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Impact of Agricultural Technical Efficiency on Farm-Gate Emission: An Implementation of Environmental Kuznets Curve in Asian Developing Countries

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Abstract

The Environmental Kuznets Curve (EKC) explains that economic activities in developing countries, including agriculture, increase environmental damage. Increased technical efficiency is one approach that is frequently suggested for reducing the negative impacts of farming practices. Unfortunately, there are no studies that investigate this at the macro (national) level. This study examines the impact of technical efficiency on farm-gate emissions in Asian developing countries. Data were collected from 25 developing countries in Asia from 1992 to 2021 and were analyzed using frontiers and the generalized method of moments. The findings demonstrate that technical efficiency is insufficient to prevent increases in CO_2, CH_4, and N_2O emissions. This finding is consistent with the EKC. Gas emissions also rise because of gross domestic product (GDP) and population growth. Human development is the only way to prevent a rise in emissions of these 3 gases. Meanwhile, renewable energy and food prices have varying impacts on CO_2, CH_4, and N_2O emissions reduction. Therefore, based on these findings, it is suggested that developing countries increase the utilization of natural production factors and organic farming, improve human capital development, and conduct a wise selection of renewable energy sources.

Keywords: developing countries; food prices; GDP; human development; renewable energy

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INTRODUCTION

Increasing environmental degradation, greenhouse gas (GHG) emissions, and global warming have prompted the entire globe to prioritize efforts to investigate the causes of climate change and devise appropriate policies to minimize its effects (Nugroho et al., 2023). Nearly 200 world leaders convened in November 2021 at the United Nations Climate Change Conference and increased commitments to expedite action toward the Paris Agreement's goals, such as slowing the rate of increase in climate change. Effective adaptation and mitigation actions can significantly reduce vulnerability and contribute to climate resilience by limiting global warming below 1.5 to 2 °C. Common methods are encouraging responsible production and consumption to ensure sustainability (Acevedo-Ramos et al., 2023).

Although the agreement's impact is quite positive, countries will require time to achieve it. In fact, delays in implementing climate change mitigation can have extremely negative implications for ecosystems, land, and food (Hasegawa et al., 2021). Furthermore, climate change has harmed the environment in all sectors, particularly agriculture, which supplies food,

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income, and employment. By 2050, climate change will diminish agricultural productivity (by 2 to 15%) and boost food prices (by 1.3 to 56%) worldwide (Delincé et al., 2015). Climate change is also projected to decrease food production in South Asia by up to 4%, 11%, and 7% by 2030, respectively, for rice, wheat, and cereal grains. Reduced agricultural productivity due to climate change is predicted to put pressure on food prices and food security in the region. Rice, wheat, and other grain prices are expected to rise at substantially faster rates, by up to 10%, 25%, and 45%, respectively (Bandara and Cai, 2014).

The primary cause of climate change and environmental degradation in agriculture is the usage of chemical production factors. For example, enteric fermentation (CH_4) accounts for 23% of all GHG emissions from agriculture. Meanwhile, managed soils and pasture (CO_2, N_2O), rice cultivation (CH_4), manure management (N_2O, CH_4), synthetic fertilizer application (N_2O), and biomass burning (CH_4, N_2O) generate 11%, 8%, 3%, and 1%, respectively (IPCC, 2022). Massive usage of production factors follows the Green Revolution to increase agricultural yield. Indeed, its use surpasses the recommended limits, resulting in residues that harm the environment (Batmunkh et al., 2022). Increased technical efficiency is one approach that is frequently suggested for reducing the negative impacts of farming practices (Ma et al., 2024). Technical efficiency is a method of increasing output-input ratios by optimizing production procedures using existing technology and resources (Věžník et al., 2013; Suwardi et al., 2023). At the same time, efficient land management is a solution to mitigate climate change as agricultural land is increasingly used to provide enough food, feed, fuel, and wood. This activity also requires relatively lower costs than other mitigation efforts and reduces 13 to 21% of total GHG (IPCC, 2022). However, this is not easy due to limited technology in agriculture and a lack of studies at the macro level (Pattiasina et al., 2023). Indeed, failing to control climate change has proven to negatively affect food production, agricultural competitiveness, and employment in developing countries (Nugroho et al., 2023).

This study uses the Environmental Kuznets Curve (EKC) as the main framework for demonstrating that modern economic growth is a mix of high aggregate growth rates, disruptive impacts, and new problems. The relationship between the mass implementation of technological innovation is based on additions to the stock of knowledge that supports high growth rates. Disruptive effects are those caused by rapid changes in economic, social, and environmental structures as an unexpected result of the spread of innovation. However, the EKC theory focuses more on the relationship between environmental degradation, economic development, and other variables since its initial contributions in the 1990s (Kuznets, 1973).

