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The role of knowledge-based economy on environmental pollution: The case of selected asian countries

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Abstract

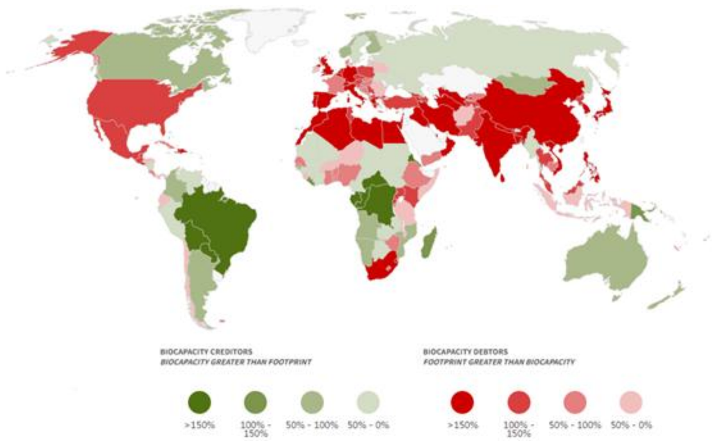
In recent decades, Asian countries have faced increasing environmental challenges with rapid economic growth, increasing urbanization, and rapid industrialization. This study examined the role of factors affecting the ecological footprint of selected Asian countries, with an emphasis on the components of a knowledge-based economy such as improving the quality of governance, technological development, and innovation. Due to the cross-sectional dependence (the existence of connections between the countries under study), the Panel-Corrected Standard Errors (PCSE) method was used. The results of the PCSE model estimation for the period 2002 to 2022 showed that the variables quality of laws, corruption control, and agricultural share in the labor force have the greatest impact on the ecological footprint. Also, factors related to the knowledge-based economy such as corruption control and quality of laws, the share of exports of single goods in total exports, and innovation (domestic patents) can increase the ecological footprints in the absence of efficient environmental policies. Hence, moving towards a sustainable knowledge-based economy requires directing innovations towards green technologies, improving energy efficiency, and implementing environmental protection policies along with institutional and technological development.

Keywords: Corruption control, ecological footprint, panel-corrected standard errors (PCSE), quality of governance

INTRODUCTION

Pollution has widespread impacts on the economies of countries through the effects of environmental pollution on human health, and its role in reducing investment because of government supervision and regulations[1,2,3]. It also reduces labor productivity and the overall production productivity of the economic sectors[4-14]. Environmental pollution is because of the overall pattern of human consumption and exploitation of natural resources. Given the widespread impact of pollution on human health, quality of life, and environmental sustainability, and to understand the roots and consequences of pollution more deeply, this study focuses on the state of the ecological footprint of societies. The ecological footprint is a comprehensive indicator of human pressure on the Earth's biological capacity, which shows the amount of energy, resource consumption, and carbon dioxide absorption compared to the planet's natural reproductive capacity. An increase in the ecological footprint reflects excessive consumption and, as a result, an intensification of environmental pollution[15,16]. Therefore, examining this index can provide a more complete picture of the state of sustainability of society and its relationship with the level of pollution.

The long-term trend from the 1960s to 2023 shows that the global per capita ecological footprint has steadily exceeded the biocapacity, leaving the planet in an ecological deficit[17]. The state of the world's ecological balance shows that most of the Asian continent (especially East and Southeast Asia) has a significant deficit due to the increased consumption of ecological resources. The spatial distribution of the ecological deficit is not uniform, and the central parts of this continent have a greater deficit intensity[17]. Therefore, it is necessary to examine the factors affecting the difference in the ecological footprint in this continent.



Ecological Deficit/ Reserve 2025.

In recent decades, four main factors (international trade, energy consumption, agricultural practices, and population dynamics) have been identified as the main drivers of the increase in the ecological footprint. However, recent structural changes have necessitated the emergence of a new fundamental factor. The knowledge-based economy is considered as one of the important solutions based on innovation, technology, and human capital to reduce negative environmental impacts[18]. The knowledge-based economy is a model that pursues economic growth through the

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production and application of knowledge, new technologies, information infrastructure, and capable human capital. This model can reduce environmental pollution by "improving resource efficiency, replacing traditional technologies with clean technologies," "increasing institutional capacity and data-based policymaking for environmental management"[18,19,20].

