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Moving toward sustainable agriculture: The nexus between clean energy, ICT, human capital and environmental degradation under SDG policies in European countries

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ABSTRACT

The United Nation's adaptation of the 2030 sustainable Development Goals (SDG) agenda has swung the attention toward sustainability. However, in achieving SDGs, this study investigates the nexus between agricultural productivity, renewable energy, ICT, human capital, CO_2 emissions, and natural resources in a panel of ten European Union (EU) countries from 1996 to 2019. Our study uses the panel autoregressive distributed lag (ARDL) model of the Pool Mean Group (PMG) to estimate the long-run and short-run effects and heterogeneous causality approach. The empirical results ratify that a 1 % upsurge in the coefficient of renewable energy, ICT, and human capital increases agricultural productivity by 0.174 %, 0.030 %, and 2.158 % in the long run. Whereas, CO_2 emission and natural resources decrease agricultural productivity. Finally, various causality exists among variables for EU countries. Our empirical results for the EU countries are notionally reliable and offer important policy implications accordingly.

1. Introduction

In recent years, the concept of "sustainability" which incorporates economic, social, energy, and environmental dimensions has become a main challenge worldwide. To ensure global prosperity and a sustainable future for humanity by 2030, the United Nations introduced the Sustainable Development Goals (SDGs), which focus on sustainable agriculture and economic growth, clean and efficient energy, and innovations [1]. In recent years, many countries have struggled to maintain the balance between environmental performance and economic growth in order to achieve the SDGs, but global warming and climate change are drifting countries away from this ideal track of sustainability. The main factors that contribute to environmental degradation include alterations to the biophysical surroundings, fertilizers based on fossil fuels in agriculture, deforestation, traditional agricultural machinery, and biodiversity loss [2,3]. The Intergovernmental Panel on Climate Change (IPCC), in 2019, proposed that agriculture and global food demand such as utilization of land, food production, and consumption by technologies and population growth emit greenhouse gas (GHG) emissions [4].

The agriculture sector is the backbone of the economy for nations and is the main source of income generation and employment opportunities. Most of the people, in particular rural areas, depend on the agriculture sector for better standards of living and sufficient food security. The demand for food is growing rapidly due to the increasing populace, which has increased agriculture production, and consequently leads to increases in CO_2 emissions. However, due to the connection between agricultural transformation and modernization, GHG emissions and CO_2 emissions become major challenges for EU countries [5,6]. Agriculture contributes 19%–29 % of global GHG emissions including food systems, burning of crop residues, and livestock [7]. [8] argues that agriculture adversely influences on environment through traditional

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energy consumption, conventional machinery used for production, transportation procedures, chemicals, and fertilizers. Thus, it is necessary to accomplish a balance between agricultural productivity and the growing food demands to meet the two primary goals of food security and sustainable agriculture. For this, the role of climate change mitigation is considered important in the agriculture sector through cleaner agricultural methods such as animal manure as compared to artificial fertilizer and replacing fossil fuel energy with renewable energy sources (RE) [9,10].

In the agriculture sector, an important factor, energy is used for irrigation, used in machinery for fertilization, and transportation of the products. However, an adaptation of renewable energy is a surrogate and potent key to reinforcing food security and environmental quality for sustainable agriculture. In 2020, according to the European Commission, the EU nations' proportion of RE (production + gross import) was 22 %, 2 % more than the 20%-by-2020 level [11,12]. Renewable energy sources can be divided into multifold forms including solar, wind, geothermal, and hydropower, etc., Renewable energy sources for agricultural tasks for instance, solar and wind energy may be used for multiple purposes such as heating, cooling, and spray irrigation as well as eliminating CO_2 emissions. In addition, hydrogen energy can be used for storage, heat, and electricity production in the agriculture sector. Geothermal power is another source of renewable energy that could warm dirt in farmland and parched farm products, whereas hydropower can be used for electricity generation, irrigation, and availability of water [13]. This generated electricity from clean utilization of renewable energy sources could help to operate heavy machinery in the processing of agriculture production that leads towards sustainable agriculture goals.

Besides the development of clean energy, technological innovations play an important role in the agriculture sector. Technology innovation can be defined as the creation and utilization of new patents, recent production techniques, and technologies, that support the high-value-added creation of goods [14]. Technological innovation significantly affects three factors social, economic, and environmental performance. On the other hand, this innovation goes through a technology life cycle, which can be divided into three steps: invention (creation or development of new ideas); innovation (adaptation and implementation of the original innovation and making it ready for use); diffusion (spread or dissemination of new idea, products by individuals, different channels and organizations [15]. However, technological innovation in the agriculture sector is a crucial driver of modern productivity for more sustainable and green agricultural development. In the agriculture sector, it helps to increase yield per year, farmers can use and check accurate data for making decisions to increase the quality of products as well as lessen harvest losses. The utilization of innovation and natural resources in the agriculture sector increases the production process and ensures food security. There are many emerging technologies including, robotics, wearable sensory innovations, drone innovation ICT, etc., that can help farmers to achieve accurate data and higher productivity to maintain sustainable agriculture. However, technological innovation is a proxy of Information and Communication Technology (ICT) used in this study. ICT decreases pollutant emissions, improves energy security, and implements the development of the agriculture sector [16,17]. Moreover, ICT is helpful for firms and households in making assessments with low costs and substantially boosts their productivity. In 2050, it is expected that the world's population will increase to 9 billion people, which will put further strain on resources and increase the demand for food, therefore, a 70 % surge in food production will be necessary to sustain that populace [18]. However, there is a need for structural changes in agri-food systems to increase more sustainable productivity.

This study includes human capital because it is considered an important factor in contributing to higher labor productivity and development [19]. Human capital is known as the utilization of knowledge in the creation of goods, skills, abilities, and creativity that people invest in and amass throughout their lifetimes. However, sustainability in agricultural productivity cannot be attained without erudite and skillful human capital. Societies' willingness to adopt environmentally friendly and efficient technologies in agricultural sustainability is stimulated by human capital that increases productivity [20]. However, for a sustainable agri-food system, a new sort of knowledge-intensive system, information, skills, and technologies are needed. Exploring the impacts of human capital on farmers' capacity to adapt to new technology in specific circumstances, including swings in demand, space limitations, and environmental concerns [21]. The literature suggests that human capital helps in improving the agricultural sector and ambient quality, however, this present study explores the influence of human capital on agricultural productivity. The literature on the impact of human capital and agricultural productivity is limited and shows dissent.