The EKC indicates an ‘inverted U’ relationship between a country’s economic development, specifically its income level and its proclivity to produce certain types of pollution. The idea underlying the EKC is that developing countries prioritize industrial development and basic infrastructure, resulting in a comparatively high tendency for developing countries to emit pollutants. However, as affluence rises, the demand for health and environmental quality and per capita pollution emissions finally fall (Mason and Swanson, 2003). Increased incomes lead to improved environmental awareness, environmental regulation enforcement, cleaner technology, and increased environmental spending, leading to a steady decrease in pollution levels and environmental degradation (Acevedo-Ramos et al., 2023). For example, agricultural activities in developing countries have been proven to increase temperatures in the regions. In developed countries, agricultural activities have the opposite effect, lowering temperatures (Nugroho et al., 2023).

In this study, other factors that have the potential to influence farm-gate emissions are also involved, including natural, economic, and social factors. From a natural point of view, promoting renewable energy consumption is critical for a country’s economic development to reduce emissions (Yao et al., 2019). Economic growth and rising food prices contributed to environmental degradation. Human activity will always rise to generate money and meet essential needs. Similarly, rising food prices provide an incentive for producers to fulfill market demand but overexploit the environment (Abbas, 2022). Socially, an increase in population will raise consumer demand for goods and services, allowing producers to make significant revenues to supply this need. Hence, environmental degradation will worsen because of market participants’ indifference. In contrast to quantity, enhancing human quality will boost environmental concerns (Schneider et al., 2011).

Next, Asia was selected as the study sample because Asian economies are rising at an exponential rate. Simultaneously, several new industrial countries arose in Asia, most notably China and India. China's share of world output climbed from 4% in 2002 to 15% in 2017. India's contribution to the global gross domestic product (GDP) more than doubled in the same period, rising from roughly 1.5 to 3% (Gopalan et al., 2020). However, environmental damage tends to increase due to changes in the economic structure of urbanization and the shift from agriculture to industry. This activity is intended for mass production and to fulfill rising demand. This then declined as the economic structure shifted from energy-based sectors to technology-based industries and services (Grossman and Krueger, 1995).

Meanwhile, developing countries were chosen because they are in a race against time to increase GDP while also dealing with high population growth. Environmental degradation in developing countries becomes increasingly severe at the early stages of growth as society modifies economic, social, and environmental systems, increasing demand for natural resources (Ahmed et al., 2022). The situation in developing countries may deteriorate and render them unable to adequately adapt to climate change because political and economic conditions are often unstable and conservation policies are rarely successfully implemented (Imamoglu, 2019).

Based on this description, an important question arose: can technical efficiency lower farm-gate emissions in Asian developing countries? This research aims to investigate the impact of technical efficiency on farm-gate emissions in Asian developing countries. The hypothesis is that technical efficiency is insufficient to reduce farm-gate emissions in Asian developing countries since the EKC has indicated that economic activity will increase environmental damage in developing countries.

MATERIALS AND METHOD

Data source and variable

This study employed panel data, combining the time-series and cross-sectional data to prove the hypothesis of this study. The time-series data in this study are from 1992 until 2021 and the cross-section data are from 25 Asian developing countries: Bahrain, Bangladesh, China, India, Indonesia, Iran, Iraq, Jordan, Kazakhstan, Kuwait, Kyrgyzstan, Lao PDR, Malaysia, Myanmar, Nepal, Pakistan, Philippines, Qatar, Saudi Arabia, Sri Lanka, Syria, Tajikistan, Thailand, Turkiye, and Vietnam. This study will use several variables and data sources, as shown in Table 1. The main challenge of this study is the incomplete data that is accessible from many international data provider institutions. Hence, the study only uses a small number of countries and variables.