This study attempts to analyze the relationship between knowledge-based economy indicators and the ecological footprint of the environment using data from selected Asian countries and provide empirical evidence for policy directions at the regional level.

Traditionally, economic development, energy consumption, and population growth tend to expand the ecological footprint. While the emergence and development of the knowledge-based economy as a new paradigm provides the potential to mitigate these detrimental effects.

Background

The knowledge-based economy is based on the production, distribution, and application of knowledge and innovation for economic growth and unlike traditional growth patterns, relies on intellectual assets and clean technologies instead of relying on physical and energy-intensive resources[21]. Theoretically, this type of green model can change the course of the economy from a "polluting growth" model to a "clean and sustainable growth" model by increasing resource efficiency, improving green production processes, and developing renewable energies[22]. According to the theoretical framework of the Porter Hypothesis, technological innovation resulting from investment in knowledge and research and development (R&D) not only reduces environmental costs, but also creates a new competitive advantage for countries[21,23]. In this context, the use of smart technologies, artificial intelligence, and digitalization of processes leads to a reduction in energy and raw material consumption per unit of production, and as a result, the ecological footprint is reduced[24,25,26].

In addition, the theoretical framework of the knowledge-based economy also emphasizes the role of human capital. Skilled human capital, freedom to research and innovation, and efficient educational structures are key factors in the transition of economies towards green models[21,27]. The existence of these infrastructures makes firms move towards the use of clean technologies, smart resource management, and environmentally friendly design. Hence, countries with higher levels of human capital and technological innovation tend to have lower ecological footprints[28,29]. From an empirical perspective, Guan *et al.*[28] showed that technological innovation and knowledge-based investment in G10 countries have a significant negative effect on the ecological footprint of tourism. Rafique *et al.*[29] also reported that in countries with high economic complexity, increasing human capital and research and development can moderate the effects of economic growth on environmental degradation.

Agricultural sector

A large part of the active population in developing countries is engaged in agriculture. Agriculture in these countries is mostly traditional, and their population is dependent on agricultural activity for their livelihood and essential needs. Unfavorable economic and social conditions lead farmers to solutions having further environmental degradation, and along with further environmental degradation, poverty also increases. So that low-income countries remain permanently in the poverty net[30,31]. On the other hand, agricultural practices also have a negative impact on the environment and exacerbate environmental degradation[32,33]. Among the measures taken in agriculture are monoculture or concentrated cropping systems instead of diversified cropping[34], use of fertilizers and pesticides, high energy consumption[35], water consumption, livestock farming and provision of animal feed and methane emissions resulting from this activity[32,35], and deforestation to increase agricultural land[36,32], which cause environmental degradation and increase the ecological footprint.

In contrast, within the framework of sustainable development, agriculture cannot be a source of environmental pressure but also acts as part of the solution to reduce the ecological footprint[37]. Sustainable agriculture, relying on green technologies, biodiversity, and resource efficiency seeks to produce more with minimal environmental damage. The use of methods such as crop rotation and multi-crop farming, the use of biological inputs instead of chemical fertilizers and pesticides, smart irrigation, and renewable energies on the farm reduce energy consumption and greenhouse gas emissions[38,39]. Precision Agriculture also optimizes the use of inputs and increases production efficiency by using data and digital technologies[40]. These processes increase the ratio of production to resources consumed, and as a result, the ecological footprint of each unit of production is reduced[37].

In addition, carbon sequestration in the soil and maintenance of vegetation through conservation agriculture can offset some of the carbon emissions[41,42]. Furthermore, the results of the study by York *et al.*[43] showed that the agricultural sector has a lower ecological footprint than the industrial and service sectors, especially if agriculture is mechanized or industrialized.

