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Influence of energy efficient infrastructure, financial inclusion, and digitalization on ecological sustainability of ASEAN countries

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ASEAN countries are emerging economies facing substantial, sustainable energy production and consumption challenges. Power sources' availability, sustainability, and efficiency are imperative to ensure ecological sustainability. Therefore, these countries must explore the factors that promote sustainable energy supply. The current study investigates the interlinkages between energy infrastructure, financial inclusion, and digitalization on the ecological sustainability of ASEAN region from 1980 to 2018. The study applied the continuously updated fully modified (CUP-FM) and continuously updated bias-corrected (CUP-BC) estimators to address cross-sectional dependency and slope heterogeneity issues. The study's findings show that energy infrastructure, financial inclusion, and digitalization help to reduce ecological footprints in the long run. Moreover, digitalization complements the impact of energy-efficient infrastructure on ecological footprints. These findings recommend that ASEAN countries should improve energy infrastructure by integrating digitalization into energy supply production, management, and distribution.

KEYWORDS

energy efficiency, financial inclusion, digitalization, CUP-FM, CUP-BC, ASEAN

1 Introduction

In today's world, the most severe challenges are ecological changes and environmental pollution, and environmental policies and practices have become essential solutions for developed and developing economies (Yao et al., 2021). Various international organizations, including the World Bank, International Monetary Fund (IMF), International Energy Agency, Environmental Investigation Agency, and many others, are constantly working through financial and non-financial resources to mitigate adverse ecological changes like carbon emission, haze pollution, and ecological footprints (EFP). In this regard, the Paris Climate Conference conducted in 2015 has mainly emphasized how developing economies can reduce adverse environmental impacts through legal and independent national contributions (UNFCC, 2022). In recent years, COP26 has aimed to bring together different parties to accelerate actions toward the goals of the Paris

Agreement while focusing on critical issues like recognizing the emergency for the global average temperature well below two°C, moving away from fossil fuels, supporting developing economies through US$100 billion a year against climate finance (UN, 2022). These efforts have reasonably justified the argument that there is a growing trend for focusing on controlling the environmental damages for which efficient utilization of energy-related sources is quite essential. Figure 1 shows the tendency of EFP (total constant per capita) of ASEAN economies from 1980–2018. It shows that Singapore has the highest footprints, followed by Brunei Darussalam, Malaysia, and Thailand. However, the rest of the economies have presented approximately a similar trend regarding EFP.

Due to rapid economic growth, the above economies are also observed with a growing level of energy consumption in recent decades. Liu and Noor (2020) report that the final energy consumption in ASEAN economies has significantly grown from 530.9 thousand tons of oil equivalent or ktoe (2000) to 721.7 ktoe (2016). However, these economies' per capita energy consumption has dropped by 0.3% in the residential sector. Moreover, six out of ten ASEAN economies are not energy exporting economies; however, many will be unable to maintain their self-independency in the upcoming decades. This is because of rapid energy demand growth and usage growth for domestic production and supply purposes (Liu and Noor, 2020). Consequently, the growing energy demand has posed many challenges for policymakers and environmentalists when considering the ecological consequences. For this reason, advancing energy efficiency is a significant need for these economies, specifically in dealing with the changing climate and related concerns. About USD11.7 trillion investment in the power and energy sector is suggested in the ASEAN region (Liu and Noor, 2020).

Although energy-efficient infrastructure would play a significant role in controlling climate changes *via* low dependency on fossil fuels and similar other sources; however, without solid financial systems, these economies cannot achieve their sustainability objectives on reasonable grounds (Yao et al., 2021). An efficient and wholesome financial system may provide financing facilities to different sectors and industries, specifically energy-efficient technologies, and enable green transformation (Ahmed et al., 2021b). Also, scholars have argued that with the development of green financing facilities, energy efficiency will be improved, which in turn helps in effectively managing natural resources, hence low ecological footprints. More specifically, two different schools of thought have been presented regarding the relationship between financial sector development, energy consumption, and the environment. According to the first view, financial development increases energy consumption, destroying the natural environment (Al-mulali et al., 2013). On the other side, the second view reflects that financial development helps promote energy efficiency due to its decisive role in improving environmental quality (Yao et al., 2021).

At the same time, the advancement in digital technologies has significantly changed the business models, economic outlook, and community living standards. Digitalization provides new revenue and value-producing opportunities while changing

