenous communities in the procedures of decision-making and initiatives for support that encourage and preserve the knowledge regarding ecology to improve the efficiency of resources and encourage environmental sustainability in the region. Moreover, government should provide tax incentives or targeted grants to firms which develop high-impact eco-innovations in those sectors which have high resource consumption. Likewise, the government must focus on redesigning products for reusability and durability to reduce the recycling in the first place needed and must support the shifting of recycling methods from traditional to closed loop and highly efficient systems. Communities, policymakers and business can implement these targeted policies and interventions that encourage sustainable resource management, enhance innovation and integrates indigenous knowledge for prosperity of the economy and long-term environmental benefits.

Limitations

While this study offers valuable insights, several limitations should be acknowledged. Firstly, the use of panel data analysis, while robust, may be subject to data limitations and measurement errors. Despite efforts to obtain reliable data from reputable sources such as the OECD and IMF, discrepancies or inaccuracies in the data could affect the validity of the results. Also, the sample of present research is limited to two countries only, which can be extended in future research studies. Additionally, the chosen econometric approach, specifically the quantile regression may have its own assumptions and limitations. For instance, the quantile regression model assumes that the relationship between variables remains constant across different quantiles, which may not always hold true. Moreover, the focus of study is on the ASEAN region might restricts the finding's generalizability to other regions, that have different context of environment and social economy. In terms of culture, natural resources and levels of development, the ASEAN countries are diverse and this also proposes heterogeneity in the analysis, significantly influences the result's reliability.

Furthermore, while the study acknowledges several determinants like recycling, financial development and eco-innovation it might not completely capture all the related variables that can impact the efficiency of natural resources. For instance, global economic trends, socio-political determinants and government policies can also play an important role but that were not included in the current study.

Lastly, the study's reliance on secondary data sources means that it is constrained by the availability and quality of existing data. This may limit the depth of analysis and the ability to explore certain aspects of natural resource efficiency in greater detail. Future research could address these limitations by employing primary data collection methods and incorporating a more comprehensive set of variables.

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The article has been reviewed.

Received in June 2025; accepted in January 2026.