Population

Population growth increases the ecological footprint through increased demand for resources and their consumption. Also, with the increase in population and urbanization rates, land use changes and waste production increases. As the results of the studies by Sharma *et al*[44], Abd Kadir *et al*[45], Nathaniel[46], Yousaf *et al.*[47], Chen *et al.*[22], Rafique *et al.*[29] in 10 countries of economic complexity, Aziz & Sarwar[48] and Zhou *et al.*[49] in Silk Road countries in the field of population and Majeed *et al.*[50] showed that the age composition of the population, such as the rate of population concentration and urbanization, has a positive effect on the ecological footprint and causes deterioration in environmental quality. In contrast, studies such as Kazemzadeh *et al.*[51], Qurat-ul-Ann & Noreen[52] and Khan *et al.*[8] in top 10 manufacturing countries reported the negative effect of urbanization because of expanding the use of renewable energy, increasing the efficiency of economic activities, and moving towards cleaner technologies and increasing energy efficiency.

Energy consumption

The amount of energy consumed is not only a reflection of the level of economic activity, but its type and source also play a decisive role in the pressure on the environment[53]. In countries where most of the energy is supplied by fossil fuels, high energy consumption leads to increased greenhouse gas emissions, destruction of natural resources and growth of the ecological footprint[54-56]. In contrast, the development of renewable energies and the use of energy-efficient technologies can reduce energy intensity and, as a result, reduce environmental pressure[57]. In general, the positive relationship between energy consumption and the ecological footprint indicates that economic development leads to an increase in the use of biological resources and the absorption capacity of nature without improving energy efficiency or changing the consumption structure towards sustainable resources[58]. Theoretically, the studies of Sharma *et al.*[44]; Kazemzadeh *et al.*[51]; Alqaralleh[59]; Rafique *et al.*[29] pointed out the positive role of fossil fuels and fossil fuel consumption on greenhouse gas emissions and ecological footprint.

Trade openness (Trade liberalization)

In addition to being affected by domestic economic developments, each country's environment is also subject to changes in foreign trade. This interaction of the environment with foreign trade is mainly achieved through trade liberalization. In fact, some of the main criticisms of the environmental Kuznets curve are its lack of attention to the trade patterns, while trade pattern resulting from the pollution hypothesis is proposed as one of the main reasons for the reduction of pollution in high-income countries and the increase in pollution in low-income countries. Grossman & Krueger [60] divided the effects of trade liberalization on the environment into three effects: scale effects, composition effects, and technology effects. The scale effect represents a change in the size of economic activities, the composition effect represents a change in the mix or basket of goods produced, and the technology effect represents a change in production technology, especially the move towards clean technology. Hence following trade liberalization, scale effects tend to increase environmental degradation, and the technology effect tends to reduce environmental degradation. The composition effect also depends on the type of comparative advantage. So, considering the comparative advantage in a country, if a country has an advantage in the production of polluting goods, then the composition effect leaves negative effects on the environment by changing the mix of goods produced by the country towards polluting goods[18,27,61].

If, due to a country's comparative advantage in clean goods, the composition of that country's manufactured goods changes towards clean goods, then the composition effect will have positive effects on the environment. The results of studies by Uddin *et al.*[62] in polluting countries, Naqvi *et al.*[63] in high- and upper-middle-income countries, Ansari & Khan[64] in Asian countries, Okelele *et al.*[65] in Southern African countries, Kızılgöl & Öndes[66] in 31 OECD countries, Cutcu *et al.*[67] in developing countries, Alqaralleh[59] in 4 ASEAN countries, Pata *et al.*[68] in BRICS countries show that trade liberalization has a negative effect on environmental pollution. In contrast, studies by Jiang *et al.*[69], Ansari & Khan[64] in the developed countries with complex economies, Khan *et al.*[8] in top 10 manufacturing countries, Guan *et al.*[28] in the G10 countries, and Rafique *et al.*[29] in the 10 countries with complex economies indicate a positive effect of trade liberalization on the ecological footprint and environmental pollution.