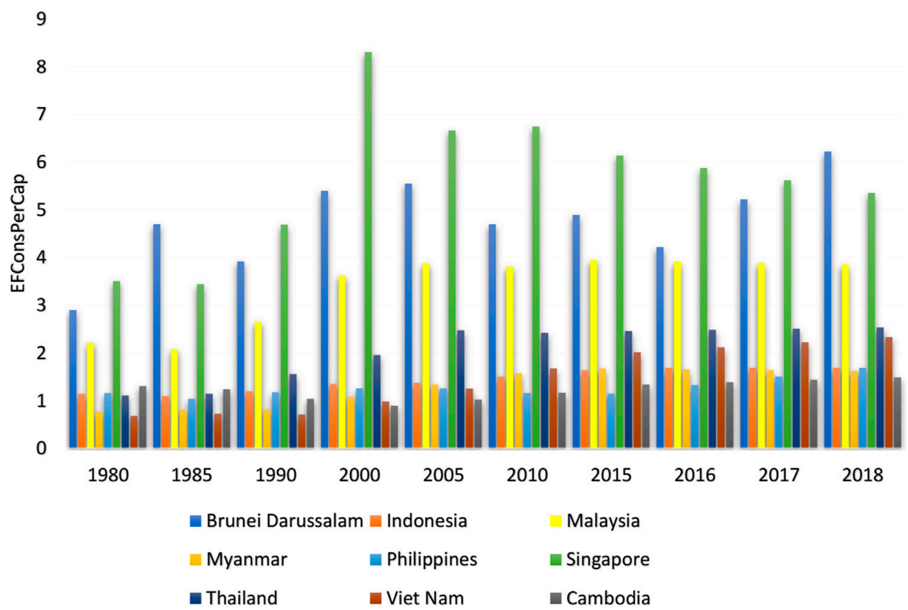

FIGURE 1
EFP (constant per capita) for ASEAN economies Source: Visuals drawn by authors, data from GFN.

business models and moving to more digital business trends (Merimi and Taghipour, 2021). One form of digitalization is information and communication technologies (ICTs), potentially controlling environmental degradation by avoiding unnecessary transportation costs, creating awareness about environmental concerns, and using green technologies (Belkhir and Elmeligi, 2018). The potential benefits of ICTs are well-known in front of the world; however, few studies have discussed their role in air pollution, whereas the ecological aspect is yet to be explored in different regional contexts.

Urbanization (URB) results in the migration of individuals from rural to urban areas. Similar has been observed in the ASEAN economies because of rapid economic growth and physical extension of urban areas. For instance, the rate of URB in the Malaysian economy has increased from 25% to 75% over the past threedecades (Tenth Malaysian Plan, 2010). Whereas, in Indonesia, there was an increase of 2.5% in the URB rate for the Indonesian economy during 1970–2018, reaching a medium URB level of 55% by 2017 (World Bank, 2019). Additionally, urbanization has increased dramatically in Thailand, where 50.69% of the total population lived in urban areas in 2019 (World Bank, 2019). The rapid growth of urbanization has increased the energy demand, more pressure on natural resources, higher greenhouse gas emissions, and ecological consequences (Ahmed et al., 2020a). Thus, most of the environmental quality dimensions are damaged due to large-scale deforestation and degradation of the land over URB (Hashmi et al., 2021).

The primary interest of current research is to analyze the effect of energy-efficient infrastructure, financial Inclusion (FIC), and digitalization while controlling the urbanization and economic growth on the ecological footprints of ASEAN. Prior studies primarily explored the influence of renewable energy and financial development on ecological sustainability; however, no noticeable study explored the role of efficient energy infrastructure integrated with digitalization. It also applies advanced panel estimators to address panel data issues and offers reliable outcomes.

The research proceeds as follows. Section 2 covers the literature review. Section 4 deals with the research methods, whereas Section 4 presents results and discussion. Lastly, Section 5 prescribes the conclusion and policy implications.

2 Literature review

2.1 Energy efficient infrastructure and ecological sustainability

Sustainable communities must include green infrastructure techniques to preserve public health and the environment while bringing about other economic and social benefits that help residents get more for their investments. Nations can realistically minimize consumer energy costs, promote job creation, and lower energy-related CO2 emissions by improving the energy efficiency of buildings. Buildings provide a considerable chance to renew the foundation of infrastructure and enhance local communities around the nation (Majumder and Bassett, 2019).

lo Storto and Evangelista (2022) compare logistics systems for 28 European nations and their environmental impact based on the data between 2010 and 2017. The land logistic systems are compared in terms of logistics quality, infrastructure efficiency, and their overall impact on environmental sustainability. The study employs Data Envelopment Analysis (DEA) to measure the effectiveness of logistics infrastructure. Utilizing Shannon's entropy, the various efficiency indicators are integrated to create a single composite measure that represents the effectiveness of the logistics infrastructure. They found the effectiveness of the EU nations' land logistics systems in terms of infrastructure and their environmental impact. The comparison of separate efficiency indicators concludes that the service component alone cannot guarantee and maintain national logistics systems' competitiveness without a reasonable infrastructural efficiency level. Energy efficiency makes it possible to save energy throughout the production of products and services (Zheng et al., 2021), and like renewable energy, it is essential for lowering CO2 emissions. Ponce and Khan (2021) research the energy efficiency of cotton producers in South Punjab, Pakistan. According to their findings, reserving 23% of power use and drastically lowering CO2 emissions is possible. Xia et al. (2020) studied the secondary economic sector of Xinjiang, China, and estimated the energy efficiency potential of seven main sectors would cut energy consumption and CO2 emissions by 70% and 50%. Likewise, H. Wang et al. (2021) argue that energy efficiency reduces CO2 emissions by 6% in the secondary metallurgical industry in Switzerland.