Moreover, this study is critical in achieving SDGs to assess to which extent these goals are supported to bring transformation towards sustainability. However, SDG 7 (ensure availability of modern and clean energy for all); SDG 9 (establish strong infrastructure and nurture innovations); and SDG 13 (immediate action against climate change) are directly related to our study and effective solution to achieve the sustainable agricultural development in EU countries; and SDG 15 (cease land deterioration and sustainable use of resources). This study aims to explore the influence of renewable energy, ICT, human capital, CO_2 emissions, and natural resources on agricultural productivity in a panel of ten EU countries under the SDG framework.

Why did we select EU countries in our paper? The EU countries are the world's largest agricultural producer and consumer, main trade partner and contender in the international market, as well as a major dominator of investments in technologies and clean energy. Agricultural production in EU countries accounted for approximately 52.8 %, 9.5 % of its total exports more than imports and 1.3 % of GDP in 2020. Despite its importance, agriculture has indirect environmental influences such as cropland fires leading to large amounts of CO_2 emissions, resulting in deforestation and reduction of soil erosion. However, sustainable agriculture is the priority of EU countries for economic development as well as in achieving the SDGs. Sustainable agriculture means lessening water pollution and carbon dioxide (CO_2) emissions, providing strong and healthy food, and reducing poverty. According to the World Economic Forum (WEF, 2022), 40 % of the region's land mass is currently responsible for 10 % of agriculture GHG emissions in the EU, and major crops decreased by 6.3 %–21.2 % because of CO_2 emissions. Moreover, around 22.6 % of people who lived in rural areas were at risk of poverty or social alienation in 2019 [22,23]. Therefore, any shift to assist the implementation of free-environmental technologies and strategies related to sustainable agriculture needs to be engaged in these countries.

Given this background, sustainable agricultural productivity is of key importance for contributing to the literature on the energy and environment field. However, this present study examines the impact of renewable energy, ICT, human capital, CO_2 emissions, and natural resources on agricultural productivity in ten European Union (EU) countries from 1996 to 2019, which is still an under-researched area. The novel idea is to improve sustainable agriculture production through clean energy, innovations, and human capital that can also benefit the environment in EU countries. Although the study [24]analyzed the determinants of agricultural production that have been evaluated in ASEAN countries, for the context of EU countries with additional variables ICT and human capital the literature is scant. Thus, our study addresses the significant contributions to the current literature. First, unlike earlier works, this study analyzes for the first time the energy-environment-agriculture nexus with human capital and ICT in EU countries, the importance of ICT and human capital on agriculture productivity has less been given attention in developed countries. Second, this study evaluates long-run and short-run estimations of underlying parameters on agriculture production for the full panel and for the individual regions, which will provide some strategies based on the empirical results. Third, robust tests employed in this study on the combined effects of independent variables renewable energy, ICT, human capital, CO_2 emissions, and natural resources on agricultural productivity; which is commonly ignored in the previous works. Fourth, we use the panel autoregressive distributed lag (ARDL) model of Pool Mean Group (PMG) to analyze long-run and short-run results and the panel heterogeneous [25] test to validate the causality directions among selected indicators.

The rest of the study is structured as follows: section 2- exhibits the main empirical literature, section 3- documents the model estimation, data, and methodology, and section 4 offers the final results and discussion. Finally, section 5 ends with a conclusion and appropriate policy implications as well as offers some suggestions for additional research.

2. Literature review

This section discusses the renewable energy-agriculture-environment nexus with additional factors human capital and ICT. The literature is categorized into four main segments: the renewable energy-environment and agriculture nexus; ICT and agriculture relationship, the human capital-agriculture nexus, and the natural resources and agriculture nexus.

2.1. Renewable energy-environment and agriculture productivity

Conventional energy causes environmental pollution and negatively influences the agricultural sector; deploying clean and efficient energy can provide social, economic, and environmental benefits [26]. Several researchers have studied the relationship between renewable energy and other series including environmental degradation [27–30] and economic growth [31–35] concluded that renewable energy technologies eliminate carbon emissions. Other studies [35,36] in BRI countries' CO_2 emitter economies assessed the influence of sustainable and unsustainable energy on CO_2 emissions and found that the utilization of clean energy can help to improve environmental quality.

There are some substantial kinds of literature examining the nexus between RE-environment-agricultural with paradoxical outcomes. For instance Ref. [37], uses the quantile autoregressive distributed lag (QARDL) model to investigate the connection between economic growth, forest area, agriculture production, renewable energy, and CO_2 emissions in Pakistan. The results indicate that RE and forest areas negatively affect CO_2 emissions in the long term and agriculture production has an inverse influence in the short term but in the long run. Similarly, another study analyzes that the utilization of agricultural land for crop production increases CO_2 emissions [38,39] employs FMOLS and variance decomposition analysis in South Asian economies from 1990 to 2018 and concluded that agricultural productivity reduces CO_2 emissions [40]. scrutinize the role of globalization, renewable energy consumption, and agriculture production on the ecological footprint in emerging countries from 2002 to 2016, and they concluded that agriculture increased environmental degradation. Another study such as [41]evaluates the role of deforestation, renewable power use, trade, and natural resources in agriculture production in Southeast Asian Nations. By using the regression analysis, the results indicate that CO_2 emissions lessen agriculture, but renewable energy significantly improves the agriculture sector [42]. uses the VAR and VECM causality to investigate the nexus among CO_2 emissions, energy usage, agriculture labor, and land production as well as an agricultural commodity in Portugal from 1960 to 2015. The findings reveal that agricultural labor land production and agricultural commodity significantly positive effect on CO_2 emission.

Moreover, other studies have considered the relationship between agriculture and CO_2 emissions with the Environmental Kuznets Curve (EKC) hypothesis and reached mixed results [5,43].determine the impact of RE and agriculture on CO_2 emissions, testing the EKC hypothesis. Their estimated results contradict the validity of the EKC [44]. determined the association between CO2 emissions, real income, energy usage, and agriculture in Russia from 1990 to 2016, and this study concluded that the results support the EKC [45]. explores the agriculture-economic growth-renewable energy nexus on carbon emission in G20 countries from 1990 to 2014. The results are consistent with the EKC. The literature shows that the impact of environmental deterioration and renewable energy on agricultural production has not been extensively studied.

2.2. ICT and agriculture productivity

ICT has a substantial contribution to economic growth and the environment, but it may influence the development and implementation of production in the agriculture sector on the other hand. Several systematic review papers concluded that ICT innovations containing digital ledgers, neural networks, and the Internet of Things (IoT), can increase sustainable agriculture [46]. ICTs can assist the transition to agricultural sustainability by increasing refuge output, reducing incompetence and management costs, and enhancing regulation of the supply food chain [47]. [48]. conduct research in the case of Bangladesh and stated that the deployment of agriculture production in food crops cannot be achieved without the application of ICT [49]. found that ICT has a favorable and considerable impact on the growth of agriculture. Few empirical studies focus on African countries, for instance Ref. [50], examined the role of ICT, real output, and export in the agriculture sector in Sub-Saharan African countries from 1995 to 2017 and concluded that ICT enhances agricultural production in these regions. Similarly, another study [51] determined the effect of ICTs on agriculture in 34 African countries from 2000 to 2011. The findings concluded that ICT significantly improves agriculture production. ICT is the development of knowledge that can effectively and efficiently share knowledge for agricultural production.