In recent years, several studies have examined the factors affecting the ecological footprint in different countries. Jiang *et al.*[69] in their studies on APEC countries and 96 countries in the world showed that income inequality and import diversity reduce environmental quality, and globalization and export diversity increase it; also, in the long run, agricultural employment and population density have a negative effect on the ecological footprint. Kazemzadeh *et al.*[51] showed with a quantile panel model that GDP, non-renewable energy and population cause environmental degradation, while urbanization, export quality and trade openness have a reducing effect. In BRICS countries, according to Sharma *et al.*[44], diversified imports and industrial production

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increase the ecological footprint, but renewable energy consumption has the opposite effect. Guan *et al.*[28] stated in G10 countries that tourism, globalization and economic growth exacerbate environmental pressure and reduce its technological innovation. In African countries, Okelele *et al.*[65] found that trade openness reduces the ecological footprint, but foreign investment increases it and there is an inverted U-shaped relationship with income. Kızılgöl & Öndes[66] confirmed the validity of the environmental Kuznets curve in OECD countries and showed that urbanization and GDP have an increasing effect, while natural resource rents, FDI and trade freedom have a decreasing effect.

Rafique *et al.*[29] found in Economic Complex Countries that growth and trade increase the ecological footprint, but human capital and renewable energy reduce it. Pata *et al.*[68] in BRICS countries showed that increased production exacerbates pollution, but innovation has no significant effect. In Silk Road countries, Zhou *et al.*[3] identified population, exports, and foreign investment as increasing factors and urbanization as decreasing factors. Finally, Alqaralleh[59] found that energy consumption causes environmental degradation in ASEAN countries, while economic growth, free trade, and human capital reduce the ecological footprint. Overall, the findings show that economic growth, industrialization, and non-renewable energy consumption are the main drivers of increasing the ecological footprint, and technological innovation, renewable energy, human capital, and trade freedom are the most important factors reducing it.

Empirical model

The implicit panel model in the study of selected Asian countries is as follows:

$$EF = F\,(\text{Tradeopp, Energy, Popden, Agrilabor, Ferti, Hightech}) \qquad (1)$$

In relation (1), each of the variables EF, Tradeopp, Energy, Popden, Agrilabor, Ferti, Hightech respectively represents the ecological footprint (in global hectares per capita), the trade freedom index (percentage of trade volume to GDP), population density

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(number of people per square kilometer), the energy consumption index (per $1,000 of GDP), the share of the agricultural sector in the country's labor force, fertilizer consumption in the agricultural sector, and the knowledge-based economy index (including the variables of the share of exports of medium and high-tech products in exports, corruption control, quality of laws, access to the Internet, and the number of domestic patents).

Due to the nature of the information used in this section, it is necessary to perform a Cross-section Dependence test to select an appropriate unit root test before testing the stationarity (reliability) of the combined (panel) data. There are various tests to examine the stationarity of panel data variables, and selecting the appropriate test among them requires examining the existence of cross-sectional independence in the first step[70]. Cross-sectional independence means that the data used for each section do not have any dependence on the data used for other sections. However, according to economic theories, the behavior of economic agents may lead to a type of dependence between them[71]. Dependence between sections may exist due to factors such as regional and economic connections, mutual dependence of uncalculated residuals, and unusual factors not observed between different sections. Pesaran[72] showed that if cross-sectional correlation is ignored, the estimation results will be biased. There are tests such as Breusch-Pagan and Pesaran's cross-sectional independence[73,74] to investigate this issue, and in this study, Pesaran's cross-sectional independence test was used. This test is applicable to balanced and unbalanced panels and provides reliable results for small cross-sectional dimensions (N) and time dimensions (T). It is also resistant to the occurrence of structural failures in the regression coefficients of each cross-sectional unit. The null hypothesis of this test implies cross-sectional independence.

In the presence of cross-sectional dependence, the use of common methods for assessing the reliability of panel data, such as Levin, Lin & Chu, Im, Pesaran and Shin, Hardi and Fisher, will be associated with errors[75] and will increase the likelihood of false unit root results. To overcome this problem, panel unit root tests are used that take cross-sectional dependence into account, such as the Cross-sectionally Augmented Dickey-Fuller (CADF) Unit Root Test. If the reliability of the variables under study is not the same, their cointegration can be examined using the Westerlund[76] test. The null hypothesis of this test is the absence of convergence between the variables under study in the group and panel means.