The assessment framework for developing green infrastructure for promoting environmental sustainability is still insufficient, despite increased research and urban policy advocating and implementing the development of green infrastructure (GI). S.-H. Lin et al. (2021) built the assessment framework to create and improve the GI, which includes four dimensions and ten associated criteria, utilizing Multiple Attribute Decision-making (MADM) techniques. Their findings suggest the application of GI to enhance environmental sustainability, and decision-makers should pay greater attention to improving materials and design in infrastructural dimensions. The synchronization of species and energy will be improved due to the enhancement of these dimensions. Regarding criteria, five essential fundamental requirements should be prioritized first: raising the percentage of green space, using sustainable materials, ecological engineering, and lowering energy use. Additionally, renewable energy has been demonstrated to lessen air pollution; therefore, this would be a solution to prevent environmental contamination.

Ponce and Khan (2021) investigate the long-term relationships between carbon emissions, clean energy, energy efficiency, and GDP in nine industrialized nations based on data from 1995 to 2019. The findings show that developed European nations exhibit a long-term equilibrium connection. The key findings indicate that CO2 emissions are inversely associated with energy efficiency and renewable sources. In wealthy European nations, a 1% increase in the use of renewable energy corresponds to a 0.03% reduction in CO2 emissions. Furthermore, several recommended legislative changes for achieving ecological sustainability are made. CO2 emissions have increased significantly worldwide and have been the source of air pollution, including decreased air quality, increased temperatures, and global warming. The industrialization seen over the past century is linked with this increase in greenhouse gas emissions. Energy efficiency and low-carbon energy production must be promoted together rather than separately. They also suggest that regional regulatory convergence is an effective technique to achieve high efficiency, which also lowers costs, increases market size, and lowers trade barriers. Investment in sustainable and efficient energy will provide various benefits for future infrastructural development.

2.2 Financial inclusion and ecological sustainability

Financial development helps to expand the economic sector through financial intermediaries and key role players. Scholars have investigated whether or not the FIC helps in promoting environmental sustainability. However, FIC significantly impacts economic development (Dahiya and Kumar, 2020). Literature suggests that financial institutions should support the manufacture of environmentally friendly commodities rather than those with a high carbon footprint. In this regard, governmental institutions may also aid in improving sustainable development through proper regulations and promote projects with minimum or low environmental consequences (Irfan et al., 2022).

In addition, environmental economists have focused on FIC in recent years to see how it affects environmental deterioration (UNSGA, 2022). Ahmad et al. (2022) explore the relationship between FIC and ecological sustainability in the ASEAN countries using panel data from 2000 to 2019. Their findings imply that FIC negatively influences environmental sustainability due to higher economic expansion. More specifically, a 1% rise in FIC causes a 0.15% and 0.42% increase in environmental damage in the short and long run, respectively. Xing et al. (2017) examine the association between FIC and CO2 emissions in China from 2000 to 2013. Their results show that financial development pointedly increases CO2 emissions. It is inferred that one of the primary causes of China's rising carbon emissions is financial globalization. Adebayo et al. (2021a) observe the impact of financial practices on carbon emissions in Pakistan from 1985 to 2014. The study discovers that FIC stimulates carbon intensity.

Le et al. (2020) examine the association between FIC and CO2 emissions in Asia during 2004–2014. Three proxies of FIC were developed based on the principal component analysis (PCA). Their findings show that FIC leads to higher energy consumption and associated emissions. Renzhi and Baek (2020) identify the impact of FIC on CO2 emissions between 2004 and 2014 for 103 economies. They argue that FIC reduces CO2 emissions and improves ecological sustainability, suggesting that policymakers need to consider the synergy effect of FIC in designing and developing climate policies and practices. Using yearly data from 2004 to 2014, Zaidi et al. (2021) focus on 21 OECD economies during 2004–2017 and find that FIC is significantly and negatively linked with CO2 emissions. Musah (2022) applies the dynamic ARDL model and explores that FIC contributes to severe ecological damages due to associated energy consumption. He also finds that trade openness, population, and energy use lead to higher emissions and suggest that financial institutions should support the manufacturing of environmentally friendly commodities.

FIC improves energy effectiveness by creating new markets and generating money for affordable, replicable clean energy technologies, particularly for energy purposes in underdeveloped nations. FIC and ecological sustainability are closely linked with the presence of GDP and urbanization as control variables. Financial companies may play a crucial role in financing and implementing improved energy products when working with states and other organizations. A network of financial firms may succeed in financing and marketing sustainable energy products in addition to initiatives to inform consumers about clean energy for enhanced environmental sustainability (Irfan et al., 2022).