Data analysis

The data were analyzed using frontiers and the generalized method of moments (GMM). Frontiers were used to assess the TE. The stochastic frontier analysis (SFA) model is assumed to have the form of the Cobb-Douglas equation. SFA was chosen because it captures non-negative random errors (effects of inefficiency) and symmetric random errors that are noise (random traditional mistake) from the estimated function, bringing it closer to actual conditions (Aigner and Chu, 1968). SFA in this study is estimated using the maximum likelihood estimation (MLE) approach, with the primary principle of maximizing probability, which changes into natural logarithm form as Equation 1 (Battese and Coelli, 1992).

$$\begin{aligned}\ln GPI_{it} = {} & \beta_0 + \beta_1 \ln NIT_{it} + \beta_2 \ln PHO_{it} + \\ & \beta_3 \ln KAL_{it} + \beta_4 \ln MAN_{it} + \beta_5 \ln PES_{it} + \\ & \beta_6 \ln IRRI_{it} + \beta_7 \ln EMP_{it} + V_{it} - u_{it} \quad (1)\end{aligned}$$

Where V_{it} is the random error of the model and u_{it} is a random variable that represents the technical inefficiency of the *i*-country sample at the *t*-period.

The term "technical efficiency" refers to the quantity of output that can be generated in a process of production by employing specified inputs. The agricultural TE of each country (*i*) per year (*t*) is estimated using Equation 2.

$$TE_{it} = \frac{GPI_{it}}{GPI_{it}^{*}} = \frac{\exp(\beta X_{it} + V_{it} - u_{it})}{\exp(\beta X_{it} + V_{it})} = \exp(-u_{it}) \quad (2)$$

Where X_{it} = production factors in a country per year, V_{it} = external factors in a country per year, u_{it} = the effect of technical inefficiency in a country per year.

The second analysis was GMM, which was used to determine the impact of TE on farm-gate emissions/EMS (CO_2, CH_4, and N_2O). Other explanatory variables were also used in this analysis as detailed in Table 1. GMM analysis was used since this study employs a persistent time-series with a short number of periods.

Table 1. Variable and data source

Variable	Symbol	Source
Gross production index number (2014-2016 = 100)	GPI	FAO (2023)
Nutrient of nitrogen for agricultural use (ton)	NIT	FAO (2023)
Nutrient of phosphate P_2O_5 for agricultural use (ton)	PHO	FAO (2023)
Nutrient of potash K_2O for agricultural use (ton)	KAL	FAO (2023)
Manure applied to soils (kg)	MAN	FAO (2023)
Pesticides for agricultural use (ton)	PES	FAO (2023)
Land area equipped for irrigation (ha)	IRRI	FAO (2023)
Employment in agriculture, forestry, and fishing (000 person)	EMP	FAO (2023)
Technical efficiency	TE	Index, calculated by the author
CO_2 emission in farm-gate (kt)	EMS CO_2	FAO (2023)
CH_4 emission in farm-gate (kt)	EMS CH_4	FAO (2023)
N_2O emission in farm-gate (kt)	EMS N_2O	FAO (2023)
Renewable energy (% total consumption energy)	REN	World bank (2023)
GDP growth (%)	GDP	World bank (2023)
Food price index	FPI	World bank (2023)
Total population (000 person)	POP	World bank (2023)
Human development index	HDI	World bank (2023)

Furthermore, the GMM estimator can eliminate country-specific effects and then use all available lagged levels as instruments. Hence, the GMM estimator with first differentiation is the appropriate choice for this study.

The first step in this analysis was the unit root test to eliminate spurious regression. The unit root test used in this study was Levin Lin Chu (LLC). Then, the GMM was utilized to solve serial correlation and heteroscedasticity concerns in panel data. The GMM can be defined as follows using a system of Equation 3 (Baltagi, 2005).

$$EMS_{it} = \beta_0 + \beta_1 EMS_{it-1} + \beta_2 TE_{it} + \beta_3 REN_{it} + \beta_4 GDP_{it} + \beta_5 FPI + \beta_6 POP + \beta_7 HDI + \alpha_t + U_{it} \quad (3)$$

Where U_{it} is the random term and $U_{it} = \eta_i + v_{it}$. It also considers ΔEMS_{it-1} as instrument for EMS_{it-1} (Equation 4).

$$\Delta EMS_{it} = \beta_0 + \beta_1 \Delta EMS_{it-1} + \beta_2 \Delta TE_{it} + \beta_3 \Delta REN_{it} + \beta_4 \Delta GDP_{it} + \beta_5 \Delta FPI_{it} + \beta_6 \Delta POP + \beta_7 \Delta HDI + \Delta U_{it} \quad (4)$$

The GMM must pass several post-estimation tests to be valid: 1) the Arellano-Bond test to detect the presence of second-order serial autocorrelation (Baltagi, 2005), and 2) the exogeneity (Hansen and Sargan) test checks all instruments are exogenous or valid as a group (Sargan, 1958).