If there is cross-sectional dependence in the variables under study, Feasible Generalized Least Square (FGLS) and Panel-Corrected Standard Errors (PCSE) models can be used[77]. Both methods are highly efficient in estimating models with problems of autocorrelation and variance heterogeneity and cross-sectional correlation in panel data and are widely used[78]. The PCSE method is developed based on the generalized least squares (GLS) model, but its main difference is in the way the covariance matrix of the error terms is estimated.

Unlike FGLS, this method does not require a complete and accurate estimate of the covariance matrix, but rather, by using robust estimates of the variance and covariance of the errors, it corrects the standard deviation of the coefficients in such a way that the statistical results are valid and reliable even in the presence of variance heterogeneity and correlation between cross-sectional units. In other words, instead of re-estimating the parameters based on the estimated error matrix as in the FGLS model, the PCSE model takes the coefficients from the OLS or Prais-Winsten estimates and corrects the standard errors[79]. This feature makes the parameter estimates in PCSE more consistent and stable, especially in samples with many cross-sectional units (N) and a relatively limited number of time periods (T) - a situation common in many international econometric studies (such as comparing Asian countries)[80,81]. Beck and Katz[79] also showed that in panel samples with large N and small T, the FGLS method tends to underestimate the error variance, thereby overestimating the t and F statistics and leading to overconfident estimates. In contrast, PCSE provides more reliable and conservative results by directly correcting standard errors.

Data

To investigate the factors affecting the ecological footprint among Asian agricultural countries, information from the top 10 agricultural countries in terms of agricultural value added (including China, India, Bangladesh, Pakistan, Indonesia, Iran, Japan, Thailand, Turkey, Vietnam) in this continent was used during the period 2002 to 2022. The required information was collected from the websites of the Food and Agriculture Organization (FAO) and the World Bank.

RESULTS

The results of the descriptive statistics of the variables examined in Table 1 provide a picture of the considerable diversity among the ten selected Asian economies (including China, India, Bangladesh, Pakistan, Indonesia, Iran, Japan, Thailand, Turkey and Vietnam). The average value of the Ecological Footprint Index, which reflects the amount of resource consumption in global hectares per capita, is estimated to be 2.2. The very wide range of this index (from a minimum of 0.5 to a maximum of 5.2) indicates a strong heterogeneity in the level of resource consumption in this group of countries. Among them, Japan, with the highest index value of 5.16 (and the domestic average of 4.57), has the heaviest ecological pressure. Countries such as Turkey (3.2), Iran (3.12), China (3.01) and Thailand (2.26) also show values higher than the group average.

The average trade openness index is 51 percent. This index, especially in Vietnam (139.69) and Thailand (107.94), indicates the high dependence of the sample economies on foreign trade. In contrast, Japan, with a value of 13.55, has the lowest level of trade openness in the set. In the structure of the labor force, a sharp difference is observed in the share of employment in the agricultural sector; so that the countries of Bangladesh, India and Vietnam employed almost half of their labor force in this sector, while this share has decreased to less than 5 percent in Japan. The average energy intensity index (energy consumed per GDP) for the entire sample is calculated to be 102.1. This intensity of consumption is significantly higher in economies such as Iran (193.49) and China (171.49), while Bangladesh (45.39) shows the lowest energy intensity. In terms of population density, the average group is 308 people per square kilometer. This average is strongly influenced by countries with very high population concentration, such as Bangladesh (1,189.6 people per square kilometer). In contrast, Iran (48.8) and Turkey (98.1) have the lowest population densities in this Asian sample.

The average share of exports of medium and high-tech products in the total exports of the sample is 38.4%. Japan (80.7%), Thailand (61.43%) and China (58.53%) are the leaders in this field, while Bangladesh (2.37%) and Pakistan (9.84%) are lagging in this area.

The average number of patents registered by indigenous people in the sample is 98,643. China and Japan dominate this indicator with more than 600,000 and 291,000 domestic patents, while in Bangladesh this number is only 54 on average.

In the area of digital infrastructure, the percentage of the population using the Internet in 2022 in Japan, Turkey, Vietnam, China, Iran and Thailand has reached 80%. This rate is less than 30% in Pakistan and ranges between 41.6 and 66.5% in Indonesia, India and Bangladesh.