2.3 Digitalization and ecological sustainability

Over recent years, there has been a tremendous increase in digital technologies and associated infrastructure. However, It is required to ensure that this has no adverse effects on digital technologies on the environment (UN, 2022). Recent technological developments provide the game-changing potential to monitor and safeguard the environment. Moreover, digitalization may enhance environmental protection, human welfare, and global sustainability by effectively utilizing similar technologies (Bekezhanov et al., 2022).

Brenner and Hartl (2021) examine how various factors interpret the link between digitalization and ecological sustainability based on framing and social response theories. Their study also determines how management and politicians, among other players, respond to the digitization and environmental sustainability demands. A multi-method technique that combines media analysis with two experimental investigations has been applied to examine how different factors construct the connection between digitalization and environmental sustainability. The results confirm that the degree of digitization appears to impact people's perception of ecological sustainability. Digitalization positively influences environmental efficiency and societal connectivity (Maria E Mondejar et al., 2021). Developing intelligent systems based on the latest technologies would strategically address the problems related to the Sustainable Development Goals (SDGs). It indicates the possibilities that digitization would offer for developing a future environmentally-sustainable society where the integration of smart technology is seen as a game-changer (Maria E. Mondejar et al., 2021). Finally, the perspective encompasses the advantages of digitization by offering a comprehensive vision of how technology might help address global biodiversity and environmental degradation.

Ahmed and Le (2021) exhibit that earlier studies consider ICT as a two-edged sword that can benefit or harm environmental sustainability. Using advanced-panel estimation for the six ASEAN economies, they found that ICT improves environmental sustainability by reducing carbon emissions. Ahmed et al. (2021a) argue that ICT has affected every aspect of life, including education, social activities, business, and the environment. Their findings investigate ICT's role in determining environmental sustainability in the Latin American and Caribbean (LCA) region and endorse that ICT and globalization contribute to reducing CO2 emissions in the long run.

Adebayo et al. (2021b) focus on Europe, North America, and Japan while exploring the relationship between technological innovation and environmental quality. They conclude that technological advancement reduces environmental deterioration. Technological advancements and the energy sector play a significant role in Europe's recent decline in emissions. On the other side, the relationship between digital technology and environmental quality in China is determined by Lin and Zhu (2019). The linear regression model demonstrates that renewable energy technologies have a detrimental effect on carbon emissions. Besides, technological innovation is the main counterbalancing force in footprint reduction. Wang et al. (2022) find that technical innovation fosters environmental sustainability and helps N-11 economies to meet COP21 targets. The negative relationship between environmental deterioration and technological innovation in China is also established by Guo et al. (2021). The study demonstrates that technological advancement may aid in accomplishing SDGs.

2.4 Control variables

2.4.1 Gross domestic product and ecological sustainability

Contemporary capitalist theory frequently equates money with prosperity, attributing increases in living quality to economic expansion. A country is more prosperous when more products and services are produced and exchanged. For this purpose, the Gross Domestic Product (GDP), which measures output and transactions over a certain period, has been a crucial instrument for assessing economic progress. The globalization of the GDP as a measure of economic success directly impacts governmental and economic management (Bove, 2021). Nevertheless, GDP does not address the detrimental impacts of externalities like inequality and climate change.

Environmentalists and researchers both believe that the deterioration of the environment results from the global economy's fast expansion and human activity. Familiar energy sources like non-renewable sources are thought to contribute to environmental destruction. Using annual data sets from 1971 to 2016, Mohsin et al. (2022) examine the connection between environmental sustainability and economic growth in European and Central Asian nations. The short- and long-term relationships between the chosen set of parameters are ascertained using the ARDL technique. They find that energy consumption and GDP are two main drivers of CO2 emissions. Furthermore, energy consumption and FDI are the Granger causes of CO2 emission, whereas CO2 emission Granger causes GDP.

Munir et al. (2021) assess whether the environmental Kuznets curve (EKC) theory is valid in the context of eleven developing nations. The study investigates the possible inverted U-shaped relationship between CO2 emissions and GDP in the sample data using balanced yearly panel data between 1992 and 2014 and two different estimating methodologies. Their findings support an inverted U-shaped correlation between long-term CO2 emissions in emerging nations, thus, validating EKC. However, Mexico, the Philippines, Indonesia, and South Africa did not support the EKC theory. It became clear that these nations needed to develop policies to lower CO2 emissions from economic activity and power generation by increasing efficiency or promoting renewable energy sources.

There is a tradeoff between environmental quality and economic growth in certain nations. For instance, China's recent economic development has dramatically lowered poverty, allowing it to join the group of upper-middle-income nations. Thus, the literature on GDP and environmental quality nexus strongly encourages the global community to take additional steps to gather, standardize, and retain high-quality data that will enable in-depth evaluations of national trends concerning the Sustainable Development Goals. It will be essential to ensure national ownership of these initiatives to build the state capability necessary to make them sustainable.