RESULTS AND DISCUSSION

From 1992 to 2021, all Asian developing countries in this study witnessed a rise in TE (Table 2). Kuwait had the greatest gain in efficiency, at 8.66 times. Bahrain (3.41 times), Lao PDR (3.17 times), and Vietnam (2.49 times) also witnessed remarkable increases in TE. Traditional agricultural exporters noticed advances in TE as well: China (2.12 times), India (1.95 times), Indonesia (1.77 times), Malaysia (1.70 times), and Thailand (1.47 times). Meanwhile, Kazakhstan witnessed the smallest gain in TE (1.04 times). TE in developing countries increases as counseling frequency increases. Continuous counseling helps improve farmers' rationality in terms of production inputs, practices, and openness to adopt innovation. TE will also rise when technology for agricultural purposes becomes more widely available (Pattiasina et al., 2023).

After the TE value for each country per year was obtained, it was used as an explanatory variable for farm-gate emissions. The first thing performed was a unit root test. The results of the LLC unit root test show that TE, REN, GDP, FPI, and HDI are stationary at level (Table 3). Meanwhile, EMS CO_2, CH_4, N_2O and POP are stationary at 1st difference.

The findings of the analysis demonstrate that TE is insufficient to prevent increases in EMS CO_2, CH_4, and N_2O. Gas emissions also rise because of GDP and POP. HDI is the only way

Table 2. Agricultural TE of Asian developing countries

Year	Bahrain	Bangladesh	China	India	Indonesia	Iran	Iraq	Jordan	Kazakhstan
1992	0.2779	0.5080	0.4085	0.4678	0.5209	0.4510	0.6921	0.4032	0.8238
1993	0.3010	0.5113	0.4395	0.4779	0.5292	0.4709	0.8026	0.3481	0.7495
1994	0.2600	0.4977	0.4560	0.4933	0.5313	0.4786	0.7889	0.3954	0.6818
1995	0.2824	0.5097	0.4949	0.5061	0.5781	0.4974	0.8065	0.4096	0.5476
1996	0.2833	0.5381	0.5163	0.5231	0.5952	0.5322	0.8132	0.3782	0.4899
1997	0.3417	0.5461	0.5319	0.5329	0.5655	0.5282	0.8013	0.3865	0.4638
1998	0.3721	0.5557	0.5553	0.5453	0.5669	0.5913	0.8428	0.4385	0.4312
1999	0.3513	0.6139	0.5795	0.5669	0.5681	0.5504	0.8180	0.3896	0.5370
2000	0.3833	0.6402	0.6056	0.5627	0.5939	0.5500	0.8050	0.4587	0.5049
2001	0.3408	0.6256	0.6147	0.5781	0.6020	0.5638	0.8803	0.4116	0.5924
2002	0.3741	0.6317	0.6344	0.5415	0.6364	0.6446	0.9188	0.5073	0.5843
2003	0.3427	0.6454	0.6379	0.5947	0.6634	0.6629	0.8018	0.4816	0.5932
2004	0.3137	0.6255	0.6688	0.5925	0.6969	0.6524	0.8361	0.5583	0.5869
2005	0.3178	0.6895	0.6879	0.6209	0.7138	0.7171	0.8540	0.5807	0.6227
2006	0.3743	0.7132	0.6992	0.6535	0.7364	0.7322	0.8620	0.5656	0.6754
2007	0.3693	0.7471	0.7137	0.7098	0.7384	0.7907	0.8373	0.5745	0.7296
2008	0.3875	0.8081	0.7484	0.7280	0.7717	0.6302	0.7765	0.5877	0.6680
2009	0.4265	0.8018	0.7583	0.7038	0.7878	0.6830	0.7928	0.6245	0.7462
2010	0.4043	0.8273	0.7689	0.7508	0.8228	0.7059	0.8719	0.7021	0.6727
2011	0.5258	0.8446	0.7875	0.7848	0.8415	0.7068	0.9047	0.7163	0.8338
2012	0.7083	0.8452	0.8046	0.7983	0.8541	0.7366	0.9043	0.7063	0.7092
2013	0.8561	0.8529	0.8106	0.8279	0.8587	0.7506	0.9287	0.7393	0.7772
2014	0.8426	0.8632	0.8168	0.8361	0.8569	0.7690	0.9234	0.7930	0.7761
2015	0.9115	0.8732	0.8344	0.8272	0.8613	0.7737	0.6621	0.8449	0.7990
2016	0.9330	0.8711	0.8310	0.8463	0.8561	0.7820	0.6570	0.8658	0.8370
2017	0.9550	0.8984	0.8364	0.8719	0.9111	0.7490	0.6336	0.8204	0.8547
2018	0.9577	0.8980	0.8410	0.8877	0.9222	0.6993	0.6138	0.8586	0.8691
2019	0.9478	0.8868	0.8407	0.8954	0.9135	0.7389	0.8832	0.8238	0.8535
2020	0.9401	0.8960	0.8444	0.9025	0.9217	0.7032	0.9334	0.8536	0.8675
2021	0.9479	0.9061	0.8644	0.9125	0.9219	0.6776	0.8811	0.8517	0.8605