The governance indicators show challenges for most countries; the average corruption control index is -0.4 and the average quality of laws is -0.30. Japan is at the top with a quality of laws index of 1.18 and a corruption control index of 1.41. In contrast, Iran with a quality of laws index of -1.44 and Bangladesh with a corruption control index of -1.1 recorded the lowest values on these measures.

Table 1. Statistical characteristics of the study sample.

Variable	Obs	Mean	Std. Dev.	Min	Max

Ecological Footprint	210	2.2	1.3	0.5	5.2
Merchandise trade share	210	51.0	39.6	8.2	182.4
Energy use per GDP	210	102.1	45.8	37.7	227.1
Employing agriculture share	210	33.4	14.6	3.1	62.0
Population density per sq. km	210	308	317	42	1301
Fertilizer consumption	210	220	122	47	484
Medium and high-tech exports	210	38.4	23.4	1.8	84.2
Patent applications reside	210	98,643	268,139	22	1,456,879
Individuals using Internet of population	210	33.4	27.8	0.1	93.2
Control of Corruption	210	-0.4	0.7	-1.6	1.7
Regulatory Quality	210	-0.3	0.7	-1.7	1.4

(Source: Research findings)

The dependence status of the variables under study is reported in Table (2). The results of Table (2) show that the variables Ecological Footprint, Merchandise trade share, Energy use per GDP, Employing agriculture share, Population density per sq. km, Fertilizer consumption, Medium and high-tech exports, Patent applications resid, Individuals using Internet of population and Regulatory Quality are dependent on each other at different cross-sections and the hypothesis of no dependence between different points is rejected and it is necessary to use a model appropriate to this type of data.

Table 2. Results of the cross-sectional dependence test.

Variable	CD-test	*p*-value
Ecological Footprint	9.09	0.00
Merchandise trade share	5.87	0.00
Energy use per GDP	14.78	0.00
Employing agriculture share	27.58	0.00
Population density per sq. km	19.58	0.00

Fertilizer consumption	6.62	0.00
Medium and high-tech exports	2.66	0.01
Patent applications resid	8.87	0.00
Individuals using Internet of population	27.78	0.00
Control of Corruption	0.86	0.39
Regulatory Quality	2.83	0.01

(Source: Research findings)

Despite the dependence of the cross-sections, the Cross-sectional Augmented Dickey Fuller (CADF) test was used to assess the stationary of the various variables. As can be seen from Table (3), the energy and fertilizer consumption variables are at a stable level, and the remaining variables will become stable with one difference.

Table 3. Stationary of the studied variables.

Variable	in Level			First difference		degree
	t-bar	**critical value 10%**	***P*-value**	**t-bar**	***P*-value**	
Products	-2.056	-2.21	0.167	-3.093	0	1
Merchandise trade share	-1.583	-2.21	0.718	-2.741	0	1
Energy use per GDP	-2.158	-2.21	0.097	-3.281	0	0
Employing agriculture share	-2.152	-2.21	0.101	-2.762	0	1
Population density per sq. km	-1.872	-2.21	0.357	-3.694	0	1
Fertilizer consumption	-2.294	-2.21	0.041	-3.922	0	0
Medium and high-tech exports	-1.928	-2.21	0.292	-3.009	0	1
Patent applications resid	-1.158	-2.21	0.975	-3.138	0	1
Individuals using Internet of population	-1.434	-2.21	0.856	-2.882	0	1
Control of Corruption	-1.369	-2.21	0.889	-2.732	0	1

Regulatory Quality	-1.452	-2.21	0.842	-2.591	0	1

(Source: Research findings)

Before running the PCSE model, Westerlund.[76] panel cointegration test was performed for each independent variable with the dependent variable due to the limitation in the number of observations at each cross-section. The results show that most of the variables are significant in all four statistics Panel alpha (Pα), Panel t (Pt), Group alpha (Gα) and Group t (Gt), which indicates the existence of a long-run relationship between the key variables and the dependent variable. Therefore, the estimation of long-run coefficients using the PCSE model is valid.

Table 4. Westerlund ECM panel cointegration tests result.