2.4.2 Urbanization and ecological sustainability

The term "urbanization" describes the concentration of people in specific geographic regions. Due to this, density transforms the land for housing, industrial, commercial, and logistic uses (EPA, 2022). The larger regional habitats are impacted by urbanization. The quantity of rainfall, poor air quality, and the frequency of storm days all rise in areas downstream from big industrial operations. Urban areas have an impact on both weather patterns and water runoff patterns.

The environmental footprint has received significant attention in the literature as a sign of environmental deterioration. In the thirty IEA member nations, Yang and Khan (2022) examine the relationships between urbanization and environmental sustainability. The study implements sophisticated econometric models and finds that short-run capital creation and biocapacity enhance ecological footprint. Long-term estimations show that capital creation and industrial value-added increase ecological sustainability. However, over time, environmental sustainability is harmed by urbanization, biocapacity, and population increase. To limit the negative effects of urbanization on ecological sustainability, policymakers in the IEA countries are urged to implement measures that support a sustained lifestyle, environmental responsibility, green technological developments, efficient development and utilization strategies, and expand cities. In recent years, ecological sustainability has taken on increased significance to ensure socio-economic sustainability through a healthy ecosystem.

Cui et al. (2022) examine the connections between urbanization, economic progress, and ecological impact in ten leading complex economic and renewable energy-consuming countries. The study uses panel data estimators, such as FMOLS, DOLS, and CCR long-run estimators, from 1980 to 2017. Their findings imply that urbanization and economic complexity increase the ecological footprint in both groups. The first panel states that human capital and renewable energy reduce ecological footprint and *vice versa*.

One of the most significant societal changes in contemporary times is urbanization, pushed by several social, financial, and ecological phenomena. Urbanization has significant, diverse regional, national, and global environmental effects (Bai et al., 2017). Cities, which are now home to half the world's population, are increasingly at the frontline of the most critical environmental concerns. With varying execution and efficacy, cities are actively experimenting with sustainability under various guiding ideas that represent their aspirational aims. More attention is being paid to public engagement and knowledge co-production with stakeholders in managing the urban environment.

3 Research methods

Table 1 presents a detailed description of the key variables, measurement proxy data source, and literature source. As panel data mainly deals with the cross-sectional units of observations over different time durations; therefore, checking for the cross-sectional dependence (CSD) is significantly important. Therefore, we initially applies the Lagrange Multiple tests as suggested by Breusch and Pagan (1980) and CSD test of Pesaran et al. (2004). The implication of these tests is quite evident, as ignoring them will lead to inappropriate results at later stages. Moreover, the below equations specify the functional form of Breusch and Pagan test.

$$CSD = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}^{2} \quad (1)$$

Additionally, Pesaran et al. (2004) is also applied and specify the following equation.

$$CD = \sqrt{\frac{2T}{N\,(N-1)}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\rho_{ij}} \quad (2)$$

In Eq. 1, t covers the time, while N reflects the cross-sectional units, which are ASEAN economies under the present study. Moreover, ρ_{ij} means the correlation coefficient. H0 under CSD assumes the non-existence of cross-sectional dependence,

TABLE 1 Variables and measurement.

Variable title	Abbreviation	Measurement	Data source	Literature source
Ecological sustainability	Ecological footprints EFP	Ecological footprint constant per capita, total	GFN	Alola et al. (2022)
Energy efficient infrastructure	EFI	UCA index*	WDI	Razzaq et al. (2021)
Financial Inclusion	FIC	Khan et al. (2019)	IMF.org	Khan et al. (2019)
Digitalization through ICT	DIG	Mobile cellular subscriptions (per 100 people)	WDI	Caglar et al. (2021)
Gross domestic product	GDP	Current USD	WDI	Caglar et al. (2021)
Urbanization	URB	Urban population	WDI	Salman et al. (2022)

*It is important to note that our study has applied universal component analysis (UCA) to calculate the cumulative energy efficient infrastructure through renewable energy consumption and production of electric power as measured through per capita terms. Electric-power transmission and distribution losses (% of output) are also considered to calculate the UCA, index, based on the methodological suggestion of Donaubauer et al. (2016). Data for these indicators have been collected from WDI.

whereas H1 rejects it. Apart from this, the order of integration for the study variables is also investigated for which second-generation cross-sectional augments commonly known as CIPS and CADF unit root tests have been applied (Pesaran, 2007). Therefore, Eq. 3 covers the functional justification for the unit root test.

$$\Delta CA_{i,t} = \varphi_i + \varphi_i Z_{i,t-1} + \varphi_i \overline{CA}_{t-1} + \sum_{I=0}^{p} \varphi_{iI} \Delta \overline{CA_{t-1}} + \sum_{I=0}^{p} \varphi_{iI} \Delta CA_{i,t-1} + \mu_{it} \quad (3)$$

In Eq. 3 above, $\overline{CA}_{t-1}$ and $\overline{CA_{t-1}}$ demonstrate the averages for the cross-sectional units. However, the implication of the CIPS test is presented through Eq. 4 of the study.