Year	Kuwait	Kyrgyzstan	Lao PDR	Malaysia	Myanmar	Nepal	Pakistan	Philippines
1992	0.1081	0.6581	0.2983	0.4999	0.4112	0.4978	0.4143	0.5895
1993	0.2302	0.6171	0.2652	0.5359	0.4295	0.5449	0.4339	0.6053
1994	0.3005	0.5583	0.2991	0.5381	0.4509	0.5229	0.4517	0.6240
1995	0.3887	0.5269	0.2759	0.5518	0.4474	0.5675	0.4853	0.6220
1996	0.3972	0.5778	0.2891	0.5583	0.4766	0.5646	0.4828	0.6668
1997	0.4720	0.6272	0.3330	0.5705	0.4661	0.5809	0.4827	0.6742
1998	0.5070	0.6638	0.3570	0.5501	0.4733	0.5873	0.5056	0.6259
1999	0.5043	0.7254	0.3931	0.5863	0.5365	0.6038	0.5241	0.6851
2000	0.5211	0.7506	0.4370	0.6073	0.5697	0.6412	0.5291	0.7062
2001	0.5171	0.7856	0.4403	0.6182	0.5964	0.6562	0.5227	0.7295
2002	0.5553	0.7653	0.4860	0.6340	0.6079	0.6676	0.5258	0.7500
2003	0.6094	0.7486	0.4851	0.6805	0.6476	0.6869	0.5459	0.7742
2004	0.6086	0.7614	0.5020	0.7204	0.6808	0.7107	0.5871	0.7954
2005	0.6624	0.7454	0.5199	0.7489	0.7725	0.7231	0.6015	0.8031
2006	0.4971	0.7640	0.5316	0.7774	0.8118	0.7551	0.6147	0.8205
2007	0.5310	0.7597	0.6011	0.7755	0.8268	0.7310	0.6402	0.8481
2008	0.5116	0.7797	0.6735	0.8124	0.8880	0.8202	0.6801	0.8737
2009	0.8517	0.8146	0.6377	0.7906	0.9121	0.8178	0.6934	0.8755
2010	0.6176	0.7970	0.7332	0.8044	0.9047	0.8226	0.6922	0.8700
2011	0.8495	0.8076	0.7352	0.8558	0.8864	0.8550	0.7382	0.8788
2012	0.8688	0.7879	0.8056	0.8633	0.8941	0.8947	0.7354	0.8953
2013	0.8632	0.8116	0.8012	0.8593	0.9154	0.8743	0.8487	0.8857
2014	0.8809	0.8209	0.9154	0.8595	0.9130	0.8907	0.8274	0.8972
2015	0.8629	0.8751	0.9251	0.8844	0.9142	0.8905	0.8222	0.8948
2016	0.9059	0.8626	0.9286	0.8531	0.9066	0.8990	0.8340	0.8829

Table 2. Agricultural TE of Asian developing countries (*Continue*)

Year	Kuwait	Kyrgyzstan	Lao PDR	Malaysia	Myanmar	Nepal	Pakistan	Philippines
2017	0.9134	0.8788	0.9135	0.8876	0.9000	0.9123	0.8658	0.8912
2018	0.9241	0.8716	0.9145	0.8724	0.7710	0.9171	0.8533	0.8920
2019	0.9298	0.8676	0.9214	0.8696	0.7661	0.9278	0.8800	0.8854
2020	0.9288	0.8726	0.9283	0.8678	0.7763	0.9372	0.8938	0.8785
2021	0.9366	0.8501	0.9460	0.8483	0.7780	0.9396	0.9135	0.8724