2.3. Human capital and agriculture productivity

Sustainable development in agriculture cannot be achieved without knowledge and skills. Human capital is significantly associated with productivity growth as it can improve more effective and efficient operating procedures which may help to increase the farmers' income and environmentally friendly technologies in nations [52]. Several researchers determined the association of human capital and the agriculture sector focus on a single country or developing countries, for example [53], used the ARDL model to examine the role of human capital on agricultural value added in Iran from 1971 to 2007. The findings show that agriculture and human capital have a positively significant link with each other [54]. determine the effects of human capital on agriculture in Senegal, and conclude that there is a positive association between human capital and agriculture. Other studies concluded similar results such as [55–57], yet, the literature on the effect of human capital on agricultural productivity in developed countries is disregarded.

2.4. Natural resources and agriculture productivity

The influence of natural resources on economic growth and environmental degradation is not only prolific to eliminate CO_2 emissions and economic development but also promotes green energy development [58]. It is worth mentioning that several studies draw attention to the relationship between natural resources and CO_2 emissions, for instance Refs. [59,60] and other variables such as economic growth, globalization [61], and renewable energy with different arguments [61–64], but not how natural resources impact on agricultural productivity. Few studies have conceded with mixed findings [65], analyzed the effects of windfalls on agriculture in Sub-Saharan countries from 1991 to 2016, and outcomes indicate that an improvement in the commodity price index resulted in a decline in agricultural productivity. Similarly, another research [66] explored the relationship between oil rents and agriculture growth in Ghana and concluded that an inverse influence of oil rents on agriculture, but these studies failed to analyze the effect of total natural resources rent on agricultural production, yet these studies ignore other natural resource rents.

Summing up the above literature, it is veritable that several studies analyze the renewable energy-environment nexus in individual or multiple economies but no serious study focused on the combined effect of renewable energy-environment nexus on agriculture under the recent variables such as human capital and ICT in the EU countries. Moreover, most of the earlier works focus on individual or developing countries, since developed countries are mostly affected by climate change and agriculture productivity issues. Therefore, the present study fills this gap and presents new and useful policies to the literature.

3. Model specification, data, and methodology

3.1. Theoretical framework and model specification

First, this section needs to address the theoretical underpinnings of the study before moving further with the agricultural growth modeling, as this discussion will assist in our selection of the model variables. The agricultural sector contributes largely to the nation's economic development. For several years, the growth of the global population has been increasing, which drives up global food demand, income, and agricultural production, on the one hand, while, on the other hand, it is reducing global resources [67]. This increased demand for agricultural food production results in huge energy consumption as well as GHG emissions. Most countries rely on fossil fuel energy in their agriculture sector which causes CO_2 emissions and reduces soil fertility.

However, cleaner production methods, which predominately depend on clean and efficient energy (renewable energy) have been introduced to combat these issues. This RE is strongly promoted in different sectors such as transport, building, and particularly the agriculture sector [68]. For this, there is a need for a substantial investment in the implementation of RE production, which leads to an increase the agricultural and economic development. The operational cost of clean energy production is lesser as compared to conventional energy production. Additionally, it must be stated that the cost of energy production is falling as a result of more sophisticated technologies.

Another option to increase modern agricultural development is composed of ICT as it offers farmers data, information, and knowledge, which can lead to farmers with the latest agricultural technology. Moreover, ICT can also lower production costs, boost crop value, and decrease the pesticides for vegetables on their farms [69,70]. However, innovations could result in lowering CO_2 emissions, consuming RE at a lower cost, and increasing agricultural production in the world.

Finally, human capital is the ongoing process of gaining expertise, training, and experience exemplified in the ability to perform workers to produce economic value for the country's economic progress. Further, human capital draws attention to foreign direct investment which leads to increased human capital in the development of its workforce by having higher innovations. However, for better sustainable growth in countries, there is a need for a perfect and vigorous level of capital investment that raises the level of skillful education through training programs in the agricultural sector [71]. Given this, it might be said that renewable energy, human capital, ICT, and natural resources are expected to positively influence agricultural productivity, except for CO_2 emissions. The functional relationship of these variables is as follows:

$$AGP = f(RE, ICT, HCI, NR, CO_2) \tag{1}$$

All the variables can be transformed into natural logarithms for smoothening the data and giving more efficient and reliable findings in the study [72]. By taking the natural logarithm, Eq. (1) can be rewritten as follows:

$$lnAGP = \beta_0 + \beta_1\ ln\ RE_{it} + \beta_2\ ln\ ICT_{it} + \beta_3\ ln\ HCI_{it} + \beta_4\ ln\ NR_{it} + \beta_5\ ln\ CO_{2it}\varepsilon_{it} \tag{2}$$

Here, in Eq. (2) t represents the time (1996–2019), i denotes the countries (1,2, 3 … …N), β indicates the slope of coefficient, ε signifies the error term, β_1, β_2, β_3, β_4, β_5, are the coefficients of carbon dioxide emissions (CO_2), renewable energy use (RE), information and communication technology (ICT), human capital index (HCI), natural resources respectively (NR), AGP is agricultural productivity.

3.2. Data

This study selected 10 EU countries including Austria, Belgium, Poland, Sweden, Germany, Denmark, Spain, Finland, France, and Italy. Annual data is used in this paper for the period 1996–2019. These EU economies were chosen due to the data available for all relevant indicators. Data on agricultural productivity value added per worker (2010 US$), use of renewable energy (% of total final energy consumption), human capital index, information, and communication technology internet users (as the % of the people), CO_2 emissions kilo tons (kt), and natural resources (% of GDP). The data on human capital is collected from the Penn World Table (PWT, 2019), measured in Index, other indicators including renewable energy consumption, information and communication technology, CO_2 emissions, and natural resources are obtained from World Development Indicators [73] provides data on A detailed description of the variables with sources is given in Table 1.

3.3. Methodology

As a synthesis of cross-sectional and time-series data, this study used panel data. Moreover, it offers some advantages compared to time series and cross-sectional data. For instance, i) panel data findings are more reliable and can control the unobservable factors that vary across either unit or over time [74], ii) panel data help to eliminate the estimation bias that may ascend by combining groups into single time series as well as it can archetypal both mutual and discrete behaviors of groups, iii) finally, panel data model covers information, erraticism, and competence as well as it can perceive and ration statical effects compared to other data sets such as time-series and cross-section.

