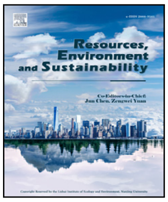
Resources, Environment and Sustainability 21 (2025) 100239

Contents lists available at ScienceDirect

Resources, Environment and Sustainability

journal homepage: www.elsevier.com/locate/resenv



Research article

European Union agro-climate policies toward sustainability: Analyzing emission trends and land use dynamics (1990–2021)

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ARTICLE INFO

Keywords:
Climate neutrality
CAP
F2F
ARDL

ABSTRACT

The agricultural sector plays a pivotal role in the carbon cycle, making the evaluation of the food–climate nexus essential for effective mitigation policy. This study assesses greenhouse gas (GHG) emission dynamics across the European Union (EU-27) from 1990 to 2021. While 20 of the 27 countries showed significant reductions in emissions ($p < 0.05$), Mann–Kendall trend analysis revealed an overall significant decline ($p < 0.0001$), with a Sen's slope of −2,190 kt CO_2 eq/year. Land use data from CORINE indicated a modest 0.08% expansion in agricultural land, primarily non-irrigated arable land, resulting in a net gain of 2.27 million hectares. Autoregressive distributed lag modeling revealed a short-run reduction (−0.07%) but a long-run increase (+0.15%) in GHG emissions linked to agricultural land expansion. Granger causality analysis identified strong unidirectional relationships from agricultural drivers—including land use, value-added agriculture, crop and livestock production, and fertilizer use—to emissions. Notably, forest area increased by 12%, contributing to significant emission reductions, and showed bidirectional causality with agricultural land. These results exposed a persistent gap between emission trends and policy targets, recommending for countries and sector-specific interventions in agriculture, livestock, and land-use governance.

1. Introduction

In future decades, global warming is expected to continue to increase in Europe, primarily because of the increasing cumulative emissions of carbon dioxide (CO_2) in projected scenarios and pathways (Bilgili et al., 2024; King and Karoly, 2017; Walsh et al., 2017). Continental eastern inland areas of the Europe are projected to be warmer between 1.5 °C and 2.0 °C than western and coastal areas with unequal distribution of rainfall (King and Karoly, 2017). Currently, the global mean temperature is approximately 1.25 °C higher than that in preindustrial times; this increase is associated with high atmospheric CO_2 concentrations (Ramanathan et al., 2022). Due to accelerated anthropogenic emissions and feedback mechanisms, the decade from 2011 to 2020 was the warmest on record, with the highest global mean temperature of 1.10 ± 0.12 °C above the 1850 to 1900 baseline in many regions of the world (Matthews and Wynes, 2022). Global climate models (GCMs) emphasize the urgent need for deep and immediate reductions in greenhouse gas (GHG) emissions to limit global warming to 1.5 °C or 2 °C (IPCC, 2023; Srivastava et al., 2022). Hence, achieving net zero CO_2 emissions is a crucial target, with pathways limiting warming to 1.5 °C reaching this goal early 2050s, and those targeting 2 °C by the early 2070s (Brazzola et al., 2021).

Environmental policies play a critical role in achieving the target of global warming limits and climate neutrality (Dupont et al., 2024). From an agricultural perspective, agroclimatic policies are essential for climate change mitigation, protecting natural resources, and ensuring food security. Environmental governance of EU-27 is run by voluntary and mandatory policies shaping the land use, emission patterns, and resource management (D'Alberto et al., 2024). Such policy measures are influential for national level outcomes reflecting the international commitment of climate agreements such as Paris agreement and EU Green Deal (Wendler, 2022). Among policy guided environmental interventions, land use change and management practices play a pivotal

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https://doi.org/10.1016/j.resenv.2025.100239
Received 12 January 2025; Received in revised form 18 May 2025; Accepted 18 May 2025