Year	Qatar	Saudi Arabia	Sri Lanka	Syria	Tajikistan	Thailand	Türkiye	Vietnam
1992	0.5563	0.5544	0.5659	0.7178	0.4344	0.5642	0.5216	0.3608
1993	0.7135	0.5641	0.6408	0.6574	0.3887	0.5515	0.5114	0.3800
1994	0.7385	0.5688	0.6858	0.6931	0.3782	0.5737	0.5296	0.3961
1995	0.8102	0.5332	0.6895	0.7467	0.3460	0.5699	0.5218	0.4127
1996	0.8000	0.5181	0.6603	0.8224	0.2928	0.5898	0.5555	0.4365
1997	0.6629	0.5622	0.6953	0.7522	0.3233	0.5965	0.5435	0.4574
1998	0.5509	0.5853	0.7101	0.8746	0.3012	0.5784	0.6020	0.4830
1999	0.6023	0.5515	0.7219	0.7828	0.2840	0.5986	0.5803	0.5218
2000	0.6267	0.5730	0.7480	0.8670	0.3205	0.6547	0.5864	0.5500
2001	0.4802	0.6466	0.7235	0.8535	0.3585	0.6713	0.5716	0.5604
2002	0.5542	0.6329	0.7413	0.9099	0.4089	0.6741	0.5962	0.5966
2003	0.5036	0.6548	0.7420	0.9005	0.4260	0.7033	0.5994	0.6188
2004	0.5201	0.6847	0.7373	0.9091	0.5116	0.6718	0.5964	0.6482
2005	0.5033	0.6908	0.7750	0.9231	0.5153	0.6801	0.6235	0.6558
2006	0.4670	0.6971	0.7718	0.9329	0.5304	0.6985	0.6386	0.6782
2007	0.5364	0.7061	0.7673	0.9059	0.5538	0.7474	0.6024	0.7041
2008	0.4614	0.7146	0.8201	0.8732	0.5850	0.7474	0.6395	0.7316
2009	0.5195	0.6880	0.7947	0.9104	0.6362	0.7658	0.6447	0.7476
2010	0.5012	0.7065	0.8601	0.8868	0.6356	0.7588	0.6683	0.7686
2011	0.5312	0.6873	0.8489	0.9154	0.6617	0.8047	0.7034	0.7927
2012	0.5733	0.6667	0.8642	0.8934	0.7380	0.8465	0.7377	0.8309
2013	0.7105	0.7226	0.8859	0.8016	0.7892	0.8632	0.7551	0.8444
2014	0.5973	0.6361	0.8612	0.9013	0.7756	0.8396	0.7409	0.8569
2015	0.7976	0.6978	0.8848	0.9256	0.9146	0.8008	0.7760	0.8698
2016	0.7599	0.7186	0.8671	0.9208	0.8970	0.8210	0.7751	0.8664
2017	0.7558	0.7828	0.8197	0.7530	0.9207	0.8327	0.8132	0.8724
2018	0.8960	0.7996	0.8593	0.7364	0.9378	0.8522	0.8203	0.8853
2019	0.8807	0.8515	0.8778	0.8265	0.9534	0.8388	0.8410	0.8811
2020	0.9275	0.9077	0.9036	0.8675	0.9528	0.8137	0.8583	0.8841
2021	0.9297	0.9064	0.9206	0.7720	0.9489	0.8317	0.8632	0.8989

to prevent a rise in emissions of these 3 gases. Meanwhile, REN and FPI have varying impacts on EMS CO_2, CH_4, and N_2O reduction (Table 4).

This year's EMS has increased because of EMS last year. This shows that EMS in Asian developing countries continues to increase over time. China's agricultural sector was the highest contributor to global active EMS CH_4 in 2014, accounting for 5.42% of global gross emissions. Agriculture-activated EMS CH_4 in India accounted for 5.42% of total global gross emissions in 2001. The rise in EMS in both countries was driven by increases in primary inputs per capita (Cheng et al., 2023).

Handling EMS in developing countries is also likewise fraught with financial constraints, limiting the role of society and the private sector. Several policies have also been issued to address EMS from agriculture, such as environmentally friendly product certification, promoted subsidies for low-emission products (such as crop and livestock production), and taxes per unit of carbon dioxide and other GHGs for various products. However, many countries, including developed ones, have rejected it, citing problems in monitoring farm-level emissions related to land use patterns and livestock production (Blandford and Hassapoyannes, 2015).