3.3.1. Cross-sectional dependence test

This study uses the cross-sectional dependence (CD) test for two reasons 1) EU countries are interconnected to each other in many ways, for instance, bilateral association, geographic propinquity, political context, and sociocultural and economic development, and 2) to better constructing the empirical model [10]. As the time series is larger than cross-sections (T > N), the Pesaran CD test, introduced by Ref. [75]was used in this study to check the cross-sectional dependence test. The

Table 1
Description of data series.

Variables	Description and unit	Expected Sign	Source Period
AGP	Agriculture, forestry, and fishing value added per worker (Constant 2010US$)	NA	(WDI, 2022) (1996–2019)
RE	Renewable energy (% of the total final energy used)	+	(WDI, 2022) (1996–2019)
ICT	Information and Communication Technology (%)	+	(WDI, 2022) (1996–2019)
HCI	Human capital (Index)	+	(PWT, 2019) (1996–2019)
NR	Natural resources (%)	+/−	(WDI, 2022) (1996–2019)
CO_2	Carbon dioxide emissions (kt)	−	(WDI, 2022) (1996–2019)

equation of the CD test is as follows:

$$CD = \frac{\sqrt{2T}}{N(N-1)}\left(\sum\nolimits_{i=1}^{N-1}\sum\nolimits_{j=j+1}^{N}\left(\hat{\mathrm{O}}_{ij}\right)\right) \tag{3}$$

Here in eq. (3), N represents the number of cross-section, T identify the time series, and $\hat{\mathrm{O}}_{ij}$ indicates the pairwise residual correlation.

3.3.2. Panel unit root tests

In econometric analysis, the order of integration is crucial to avoid spurious regression results. However, this study used a three-panel unit root Augmented Dickey-Fuller (ADF), the PP test, and the cross-sectional Im-Pesaran-Shin (IPS) test developed by Refs. [76–78] to check the stationarity of the variables. Under the null hypothesis, indicators are not stationary, while the alternative hypothesis is the opposite. IPS test consists of intermittent root, which supports a range of autoregressive coefficients and can deviate over cross-sections, whereas, the Fisher-type tests are based on the asymptotic chi-square distribution and allow heterogeneity in the panel [79]. Under the ADF regression, the unit root equation is specified for each cross-section:

$$\Delta y_{it} = (\varnothing_0)\varnothing y_{it-1} + \sum_{k=1}^{qi}\varnothing_{ik}\Delta y_{it-k} + C'_{it}\varphi + \varepsilon_{it} \tag{4}$$

Here in Eq. (4), ε_{it} indicates white noise error term Δ is difference operator, y_{it} is the number of observations for each cross-section N in panel $i=1,2,..,N$ & $t=1,.., T$ signifies period, q_i refers to autoregressive coefficients and C'_{it} indicates independent variables. PP unit root test and IPS test are pooled of ADF test where the null hypothesis of both tests are H_0: $q=0$, (for all i) and the alternative hypothesis is (H_1: $q < 0$) for at least one i.

3.3.3. Panel co-integration tests

After conducting the stationarity of the variables, we can proceed with the panel Johansen Fisher co-integration and Kao cointegration methods [76,80] to investigate the long-run connection among selected elements. According to this method, two or more series are cointegrated if there is a linear combination or any kind of co-movement among them. Fisher-type Johansen method gives better and stronger outcomes in the long run as compared with the conventional panel co-integration method [81]. This method employs two tests, such as the trace test and the maximum eigenvalue (max-eigen) test, to confirm the number of cointegrating vectors. The mathematical equation of Fisher-Johansen cointegration test is specified as follows:

$$\Delta ln\ Y_t = \sum_{j=1}^{k}\Gamma_j\Delta ln\ Y_{t-j} + \prod ln\ Y_{t-1} + \varepsilon_{it} \tag{5}$$

Here in Eq. (5) Y_t *indicates* $n*1$ vector of possible cointegrating variables, $\Gamma,\prod$ are n*n matrices of coefficients on the lagged variables, $\varepsilon_{\mathrm{it}}$ is the error term. The hypothesis for both tests is specified as follows:

H0. r = 0 (no cointegration)

H1. r > 0 (At least one)

3.3.4. Panel ARDL model

This study employs the pool mean group (PMG) panel autoregressive distributed lag (ARDL) model to ascertain the long-run and short-run equilibrium. This method is useful and has several advantages as the ARDL method can be used when factors are stationary at the first difference at *I(1), I(0),* or a mix of both but none of the variables are *I(2* (Liu & Bae, 2018). Panel ARDL model is effective and efficient for small sample data sizes as well and it requires a significant amount of lags to secure a data generation system in general to specific forms. Additionally, the panel ARDL model estimates both short and long-term effects concurrently and provides more effective outcomes [82]. The equation of the panel ARDL model is specified as follows:

$$\Delta lnAGP_{it} = \vartheta_i\left(lnAGP_{i,t-1} + \sigma_i`X_{i,t}\right) + \sum_{j=1}^{p-1}\beta_{ij}\Delta lnAGP_{i,t-j} + \sum_{j=0}^{q-1}p`_{ij}\Delta X_{i,t-j} + \omega_i + \varepsilon_{it}(6)$$

In Eq. (6) the parameter ϑ_{i} is the group-specific speed of adjustment coefficient, σ_{i}, indicates the vector of interest which measures the long-run impact of independent variables renewable energy consumption, human capital, ICT, CO_2 emissions, and natural resources on agricultural productivity. The parameter ($lnAGP_{i,t-1} + \sigma_i`X_{i,t}$) is the error correction speed of adjustment term (ECT) that captures any deviation from the long-run equilibrium relationship. The value of the error correction term is expected to be significantly negative which signifies a return to long-run equilibrium. $\beta_{ij}$, $p`_{ij}$ indicates the short-run dynamic coefficients of explanatory and target indicator, $\varepsilon_{\mathrm{it}}$ indicates the error term, P and q are the optimal lag orders and ω_i represents the constant.