$$\widehat{CIPS} = \frac{1}{N} \sum_{i=1}^{n} CDF_i \quad (4)$$

After focusing on the abovementioned tests, this study investigated the cointegrated association between the selected variables. For this purpose, this study applies the panel cointegration test as Westerlund and Edgerton (2008), which considers the cross-sectional dependence, slope heterogeneity, and stationarity properties. Eqs 5,6 reflect the specifications of LM tests.

$$LM_\tau = \frac{\hat{\Phi}_i}{SE(\hat{\Phi}_i)} \quad (5)$$

$$LM_\Phi = T\hat{\Phi}_i \left(\frac{\hat{\omega}_i}{\hat{\sigma}_i} \right) \quad (6)$$

It is essential to understand the notation in the above equations. $\hat{\Phi}$ cover the estimation for the least square, Φ's S.E. is $\hat{\sigma}_i$; whereas the reflection of $\hat{\Phi}_i$'s.E. is $SE(\hat{\Phi}_i)$. Specifically, the null hypothesis under Westerlund and Edgerton (2008) reflects cointegration, whereas H1 indicates the long-term association between the stated variables.

Afterward, it is also stated that various estimation techniques have been presented in the current literature to explore the relationship between independent and dependent variables. However, these estimation techniques are unable to consider the cross-sectional dependence. For this reason, current research has applied the CUP-FM and CUP-BC proposedby Bai and Kao (2006). Eq. 7 described and formalized the following factor model:

$$\hat{\beta}cup, \hat{F}cup = argmin \frac{1}{nT^2} \sum_{i=1}^{n} (y_i - x_i\beta)' M_F (y_i - x_i\beta) \quad (7)$$

where $M_F = I_T - T^{-2}FF'$, $I_T$indicates the elements, and T's show the identity matrix.

4 Results and discussion

Considering the cross-sectional dependence for the variables entitled ecological footprints, energy efficiency, FIC, digitalization, economic growth, and urbanization, the findings are compiled in Table 2. The findings report the existence of cross-sectional dependence among ASEAN economies, as results are significant at 1%. ASEAN economies are interdependent in the globalized world because of their economic, financial, social, and other trade-related activities. Any shock in any variable of interest would also be reflected in the rest of the economies; therefore, due to the spillover effect, the variables are dependent on each other. Pesaran et al. (2004) claim that ignoring the cross-sectional dependence would lead to inappropriate empirical estimations at later stages; therefore, investigating such data trends is essential. After confirming the CSD of the data, the next step is to investigate the integration level of the variables. The results are presented in Table 3, which shows that all the variables entitled EFP, EFI, FIC, DIG, GDP, and URB were non-stationarity at the level. However, after taking the first difference, they turn stationarity at a 1% significance level in both CIPS and CADF unit root tests.

The results in Table 4 cover the slope heterogeneity/homogeneity investigation based on Swamy's test suggested by Pesaran and Yamagata (2008). The results *via* Delta tilde and Delta tilde Adjusted shows significant test statistics at 1%, which accepts the alternative hypothesis to claim that slope heterogeneity exists.

TABLE 2 Cross-sectional dependence findings.

Variables	Breusch-pagan LM	Pesaran scaled LM	Pesaran CD
EFP	213.510***	39.152***	19.367***
EFI	316.285***	43.188***	21.963***
FIC	463.152***	51.007***	26.108***
DIG	363.587***	60.585***	32.105***
GDP	319.529***	42.205***	31.637***
URB	262.964***	35.618***	29.414***

Note: ***Significant value at 1%, **significant value at 5%, *significant value at 10%. EFP: ecological footprints, EFI, energy efficient infrastructure; FIC, financial inclusion; DIG. digitalization; GDP, gross domestic product, URB, urbanization.

TABLE 3 CIPS and CADF unit root tests result.

Variables	CIPS		CADF	
	Level	First difference	Level	First difference
EFP	−1.326	−3.696***	−1.062	−4.137***
EFI	−0.213	−4.185***	−1.338	−3.698***
FIC	−0.162	−2.982***	−1.572	−5.152***
DIG	−0.177	−3.537***	−1.320	−3.652***
GDP	−0.218	−4.682***	−0.628	−2.917***
URB	−0.151	−3.827**8	−0.198	−3.626***

Note: ***Significant value at 1%, **significant value at 5%, *significant value at 10%. EFP: ecological footprints, EFI: energy efficient infrastructure, FIC: financial inclusion, DIG: digitalization, GDP: gross domestic product, URB: urbanization.

TABLE 4 Results of Slope heterogeneity analysis.

Dependent variable: EFP	Test value (*p*-value)
Delta tilde	41.929*** (0.000)
Delta tilde Adjusted	38.152*** (0.000)

Note: ***, ** and * explain the level of significance at 1%, 5% and 10% respectively, whereas the values are in parentheses contains *p*-values.