Variable	Statistic	Gt	Ga	Pt	Pa
Merchandise trade share	Value	-3.37	-24.37	-8.06	-16.57
	Z-value	3.98	5.93	1.61	4.03
	P-value	0.00	0.00	0.05	0.00
Energy use per GDP	Value	-2.92	-20.21	-7.40	-12.37
	Z-value	2.23	3.95	0.84	1.81
	P-value	0.01	0.00	0.20	0.04
Employing agriculture share	Value	-3.15	-21.81	-8.66	-16.92
	Z-value	3.11	4.71	2.30	4.22
	P-value	0.00	0.00	0.01	0.00
Population density per sq. km	Value	-3.75	-10.64	-5.88	-8.78
	Z-value	5.48	0.60	0.93	0.09
	P-value	0.00	0.73	0.82	0.54
Fertilizer consumption	Value	-2.77	-18.99	-7.42	-13.25
	Z-value	1.64	3.37	0.87	2.27
	P-value	0.05	0.00	0.19	0.01
Medium and high-tech	Value	-2.92	-20.67	-9.05	-17.61

exports	*Z*-value	2.24	4.17	2.76	4.58
	P-value	0.01	0.00	0.00	0.00
	Value	-3.19	-20.01	-7.75	-13.91
Patent applications resid	*Z*-value	3.28	3.86	1.24	2.62
	P-value	0.00	0.00	0.11	0.00
	Value	-3.65	-22.12	-9.51	-14.38
Individuals using Internet of population	*Z*-value	5.10	4.86	3.29	2.87
	P-value	0.00	0.00	0.00	0.00
	Value	-3.82	-30.59	-9.66	-21.04
Control of Corruption	*Z*-value	5.75	8.89	3.47	6.40
	P-value	0.00	0.00	0.00	0.00
	Value	-3.33	-24.17	-8.70	-17.62
Regulatory Quality	*Z*-value	3.83	5.84	2.35	4.59
	P-value	0.00	0.00	0.01	0.00
(Source: Research findings)					

The results of the Panel-Corrected Standard Errors (PCSE) model estimation in Table 5 show that except for the fertilizer consumption variable in the agricultural sector, other variables in the model have a significant effect on the ecological footprint. According to the research findings, internet use and the share of the agricultural sector in the labor force have a negative and significant effect on the ecological footprint, while other variables showed a positive effect. The negative effect of Internet use on the ecological footprint (-0.01) indicates the role of information technology development in reducing pressure on the environment by raising public awareness, improving production efficiency, reducing resource waste, and facilitating access to efficient and low-consumption technologies. Also, the reduction in the ecological footprint in countries with a higher share of the agricultural labor force (the coefficient of the agricultural labor force share variable is -0.1) can be due to a less industrial production structure and lower energy consumption in traditional agricultural activities. So that in countries where a significant part of the labor force is still active in agriculture, the economic structure is less industrial and less energy-intensive, and as a result, energy-based pressure on the environment is reduced. In contrast, institutional and technological variables including corruption control, quality of laws, export of high-tech goods out of total exports, and domestic patent registration have a positive and significant effect on the ecological footprint. These results indicate that although improving governance indicators and expanding innovation are key components of a knowledge-based economy, in the countries studied, these improvements have led to an increase in the ecological footprint due to the expansion of industrial activities and increased energy consumption. Among these variables, the quality of laws with a coefficient of 0.25 and corruption control with a coefficient of 0.17 have the greatest positive impact on the ecological footprint. This indicates that improving governance institutions, in the absence of complementary environmental policies and monitoring of energy consumption, can have unintended environmental consequences.

The variables of trade openness, energy intensity to GDP, population concentration and fertilizer consumption per hectare of irrigated land also showed a positive effect on the ecological footprint. The expansion of international trade is usually accompanied by an increase in production and transportation and can increase energy consumption and environmental pollutants. The results of the studies of Jiang *et al.*[69]; Ansari & Khan[64]; Guan *et al.*[28]; Rafique *et al.*[29] also pointed out the positive effect of trade freedom on the ecological footprint.

The coefficient of the energy consumption intensity variable shows that with an increase of one unit of this variable; the average ecological footprint increases by 0.007 units. High energy intensity also indicates inefficiency in energy efficiency, which directly leads to an increase in the ecological footprint. The results of Sharma *et al.*[44], Kazemzadeh *et al.*[51]; Alqaralleh[59] also show that increasing energy consumption reduces environmental quality. Also, high population concentration puts additional pressure on natural resources and ecosystems, increasing the ecological footprint. The results of Zhou *et al.*[49] also confirm this issue.