3.3.5. Panel Granger causality test

In the next step, the pairwise Dumitresu & Hurlin (DH) causality test [83] is used in this study to examine the association between selected series. Additionally, to develop effective policy suggestions, it is critical to look at any potential causal relationships between variables as they are connected to dependent variables. This method is the latest procedure because of its flexibility in the heterogeneous panel as well and it generates the most useful and consistent results and is effective in addressing the dependency and heterogeneity that cross-sections exhibit [84]. The DH panel causality model is given as follows:

$$Y_{it} = \varphi_i + \sum_{K=1}^{j}\omega_i^{(q)}iy_{i,t-k} + \sum_{K=1}^{j}\alpha_i^{(q)}ix_{i,t-k}\varepsilon_{i,t} \tag{7}$$

In Eq., (7) $Y_{i,t,}$ and $X_{i,t}$ are two pairwise factors, i and t indicate the cross-section (1,2,3 ….N EU countries) and periods t. φ_i is an individual fixed effect, $\omega_i^{(p)}$ and $\alpha_i^{(q)}$ epitomize autoregressive and regression considerations, which can differ into groups. ε_{2it} Indicate an error term and lag order j is the same for all individuals and the panel must be balanced. Further, the null hypothesis is $H_0 = \alpha i = 0$ whereas, the alternative hypothesis is $H_1 = \alpha i \neq 0.$

4. Results and discussion

4.1. Results

In this empirical analysis, first, the study found the descriptive statistical method of the selected indicators that are given in Table 2. The outcomes disclosed that the highest mean value of CO_2 emissions is 11.934 and ranges from 10.298 to 13.714, demonstrating bulky environmental degradation. Agricultural productivity increased from 8.096 to 11.335, which demonstrates a substantial influence of agricultural productivity on economic growth. Information and communication technology mean value of 3.789 with a minimum of 0.023 and 4.585 maximum value, indicating a great contribution of innovations in development. Similarly, the contribution of renewable energy consumption in sustainable development increased from 0.1384 to 3.968.

Moreover, the study conducts a correlation matrix to check the multicollinearity among the studied variables as shown in Table 3. It is noted that a significant relationship is observed between clean energy and agricultural productivity for the sample period. Similarly, human capital and ICT have a positive correlation with the dependent variable. However, an inverse relationship is seen between natural resources and agricultural productivity while a negative synergy is perceived between carbon dioxide emissions and agricultural productivity. Notably, interpretations drawn from correlation coefficients are not enough, however, this study proceeds further with econometric methods which are

Table 2
Descriptive statistics.

Variables	Mean	Median	Maximum	Minimum	Std.dev	observation
LnAGP	10.292	1.474	11.335	8.079	0.695	240
LNRE	2.607	2.585	3.968	0.138	0.842	240
LNHC	1.153	1.153	1.301	0.943	0.082	240
LNICT	3.789	4.194	4.585	0.023	0.965	240
LNCO2	11.934	12.018	13.714	10.298	0.998	240
LNNR	−1.763	−1.909	1.739	−4.193	1.397	240

Table 3
Correlation results.

Variables	LNAGP	LNRE	LNHC	LNICT	LNCO$_2$	LNNR
LNAGP	1					
LNRE	0.315	1				
LNHC	0.100	0.376	1			
LNICT	0.406	0.483	0.526	1		
LNCO$_2$	−0.444	−0.344	0.013	−0.153	1	
LNNR	−0.349	0.485	0.469	0.181	−0.283	1

more reliable and robust to the objective of the study.

Before proceeding with the ARDL model, this study used (a cross-sectional-dependence test, Panel unit root test, and co-integration test) to explore cross-sectional dependence and unit root among series. The CD test is applied because countries have similar stages of social and economic development. Therefore, the author employed [75] test in this study. The findings of the CD test are shown in Table 4. The results show that at a 1 % significance level, there is the existence of cross-sectional dependence for all series, which means a shock or change in one sample of the country might have a spillover influence on another country. Since we can proceed next method of unit root tests among the series.

Table 5 shows the outcomes of the ADF-Fisher, PP-Fisher, and I'm, Pesaran, and Shin unit root tests. The findings indicate that series are not stationary at a level and stationary at first difference at a 1 % level of significance, signifying that LAGP, LRE, LHC, LICT, CO$_2$, and NR are integrated of order *I(1)*. Next, this study uses an optimal lag selection of the Schwarz Information Criterion (SIC) to select the best lag values. However, the finding indicates the lag selection is 2 as given in Table 6 with minimum values of (−19.49520*) as compared to other criterion lag values. Further, to analyze the cointegration, the variables must be incorporated in a first order, however, all the indicators are integrated in order of *I(1)* in this study.

The panel Johansen Fisher and Kao's cointegration tests can proceed to determine the cointegration association among the indicators as presented in Table 7. Panel Johansen Fisher co-integration test results for both trace and max-eigenvalue. The outcomes disclose the rejection of the null hypothesis of no co-integration H0: (r = 0) at a 1 % significance level, however, all the studied variables are cointegrated in this study. Moreover, this study uses the panel Kao cointegration technique to ensure precision and consistency of results. The findings unveil that indicators are co-integrated and have a stable long-run equilibrium association. This suggests that the null hypothesis is rejected at a 1 % significance level because ADF t-statistics's-value is less than 5 %. However, both co-integration test results support long-run equilibrium connections among agricultural productivity, renewable energy, human capital, ICT, CO$_2$, and natural resources.

Table 4
Results of the cross-sectional dependence test.

Variables	lnAGP	lnRE	lnHC	lnICT	CO	lnNR
Pesaran CD test	27.110	12.059	15.569	5.951	27.110	26.556
P-Value	0.000	0.000	0.000	0.000	0.000	0.000

Note: CD indicates the cross-sectional dependence test, and ^{a}, ^{b},^{c} indicates significance at level 1 %, 5 %, and 10 %, respectively.

Table 5
Panel Unit root tests.

Variables	Level	First difference
Fisher ADF		
LNAGP	10.259	125.341^{a}
LNRE	26.450	74.588^{a}
LNHC	16.204	5.394^{a}
LNICT	24.940	74.280^{a}
LNCO$_2$	26.358	96.091^{a}
LNNR	27.901	135.621^{a}
Fisher PP		
LNAGP	11.930	324.304^{a}
LNRE	10.355	126.349^{a}
LNHC	0.001	73.709^{a}
LNICT	0.898	76.203^{a}
LNCO2	26.469	208.793^{a}
LNNR	22.585	101.754
Fisher IPS		
LNAGP	1.248	10.708^{a}
LNRE	0.318	11.148^{a}
LNHC	2.261	10.307^{a}
LNICT	1.122	6.015^{a}
LNCO$_2$	1.155	7.707^{a}
LNNR	2.249	11.148^{a}

Notes: ^{a}, ^{b},^{c} indicate significance at levels 1 %, 5 %, and 10 %, respectively.

Table 6
The Optimal Lag order selection.

Lag	LogL	LR	FPE	AIC	SC	HQ
0	−876.62	NA	0.000	8.023	8.116	8.061
1	2133.011	5827.741	2.241	−19.009	−18.361	−18.747
2	2354.824	417.4111^{sc}	4.131^{sc}	−20.698^{sc}	−19.495^{sc}	−20.212^{sc}

Table 7
Johansen Cointegration results.