The current study applies Westerlund and Edgerton (2008) cointegration test, and the findings are compiled in Table 5. The results confirm the long-term connection between energy infrastructure, FIC, digitalization, GDP, and urbanization at a 1% significance level. More specifically, the findings are highly significant under the categories of no-shift, mean-shift, and regime-shift categories. After confirming the long-term cointegration relationship between the variables, we apply the CUP-FM and CUP-BC estimator for long-run parameters.

Table 6 shows that the EFI coefficient under Cup_FM is significantly negative (beta = −0.125, t-value = −3.578). It reveals that efficient energy infrastructure would help to reduce ecological footprints in ASEAN economies. Similarly, the results reflect that a 1% change in EFI tends to decrease EFP by 11.5% under Cup_BC estimations. The energy efficiency factor is directly linked with the less utilization of available energy sources to generate more output. For this reason, different authors have confirmed the constructive nexus between EFI and EFP. For instance, Khan et al. (2021) apply panel ARDL estimation techniques to examine the role of energy efficiency in controlling the EFP. Through stochastic Frontier analysis (SFA), their study shows an average energy efficiency score of 90% in the ASEAN economy, providing evidence for the improvement of 10%. It is integral in controlling environmental contamination by reducing ecological footprints. Besides, it is further inferred that there is a causal association between energy efficiency and EFP. Nassani et al. (2021) find the efficient use of energy, natural resources, financial development, and insurance services reduces ecological burdens. Their empirical findings suggest that energy efficiency and trade-fair policies help to reduce human demand for natural capital (Ahmed et al., 2020b). Likewise, Kazemzadeh et al. (2022) apply slacks-based (SBM) DEA models to estimate energy efficiency and find that energy efficiency has a significant and negative impact on EFP from 0.10th to 0.90th quantile. More specifically, this impact is highly significant for all the ranges of quantiles. Based on the above findings, this study infers that EFI helps in mitigating climate changes.

The long-term relationship between FIC and EFP is significantly negative in both of the stated models in Table 6. More specifically, it shows that FIC reduce EFP by 0.237% under Cup_FM and 0.168% under Cup_BC. These coefficients are highly significant at 1%, provided that more FIC implies less EFP and *vice versa*. It implies that ASEAN economies have developed financial systems that provide inexpensive credit facilities to households to buy and utilize traditional energy products (Acheampong, 2019). The developed financial sector also boosts industrialization through which more augmentation of industrial waste is evident, hence lower environmental pollution. Few argue that financial development increases research and development, promote growth, and reduces ecological damages. Usman et al. (2021) investigate the top-15 highest emitting economies through an AMG estimation strategy. Their findings show that financial development and renewable energy sources reduce environmental degradation. Hussain et al. (2022) take the sample of OECD economies over the past two decades while building an index of FIC through principal component analysis and argue that FIC discourages sustainable development.

TABLE 5 Cointegration test.

Model	No shift		Mean shift		Regime shift	
	Statistic	p-value	Statistic	p-value	Statistic	p-value
LMτ	−3.628	0.000	−3.357	0.000	−4.518	0.000
LMφ	−3.159	0.000	−4.153	0.000	−5.135	0.000

Note: Models are run with a maximum of five factors.

TABLE 6 Results of CUP-FM and CUP -BC Tests, DV: EFP.

Variables	CUP-FM	CUP-BC
EFI	−0.125***	−0.115***
T-value	[−3.578]	[−3.837]
FIC	−0.237***	−0.168***
T-value	[−4.128]	[−3.636]
DIG	−0.052***	−0.015**
T-value	[−3.315]	[−2.153]
EFI*DIG	−0.136**	−0.296***
T-value	[−2.326]	[−5.159]
GDP	0.362***	0.418***
T-value	[4.152]	[3.357]
URB	0.120*	0.113**
T-value	[1.937]	[2.056]

Note: ***Significant value at 1%, **significant value at 5%, *significant value at 10%. EFP: ecological footprints, EFI: energy efficient infrastructure, FIC: financial inclusion, DIG: digitalization, GDP: gross domestic product, URB: urbanization.

Table 6 reflects that DIG decreases EFP by −0.052% in Cup_FM and −0.015% in Cup_BC estimators, respectively. These coefficients are significant at 1% and 5%, confirming that digital technologies are environmentally beneficial in the ASEAN region. Because more advancement in the form of digitalization would help in mitigating environmental pollution by reducing transportation cost, efficient utilization of both natural and human resources, growing awareness about ecological concerns and creating more dependency on those technologies which are environmentally friendly (Belkhir and Elmeligi, 2018). However, the ecological aspect of digital technologies is yet to explore in various regions for which only a limited literature justification has been observed. For example, Caglar et al. (2021) have explored the role of information and communication technologies in dealing with the ecological footprint of the top-ten polluted economies. Similary, Huang et al. (2022) examined the dynamic association between information and communication technologies, renewable energy, and EFP for E-7 and G-7 economies during 1995–2018. The results show that ICT significantly reduces the EFP in both panel economies. Kahouli et al. (2022) have focused on Saudi Arabia and explored that technology trade and EFP are significantly and negatively linked.