The increase in TE did not result in a reduction in EMS in Asian developing countries. These findings are consistent with a study from Khatri-Chhetri et al. (2023) that increasing TE in agricultural production can reduce EMS intensity but not total EMS. Continuous TE in Asia boosts economic growth and long-term development. Increasing the structural organization of production processes, efficient use of inputs, and management competency can help to increase Asian agricultural TE (Adom and Adams, 2020). The key issue is that most of the production factors employed in developing countries are chemicals, which leave residues that disrupt environmental sustainability (Prasada et al., 2021). Furthermore, when seen globally, increasing agricultural yields by improving TE can reduce emissions because new land is not required. This will be more successful when agricultural methods are carried out organically, which has been demonstrated to result in the conservation of biodiversity above and below the ground, absorbing carbon in trees and soil to minimize CO_2 emissions and counteract climate change (Timsina, 2018). Meanwhile, in the Asian example study, the increase in TE is not only tied to the use of chemical production inputs (fertilizer, water, and machinery) but also related to land expansion, which has the potential to produce EMS (Khatri-Chhetri et al., 2023). Thus, the findings of this study support the hypothesis.

The relationship between REN and environmental damage, including gas emissions, is indeed U-shaped. At different times, the amount of technology has an impact on emissions both positively and negatively (Yao et al., 2019). This also happened in this study where REN can reduce EMS CO_2 and EMS N_2O but it was discovered that REN was not able to lower EMS CH_4. Asian developing countries may have reached the point of economic growth (structural effects) when the use of REN is most effective in lowering EMS CO_2 and N_2O, but this is not the case for EMS CH_4. The potential for REN development in developing countries is enormous because of the varied sources (sun, wind, water, and geothermal) and the large area of land availability for the cultivation of biofuel crops (Fekete et al., 2021). The use of REN reduces environmentally harmful residues such as EMS. However, REN in Asia is frequently made from plants, thus, it is grown on a large scale, over-exploiting the environment and leaving behind residue that pollutes the natural environment, such as EMS CH_4.

The rise in EMS is being driven by an increase in GDP. The increase in GDP in developing countries is carried out through excessive exploitation of nature and food demand. Increased economic development (gross domestic product, financial development, value-added, and export) led to higher EMS, average temperature, and climate change (Han et al., 2021). There is also a significant relationship in the short and long term between the increase in carbon emissions with the agricultural value-added in China (Rehman et al., 2021). Li et al. (2016) reinforced it by stating that this situation increases reliance on the environment, puts a strain on natural resources, and makes it difficult to maintain a sustainable ecosystem. Asian countries have emission-reduction plans that are in step with industrial expansion. Kazakhstan and Tajikistan, for example, prioritize energy industry modernization, efficiency, and diversification by giving incentives for REN sources (Pfeiffer and Hepburn, 2016). However, this does not appear to apply to agriculture, and therefore, an increase in GDP will still increase EMS. Aside from that, it is impossible to halt economic activity because it would have a variety of bad consequences for human life (Batmunkh et al., 2022).

FPI can enhance EMS CO_2 and CH_4 while decreasing EMS N_2O. Increasing FPI is an incentive for business actors to produce more agricultural products, either by exploiting existing resources or adding production factors, especially land. According to Agboola et al. (2021), there is a significant positive relationship between total country natural resource exploitation and EMS CO_2 in developing countries. The same phenomenon occurs in Sub-Saharan African countries, where natural resource exploitation increases EMS CO_2 (Adedoyin et al., 2020) and other pollutant emissions over time (Asongu et al., 2020). A study by Pang et al. (2021) looks deeper into the short and long-term relationships between FPI and EMS. When FPI rises, people may choose to reduce their intake temporarily. This condition harms market demand, which in turn decreases agricultural supply and EMS (like N_2O). However, agricultural product consumption will not decrease in the long run since living

Table 3. LLC unit rote test

Variable	Level	Sign.
EMS CO_2	1st difference	-12.3164***
EMS CH_4	1st difference	-6.9764***
EMS N_2O	1st difference	-10.8286***
TE	At level	-3.4672***
REN	At level	-1.7974**
GDP	At level	-6.5407***
FPI	At level	-81.4611***
POP	1st difference	-9.5663***
HDI	At level	-5.6067***

Note: *** = ($\rho < 0.000$), ** = ($\rho < 0.01$)