Although fertilizer consumption was not statistically significant, its positive coefficient confirms the potential negative impact of this variable on the environment.

Table 5. results of Panel-Corrected Standard Errors (PCSE) model.

Variable	Coef.	Std. Err.	*z*	*P* > *z*
Merchandise trade share	0.007	0.001	9.39	0.00
Energy use per GDP	0.007	0.001	6.87	0.00
Employing agriculture share	-0.07	0.003	-22.84	0.00
Population density per sq. km	0.0001	0.0001	2.47	0.01
Fertilizer consumption	0.0001	0.0002	0.32	0.75
Medium and high-tech exports	0.01	0.002	3.6	0.00
Patent applications resid	0.000001	0.0000001	8.55	0.00
Individuals using Internet of population	-0.01	0.001	-7.4	0.00
Control of Corruption	0.17	0.064	2.57	0.01
Regulatory Quality	0.25	0.102	2.43	0.02
Constant	3.26	0.089	36.44	0.00

(Source: Research findings)

CONCLUSIONS

In this study, the role of the knowledge-based economy, along with other factors, on environmental pollution in selected Asian countries was examined during the period 2002 to 2022. The ecological footprint variable was considered as an environmental indicator and the variables Medium and high-tech exports, Patent applications resid, Individuals using Internet of population, Control of Corruption, and Regulatory Quality were considered as indicators of the knowledge-based economy. Due to the cross-sectional dependence between the countries under study, the PCSE model was used. The findings of the model show that the strong dependence of economies on trade and fossil fuels has increased the ecological footprint. Therefore, policymakers need to target the export of green technology and services instead of growing exports of energy-intensive goods, reduce untargeted fossil energy subsidies, and allocate the resulting income to investment in renewable energies. Also, develop joint clean energy agreements within the framework of Asian cooperation (such as ASEAN and SCO).

The results also showed that increasing fertilizer use increases environmental pollution in the countries studied. Therefore, it is suggested that agricultural subsidies be directed towards low-consumption and sustainable methods. At the regional level, a regulatory framework for the use of chemical fertilizers is designed and Asian countries cooperate in the exchange of bio-fertilizer technologies.

The positive effect of corruption control (increasing ecological footprint) shows that in the countries studied, improving governance without considering environmental requirements has caused economic growth. Therefore, it is necessary that anti-corruption policies should be accompanied by strict environmental regulations and development projects require accurate and transparent environmental assessment (EIA). The negative effect of agricultural employment on the ecological footprint at the panel level shows that traditional agriculture is still relatively less effective than industry in environmental pressure. Therefore, it is suggested that rural green employment be created to reduce widespread migration to cities. The negative impact of the Internet at the panel level suggests that digitalization in the Asian region can be a tool for reducing environmental footprint. Therefore, it is recommended to develop digital infrastructure in rural areas to reduce physical consumption and travel, and governments should adopt a green digital economy as part of national development plans.

The results on patent registrations show that innovation in Asian countries is still mainly serving the expansion of production and industry and has not had a positive environmental impact. Therefore, it is necessary to redirect research and development resources towards green innovations and provide financial and legal support for clean technologies. Also, corruption control should be pursued simultaneously with strengthening environmental requirements so that economic growth resulting from improved governance does not lead to further pressure on the environment.

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Authors' contributions

Conception, design, rewrote and edited the entire text: SH. S;

Collected and analyzed the data: RZ.T;

Contributed to the writing of the introduction and literature review: Z.N;

All authors have made substantial contributions to the conception, design, data acquisition, analysis, and interpretation of the study.

Availability of data and materials

The data used in this study were obtained from the World Bank and FAO. The datasets used and/or analyzed during the current study are available upon request.

AI and AI-assisted tools statement

We used AI-assisted tools to find relevant articles and summarize them. AI-generated text and references were carefully checked to ensure they accurately conveyed the intended message and were factually correct.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

All authors have given their consent for publication.

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