The current study has also examined the moderating role of DIG on the relationship between EFI and EFP for ASEAN economies. The results show that the direct effect of EFI is significantly negative under both of the stated models, with relative coefficients of −0.125 and −0.115. However, with the interactive term (EFI*DIG), the coefficients tend to reflect higher magnitudes as −0.136 (Cup_FM) and -0.296 (Cup_BC), respectively. It implies that the effect of energy-efficient infrastructure with digitalization would also help in controlling environmental damages In recent years, both energy-efficient infrastructure and advancement in digital technologies have their primary concern to deal with climate change and environmental sustainability, and economies are shifting towards productive and low-cost technologies and energy sources.

Finally, our findings report that both economic growth and urbanization are causing more ecological damage in the form of footprints. More specifically, Table 6 shows that a 1% increase in GDP causes an upward shift of 0.362% in EFP under Cup_FM and 0.418% under Cup_BC. Although several benefits like the development of infrastructure, reduction of poverty, and improvement in the living standards of the individuals are linked with economic growth; however, it also has environmental fallouts. Emerging economies are trying to increase their economic growth while compromising on their natural resources, leading to severe environmental challenges (Danish et al., 2020). Danish et al. (2019) investigate whether economic growth, bio-capacity, and human capital have their role in determining the EFP. Their empirical findings show that economic growth and biocapacity are promoting the EFP. However, there is no causal association between the both. Mahmood et al. (2020) have also shared similar findings. They claim a long-term relationship exists between economic growth and EFP. Murshed et al. (2022) empirically investigate the impact of economic growth, energy usage, and foreign investment on EFP for South Asian economies. They claim that expediting economic growth is immensely imperative for reducing the EFP in the selected region.

On the other side, the results show that URB tends to increase EFP by 0.120% and 0.113% in both of the stated models. URB is also regarded as a socio-economic transformation resulting from individuals' migration from rural to urban areas. As stated under the study background, a dramatic shift in the URB has been observed for the ASEAN economies due to economic expansion and physical extension of areas. It has increased the utilization of natural resources and resulted in a higher level of natural footprints. Similar results are endorsed by Salman et al. (2022) and Nathaniel (2021). These findings contrast with Gupta et al. (2022), who claim that economic growth and URB reduce the EFP in Bangladesh.

5 Conclusion and implications

The significance of economic growth and rapid industrialization in ASEAN economies have increased both the opportunities for the standard of living and environmental costs. However, saving energy consumption and advancing energy efficiency are among the efficient ways to deal with climate change. In this regard, different economies have made remarkable efforts to improve energy efficiency, such as energy conservation, under which energy efficiency is classified as an essential plan. An improved financial system and related products are also greatly helpful in mitigating the changing climate prejudice. Financial systems would help to provide efficient credit facilities, specifically in the form of green and clean financing and renewable energy that leads to lower fossil fuel consumption. This study assessed the long-term association between efficient energy infrastructure, financial inclusion, digitalization, and ecological footprints in ASEAN members during 1980–2019. Initially, the findings confirm cross-sectional dependency, stationarity properties, slope heterogeneity, and panel cointegration. The findings through CUP-FM and CUP-BC confirm that energy-efficient infrastructure, digitalization, and financial inclusion significantly reduce ecological footprints. In contrast, economic growth and urbanization are found to be the core drivers of EFP. Digitalization offers a multiplier effect in stimulating the positive influence of energy-efficient infrastructure on ecological footprints. Based on these findings, following are a few policy recommendations:

1) The results demonstrate that energy-efficient infrastructure is an imperative tool to deal with ecological consequences. Thus, it is suggested that ASEAN members should introduce and promote those projects having energy saving and efficient indorse outputs. One possible solution might be formulating an energy conservation and energy efficiency working group based on the pattern followed by BRICS economies during 2017, under which energy efficiency is highlighted as an integral plan. Such workings groups are well known for improving energy efficiency and efficient utilization of natural resources through joint research on strategic reserves and clean energy.

2) An effective financial system, policies, and products are necessary for which the financial system may act as a sound financial intermediary. Integrating the environmental objectives with the financial development of the entire financial system through green and clean financing, renewable energy investment proposals, and micro-credit to install clean energy sources for households would be a sustainable solution.

3) As the efficient extraction of natural resources depends upon skilled human force and utilization of digital and advanced technologies, ASEAN countries should adopt a policy to accelerate digital technologies to improve environmental health through effective extraction of resources with low ecological footprints. Moreover, it is also suggested that these economies should stimulate innovative solutions through research and development funds toward a green economy.

Lastly, future studies would explore the other indicators of energy infrastructure and distribution separately in line with the government energy transition policies. Regional comparison and its impact on green growth can also be viewed. Several other factors influence ecological sustainability, such as energy investment, policy stringency, and existing energy sources, etc. These factors will be explored in a multivariate framework of energy infrastructure.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: Data will be made available upon reasonable request.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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