Table 4. Determinant factors of farm-gate emission in Asian developing countries

Variable	CO_2		CH_4		N_2O	
	Coefficient	Std. error	Coefficient	Std. error	Coefficient	Std. error
EMS (-1)	0.7878***	0.0001	0.9094***	0.0006	0.8047***	0.00003
	(7244.317)		(1592.416)		(31684.97)	
TE	138.0980**	48.2635	333.0610***	25.6109	17.3804***	0.0844
	(2.8613)		(13.0047)		(205.9638)	
REN	-126.6050***	1.0887	1.6491***	0.2743	-0.1708***	0.0046
	(-116.2900)		(6.0122)		(-37.2436)	
GDP	18.1896***	0.1766	0.5539***	0.1074	0.0923***	0.0018
	(103.0271)		(5.1594)		(49.9071)	
FPI	2.9305***	0.0364	0.0260***	0.0085	-0.0012***	0.00005
	(80.5821)		(3.0737)		(-21.8638)	
POP	0.0363***	0.0001	0.0005***	0.0001	0.00009***	0.0000004
	(252.4380)		(5.6740)		(266.5489)	
HDI	-655.8115***	198.1922	-737.2785***	128.5269	-35.7977***	0.3753
	(-3.3090)		(-5.7364)		(-95.3740)	
AR(1)		0.9107		0.9783		0.1869
AR(2)		0.9315		0.9816		0.3434
Hansen and Sargan prob.		0.2913		0.8872		0.2545

Note: *** = ($\rho < 0.000$), ** = ($\rho < 0.01$)

standards rise and so will food consumption, leading to an increase in EMS. Another point of view is that when the FPI rises, agricultural product supply will be concentrated on fulfilling market demand. Hence, the supply of REN from crops will decline, while EMS will rise once more (Yue et al., 2020).

Increased POP causes an increase in EMS. The economic activity is greater, which is caused by the more POP, and therefore, the probability of residues and pollutants that are harmful to the environment is also higher (Warsame et al., 2022). Large POP also stimulates high food demand, causing the government and food industry entities to maximize agricultural land exploitation. According to Erokhin et al. (2020), agriculture in Asian countries has low competitiveness since it still employs outdated technologies and consumes a lot of energy, causing EMS production to rise. A similar situation exists in Latin America, where the increase of POP has resulted in the emergence of EMS. Brazil's EMS CO_2 increased significantly between 2010 and 2015, owing mostly to population growth (18.6 Mt). During the same period, population growth in Chile increased EMS CO_2 by 4.0 Mt (Peng et al., 2024).

The sole element in this study that can lower EMS is HDI. Human capital development benefits from increased knowledge and awareness of environmental quality. At the macro level, climate-smart technological and institutional innovation, as well as stakeholder collaborations, improve farming households' resilience to climate change in developing countries (Das et al., 2023). The higher the HDI, the more people a country will have who can develop environmentally friendly technologies, practice low-emission agricultural production, select environmentally friendly agricultural products, carry out waste processing (recycling), and perform agricultural policies for a sustainable environment (Aydin et al., 2023). The government in developing countries can also create policies that combine climate-smart agricultural innovation with institutions to ensure decent livelihoods for farming households and improve resilience to climate change (Nugroho et al., 2023). Countries with a greater degree of human development also utilize more energy from renewable sources that are more environmentally friendly. The usage of REN in Mediterranean countries by 1% results in a 1.902% reduction in EMS CO_2 (Dradra and Abdennadher, 2023). In countries with a high HDI, the ability to maintain the environment is the cause of a long, healthy life and a decent standard of living. Developed countries also practice welfare, which is a necessary condition for environmental sustainability and can be a good lesson for Asia developing countries (Ahmad and Satrovic, 2023).

This study provides the following recommendations based on the findings: 1) assess the utilization of agricultural production factors because TE cannot control EMS CO_2, CH_4, and N_2O. Natural production factors and organic farming must be considered in Asian developing countries so that the residue produced supports environmental sustainability; 2) improve human capital development, especially education and environment literacy, so that people are more aware of environmental sustainability in the face of fast population growth in developing countries and global desire for green economic growth; and 3) select REN sources wisely so that they do not harm the environment. Because bioenergy (from crops) is produced through the overexploitation of nature, Asian developing countries might pick sun, wind, and water energy, as well as geothermal energy.

CONCLUSIONS

Agricultural TE, GDP growth, and population growth have all contributed to higher EMS CO_2, CH_4, and N_2O in Asian developing countries. This condition is consistent with the EKC theory, which states that economic activity in developing countries creates environmental degradation due to excessive resource exploitation, rising food demand and prices, and inefficient use of energy. The only method to minimize emissions in Asian developing countries is to raise the HDI through education, environmental awareness, the use of environmentally friendly technologies, and good institutional quality. This study is limited by the inability to employ all developing Asian countries as the study samples due to a lack of data. Future studies could utilize additional databases to select samples from all Asian developing countries. If possible, the other researchers can compare the conditions of developing and developed countries.

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