Hypothesized no. of CE(s)	FisherStat*	Prob.	FisherStat*	Prob.	Results
	Trace test		Max Eigenvalue Statistics		
r = 0	449.6^{a}	0.000	239.1^{a}	0.000	Reject H0
r ≤ 1	268.9^{a}	0.000	125.1^{a}	0.000	Reject H0
r ≤ 2	170.0^{a}	0.000	86.59^{a}	0.000	Reject H0
r ≤ 3	101.2^{a}	0.000	61.76^{a}	0.000	Reject H0
r ≤ 4	60.54^{a}	0.000	52.67^{a}	0.000	Reject H0
r ≤ 5	38.11^{a}	0.008	38.11^{a}	0.008	Reject H0
Kao Cointegration results					
ADF	t-statistics	Prob.			
	−2.986^{a}	0.001			

Notes: ^{a} indicate significance at level 1 %.

After the analysis of cointegration, the study uses the PMG model to identify the influence of agricultural productivity on renewable energy, human capital, ICT, CO_2 emissions, and natural resources. The outcomes of the PMG model of the long-run and short-run estimations are represented in Table 8. Regarding the long-run relationship, the results divulge that a 1 % surge in renewable energy, human capital, and ICT increases agricultural productivity by 0.174 %, 2.158, and 0.030 %, respectively. This indicates that renewable energy sources such as solar, wind, hydropower, etc. are the main components in improving the agricultural sector in the long run. However, renewable energy consumption is considered an important factor of production. This outcome is in line with [85], and [86] in ASEAN countries but contradicts the findings of [5] indicating no causal connection between renewable energy and agriculture in 4 ASEAN economies.

The coefficient of CO_2 emissions and natural resources have a significantly inverse influence on agricultural productivity at a 1 % level, which indicates that CO_2 emissions and natural resources reduce agricultural productivity in EU countries. These findings contrast with the outcomes of [87], and [88] and are consistent with ref of [89]. The error correction term is adverse and significant which confirms the long-run association amongst the series.

In the short-run results, natural resources and renewable energy have a positively insignificant influence on agricultural productivity. In contrast, CO_2 emissions, human capital, and ICT are negatively linked with agricultural productivity. Moreover, Table 9 reveals the country-specific short-term results. The findings indicate that renewable energy positively affects agricultural productivity in the short run in Austria, Belgium, Poland, Denmark, Spain, France, and Italy. However, the deployment of renewable energy sources leads to an increase in agricultural productivity and creates new job opportunities in EU countries. Whereas the findings of Sweden, Germany, and Finland have an inverse influence on agricultural productivity, these countries primarily rely on traditional energy sources in the agricultural sector and may have limited investment in the deployment of renewable energy [89].

Human capital is statistically significant in Belgium, Spain, Denmark, and France and negatively influences Austria, Poland, Sweden, Germany, Finland, and Italy. Moreover, the coefficient of ICT is positively significant in Austria, Belgium, Denmark, Spain, Finland, France, and Italy and negatively affects agricultural productivity in Poland, Sweden, and Germany. The estimated coefficient of CO_2 emission is negatively insignificant in Austria and Poland and others have a negatively significant influence on agricultural productivity. The estimated coefficients of natural resources are positively significant in Austria, Poland, Sweden, Denmark, Spain, Finland, and Italy.

Table 10 and Fig. 1 represent the findings of the panel causality test. Bidirectional causation between human capital, ICT, renewable energy, and agricultural productivity. The results also disclosed a one-way causality running from CO2 emissions to agricultural productivity which is also confirmed by Ref. [90]. This means that changes in agricultural production directly cause CO2 emissions in EU countries. In contrast, there is no causal relationship between natural resources and agricultural productivity, which supports the resource curse hypothesis in EU countries. Our outcome is in line with the study of [91] in Sub-Saharan Africa.

Table 8
Panel ARDL long run and short run results.

Variable	Coefficient	Std.Error	T-statistics	P-value
Long Run				
LNRE	0.174^a	0.003	50.779^a	0.000
LNHC	2.158^a	0.010	213.066^a	0.000
LNICT	0.030^a	0.000	44.369^a	0.000
$LNCO_2$	−0.163^a	0.005	−30.064^a	0.000
LNNR	−0.048^a	0.000	−64.714^a	0.000
ECT	−1.165^b	0.521	−2.235^b	0.027
Short Run				
LNRE	0.293	0.418	0.702	0.483
LNHC	−7.679	41.245	−0.186	0.852
LNICT	−0.017	0.175	−0.102	0.198
LNCO2	−0.275	0.338	−0.815	0.416
LNNR	0.080	0.065	1.235	0.219
Constant	10.946^b	4.759	2.299	0.023

Notes: ^{a}, ^{b},^{c} indicate significance at levels 1 %, 5 %, and 10 %, respectively.

Moreover, a robustness check and reliability of the long-run PMG estimator findings are checked by FMOLS and robust least squares (RLS) as given in Table 11. The outcomes demonstrate that most of the series including renewable energy, ICT, human capital, and CO2 emissions are in line with the results of PMG coefficients. The findings of natural resources are unconvincing, showing a positive and insignificant impact on agricultural productivity in the FMOLS model.

4.2. *Discussion*

From the aforementioned literature and the present empirical analysis of our study, several meaningful findings have been concluded regarding the connection between CO_2 emissions, renewable energy use, ICT, human capital, and natural resources with agricultural productivity.

Although the results approve that CO_2 negatively influences on agriculture sector in EU countries, the influence of this factor on agricultural productivity varies by region. Several factors associated with climate change and global warming can changes in precipitation, unsettle food availability and affect its quality, reductions in water accessibility, floods, and droughts all result in a reduction in agricultural productivity. The extensive use of fossil fuels and fertilizers, and emissions from crop and livestock production are the main reasons for CO2 emissions. About one-fifth of the world's CO2 emissions come from agriculture, forestry, and other land use sectors [92,93]. Recently, renewable source of energy has gained more attention than traditional energy sources, having the advantage of improving environmental quality and other economic sectors such as agriculture [94,95].

For instance, in the agriculture sector, renewable energy could be used for irrigation and other factors for agricultural sustainability. Although this present examined the potential of renewable energy utilization to obtain agricultural sustainability in EU countries, the influence of clean energy on agriculture also varies by country. However, the contribution of renewable energy is strongly advocated in the agriculture sector, for instance, the use of solar and wind energy in heating, lighting, product drying, and transferring water for irrigation in the farm field. Concretely, geothermal is one of the main components of renewable energy, which is also used to heat the soil in farms and dry agricultural products. In addition, hydropower is a more useful source of renewable energy for electricity generation, drinking clean water supplies, and irrigation even into fertile land.

On the other hand, in the EU countries, almost all of the nations have plans to boost their use of renewable energy consumption [96]. This study explores the potential of innovations in ICT in the agriculture sector in EU countries and the findings indicate a significant effect on agricultural productivity. However, an increase in ICT can lead to agricultural sustainability by using contemporaneous data on market prices, weather predictions, pest information, plant types, farmers' access to the market, and planting practices [97]. Farmers need to know all this information to enhance their output, make educated judgments about marketing initiatives, and bargain for higher pricing for agricultural products, all of which would ultimately result in market involvement and possible income.

Internet and digitization are important factors in addressing the issues related to the agriculture sector, but it could be done by improving asset management, enabling remote maintenance through environmental scans, and improving logistical control through precise and appropriate weather prognostication and careful scheduling [98]. Additionally, this research confirms the significant relationship between

Table 9
Short-term results of individual countries.

Country	ECT	LNRE	LNHC	LNICT	$LNCO_2$	LNNR
Austria	−0.235^{a}	0.252^{a}	−5.093	0.313^{a}	−0.732	0.164^{a}
Belgium	−0.029^{a}	0.510	0.233	0.897^{a}	−1.779^{b}	−0.139
Poland	−0.162^{b}	1.863^{c}	−1.068^{a}	−0.359^{a}	−0.666^{a}	0.079^{a}
Sweden	−0.165^{a}	−0.349^{b}	−0.565^{a}	−0.289^{a}	−0.299^{b}	0.035^{a}
Germany	−0.057^{b}	−1.067^{b}	−0.823^{b}	−0.186^{c}	−4.989^{c}	−0.613^{a}
Denmark	−0.945^{a}	2.546^{b}	2.219^{b}	0.470^{a}	−0.945^{c}	0.051^{a}
Spain	−0.621^{b}	0.354^{b}	0.284	0.199^{a}	−0.362^{c}	0.010^{c}
Finland	−0.124^{a}	−0.563^{b}	−0.608^{a}	0.140^{a}	−0.405^{a}	0.025^{a}
France	−0.689^{a}	0.350^{a}	0.536^{a}	0.422^{a}	−4.443^{a}	−0.014^{b}
Italy	0.072	0.484^{a}	−0.939	0.396^{a}	−0.041	0.028^{a}

Notes: ^{a}, ^{b},^{c} indicate significance at level 1 %, 5 %, and 10 %, respectively.

Table 10
Causality results.

Null Hypothesis	W-stat	P-value	Decision
LNRE does not cause LAGP	6.940^{a}	1.E−08	LNRE↔LNAGP (Bidirectional causality)
LNAGP does not cause LNRE	3.969^{b}	0.037	
LNHC does not cause LAGP	8.132^{a}	8.E−13	LNHC↔LNAGP (Bidirectional causality)
LNAGP does not cause LHC	3.828^{c}	0.056	
LNICT does not cause LAGP	3.873^{c}	0.050	LNICT↔LNAGP (Bidirectional causality)
LN LAGP does not cause LICT	0.677^{c}	0.052	
LNCO2 does not cause LAGP	5.263^{a}	0.000	$LNCO_2$→ LNAGP (Unidirectional causality)
LAGP does not cause LNCO2	2.338	0.930	
LNNR does not cause LAGP	1.913	0.667	LNNR ———— LNAGP (No causality)
LAGP does not cause LNNR	2.949	0.405	

Notes: ^{a}, ^{b},^{c} indicate significance at levels 1 %, 5 %, and 10 %, respectively.

human capital and agricultural productivity in EU countries by using the ARDL approach. The agriculture sector plays an important role in sustainable development; however, improvement in agricultural production is a crucial tactic, which results in structural improvements and prosperity.

Agricultural productivity can be increased by skilled labor, improved education, application, and technical knowledge diffusion []. However, human capital is a crucial source in enhancing agricultural production.

Moreover, the outcome of natural resources reveals a significantly inverse impact on agricultural productivity. This shows that natural resources decrease agricultural productivity in EU countries. This may happen because human activities such as deforestation, mining, and chainsaw operations are the main cause of destruction in water soil, and air pollution [99]. Moreover, the potential effects of overusing biomass

Table 11
Robustness results using FMOLS and RLS.

	FMOLS		RLS	
Variable	Coefficient	Prob.	Coefficient	Prob.
LNRE	0.124^{a}	0.001	0.278^{a}	0.000
LNHC	2.201^{a}	0.001	2.290^{a}	0.000
LNICT	0.073^{a}	0.004	0.103^{a}	0.001
$LNCO_2$	−0.464^{a}	0.000	−0.365^{a}	0.000
LNNR	0.035	0.135	−0.403^{a}	0.000

Notes: ^{a} indicate significance at level 1 %.

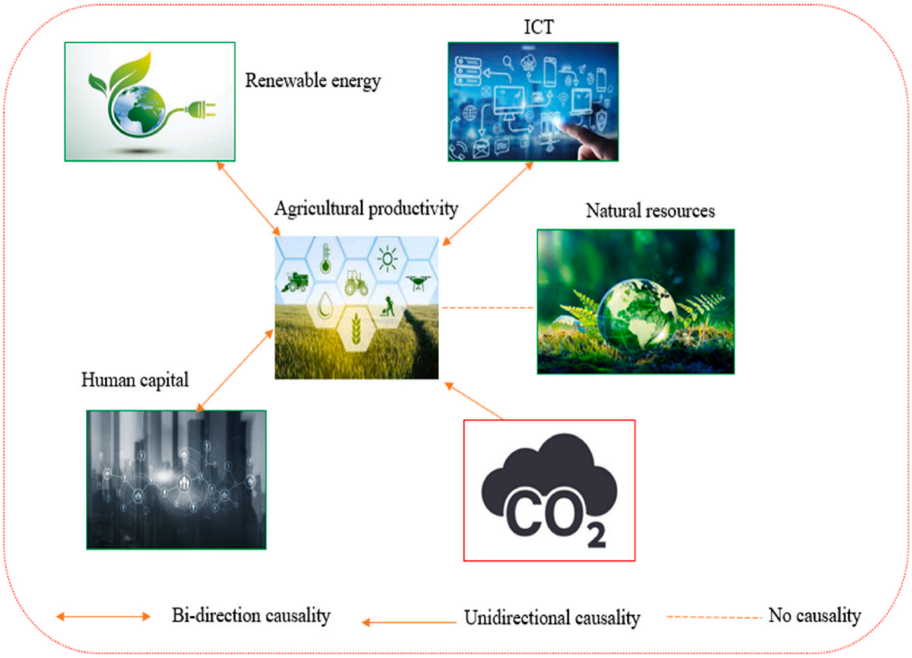

Fig. 1. Causal connection among variables.

energy include abandoning natural areas for the management of monocultures, contaminating waterways in agriculture, compromising food supply, threatening farmers due to land competition, and increasing carbon emissions into ambiance due to energy-intensive production or growing deforestation causes natural resource curse hypothesis [100].

The findings are crucial to understanding through the perspective of SDG 7 (inexpensive, consistent, and contemporary energy facilities) supports SDG target 7.2 to enhance the % of renewable energy in the global energy mix as EU countries must increase the share of non-conventional energy sources, as it improves the agricultural productivity by 0.174 %. SDG 9 (promote innovation and infrastructure) significantly encourages SDG 9c access to information and communication technologies which leads to improving 0.30 % of productivity in agriculture. On the other hand, SDG 13 (urgent action to eliminate climate change) present study also indicates that CO_2 emission decreases −0.163 % in the production of agriculture, therefore reinforcing resilience and adaptive capacity related to climate perils must be considered globally (SDG 13.1). Moreover, in SDG 15 (Life on Land), natural resources decrease agricultural productivity by −0.048 %, however, it is important to consider the end of desertification and re-establish destroyed land and soil by 2030 (15.3).

5. Conclusion and policy implications

5.1. Conclusion

The agriculture sector is a significant source for the EU's economic development as these regions are considered huge contributors to the agricultural market. However, the agriculture sector is also connected with climate change which releases greenhouse gas emissions that lead towards the lower prospects of ensuring the sustainability of the EU's agriculture sector. In this context, this study investigates the connection between agricultural productivity, renewable energy, ICT, human capital, natural resources, and environmental degradation in EU countries from 1996 to 2018. This study also employs panel econometric techniques, including unit root tests, panel Fisher co-integration tests, and Kao co-integration tests to capture cointegration associations among indicators. Moreover, panel ARDL models are also used to find the long-run and short-run impact of independent indicators on dependent variables. The robustness check and heterogenous panel causality approaches are also used to determine the causal association among series.

The empirical results suggest that renewable energy, ICT, and human capital significantly positive impact on agricultural productivity in EU countries. The findings indicate that a 1 % increase in renewable energy would increase agricultural productivity by 0.174 %, and a 1 % increase in human capital and ICT may also increase agricultural productivity by 2.158 % and 0.030 %, respectively. In contrast, −0.163 % drop in agricultural productivity due to CO_2 emissions, and a 0.048 % drop in agricultural productivity due to natural resources. Whereas, in the short term the results showed that renewable energy and natural resources positively affect agricultural productivity and other variables have an inverse insignificant effect on agricultural productivity. Robustness tests were performed by using FMOLS and RLS approaches which support the ARDL test.

Moreover, the findings of the panel DH causality test reveal bidirectional causation between renewable energy, ICT, human capital, and agricultural productivity, which supports the feedback hypothesis in EU countries. Whereas, one-way causality flows from CO_2 emissions to agricultural productivity, but no causality is found between natural resources and agricultural productivity. This study presents policy implications for achieving sustainable agricultural development in EU countries through the establishment of strong regulatory strategies.

5.2. Policy implications

This study suggests that EU countries must make environmental reduction strategies to maintain sustainable agricultural development. In this context, it is recommended that the government assist markets by developing a strong legislative structure that generates low-carbon innovative technologies to combat climate change impacts in the agriculture production system. EU countries can implement some regulations including carbon sequestration, cap & trade, and a carbon tax for emissions reduction in traditional power generation and manufacturing industries. Moreover, for more advanced agriculture, industries need to improve to build small biogas plants and clean energy power plants.

EU countries should implement efficient strategies to elevate the structure of energy use through enhancing renewable energy sources wind, solar, geothermal, and hydropower. To enhance the share of renewable energy sources, the country's government needs to finance renewable energy projects through public-private collaborations [101–104]. The sustainable agricultural production system, mainly farm production relies on the utilization of renewable energy sources, however, it is recommended to formulate sustainable technologies and propagate knowledge to farmers for its use at their farms.

EU regions need to invest in the latest innovations in agriculture that will reduce the CO_2 in agriculture. For sustainable agriculture, farms should be improved by the latest innovations such as Artificial Intelligence and ICT (internet users) to better utilization of inputs. Further, investing in the human capital index has future benefits and contributes to greater labor productivity, more yields, and effective agricultural production. Moreover, our empirical evidence is essential to focus on the education, experience, and farmers' training to enhance the production of agriculture and food security on an extensive and intensive margin. In this perspective, EU countries will not only improve the quality of agricultural production but will also assist in achieving the SDGs.

Last but not least, sustainable agricultural development is considered an important factor among nations. The empirical outcomes suggest that natural resources management including soil, water, plant, forest, etc., is an important tool for the sustainable agriculture system. However, EU regions need to set disbursements and raise chunks to enhance investment in soil and water protection in rural areas as well and these resources should be determined at central and local levels, consequently, it leads to improving agriculture. However, the system-oriented design must be considered to address food insecurity and other challenges in EU countries.

5.3. Limitations and future research

This study has extensive pragmatic evidence for EU countries; however, some limitations still exist that might be addressed in future work. Future work to assess the effect of disaggregated clean energy sources on agricultural production in other different nations, since the effect may vary across the regions. This study uses CO_2 emission as the proxy of environmental degradation; however, other emission factors could be used including methane (CH4), sulfur dioxide, and consumption-based carbon emission.

Credit author statement

Anam Azam: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Visualization, Validation, and Writing – review & editing. Muhammad Rafiq: Conceptualization, Data curation, Methodology, Writing – original draft, and Writing – review & editing. Muhammad Ateeq: Conceptualization, Methodology, Writing – original draft, Muhammad Shafique: Conceptualization, Methodology, Resources, and writing— reviewing and editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Abbreviations

ADF	Augmented Dickey-Fuller
ARDL	Autoregressive distributed lag
CO_2	Carbon dioxide emissions
DH	Dumitrescu-Hurlin
EKC	Environmental Kuznets Curve
EU	European Union
ECT	Error correction Term
FMOLS	Fully modified ordinary least squares
GHG	Greenhouse gas emissions
HC	Human capital
ICT	Information and communication technology
IPS	Im, Pesaran, and Shin
IPCC	Intergovernmental Panel on Climate Change
NR	Natural resources
PP	Phillips-Perron
PMG	Pool Mean Group
RE	Renewable energy
RLS	Robust least squares
SDGs	Sustainable Development Goals
SIC	Schwarz Information Criteria

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