List of abbreviations

European Union	*EU*	*Generalized method of moments*	*GMM*
Greenhouse gas	*GHG*	*Error Correction Mechanism*	*ECM*
Carbon dioxide	CO_2	*Augmented Dickey–Fuller*	*ADF*
Global climate models	*GCMs*	*Dickey Fuller Generalized Least Squares*	*DF-GLS*
Intergovernmental Panel on Climate Change	*IPCC*	*Phillips–Perron test*	*P–P*
Agriculture, Forestry, and Other Land Use	*AFOLU*	*Lagged error correction term*	ECM_{t-1}
UN Framework Convention on Climate Change	*UNFCC*	*Speed of adjustment*	θ
Food and Agriculture Organization Statistics	*FAOSTAT*	*Akaike information criterion*	*AIC*
Land Use Change, and Forestry	*LULUCF*	*Lagrange multiplier*	*LM*
Nitrous oxide	N_2O	*Cumulative sum of recursive residuals*	*CUSUM*
Methane	CH_4	*Cumulative sum of squares of recursive residuals*	*CUSUMSQ*
Calcium carbonate	$CaCO_3$	*Policies and Measures*	*PaMs*
Common Agricultural Policy	*CAP*	*Emissions Trading System*	*ETS*
European Union Green Deal	*EUGD*	*Common Fisheries Policies*	*CFP*
Nitrogen use efficiency	*NUE*	*Farm to Fork Strategy*	*F2F*
Land cover/land use change	*LCLU*	*Effort Sharing Regulation*	*ESR*
Autoregressive distributed lag	*ARDL*		
Agricultural land	*AL*		
Agriculture, forestry, and fishing, value added	*AVA*		
Crop production	*CP*		
Livestock production	*LP*		
Total fisheries production	*FP*		
Fertilizer consumption	*FC*		
Forest area	*FA*		
COoRdination of INformation on the Environment	*CORINE*		
CORINE land cover	*CLC*		
European Environmental Agency	*EEA*		
Geographic Information System	*GIS*		
European Space Agency	*ESA*		
Climate Change Initiative	*CCI*		
Structural equation modeling	*SEM*		

role in influencing carbon emissions and sequestrations.(Lamb et al., 2021). According to the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2017), the Agriculture, Forestry, and Other Land Use (AFOLU) sector accounts for 21% of global anthropogenic GHG emissions, with 12 ± 4.4 Gt CO_2 eq/yr from 2010 to 2019, attributed to deforestation and livestock, soil and nutrient management (Nabuurs et al., 2023). These emissions consist of various land-based carbon fluxes. These include transitions between croplands and pastures, peat drainage and combustion, and wood extraction following agricultural abandonment and harvesting (Nyawira et al., 2024; Petrescu et al., 2020). Specifically, examining pre and postproduction agricultural activities such as fertilizer application and farm inputs, transportation and food supply chain, household consumption, and waste disposal enables an understanding of their respective contributions to GHG emissions (Tubiello et al., 2022). According to the UN Framework Convention on Climate Change (UNFCC) and Food and Agriculture Organization Statistics (FAOSTAT), global GHG emissions in the year 2000 were 40 to 43 billion metric tons (Gt) of CO_2eq including all anthropogenic and Land Use, Land Use Change, and Forestry (LULUCF) emissions. In 2019 it reached to 54 GtCO_2eq with 16.5 GtCO_2eq shared by agri-food system (Tubiello et al., 2022, 2013). Crops and livestock production are significant contributors to agricultural GHG emissions (Xu et al., 2023). By the end of 2018, in EU countries, agricultural soils contributed 37.8% of Nitrous oxide (N_2O) emissions, enteric fermentation contributed 45% of methane (CH_4) emissions, and manure management contributed 14.7% of combined emissions (Mielcarek-Bocheńska and Rzeźnik, 2021). However, CO_2 emissions are primarily associated from liming and urea fertilization (N) (Ntinyari et al., 2023; Petrescu et al., 2020). Liming involves the application of calcium carbonate ($CaCO_3$) to neutralize the acidity of soil which in turn releases the CO_2 through chemical reaction (Datta and Mandal, 2018). Similarly, urea fertilization increases the carbon cycling process leading to high CO_2 and CH_4 emissions (Wang et al., 2024). Moreover, in 2020, 34% of emissions from agri-food systems were related to pre and postproduction activities and accounted for 5.8 Gt CO_2 eq/yr, whereas 25% were produced in 2000 (FAO, 2023; (Tubiello et al., 2022)). Hence, enteric fermentation (Mielcarek-Bocheńska and Rzeźnik, 2021), biomass burning (Jiang et al., 2024), rice cultivation (Qian et al., 2023), manure management (Lesschen et al., 2011), and synthetic fertilization (Mielcarek-Bocheńska and Rzeźnik, 2021) account for significant contributions to CH_4 and N_2O emissions in the European Union (EU-27) agri-food system. Estimations indicate that 65% of the agricultural land in EU countries is occupied by livestock production systems, which have major environmental impacts, including soil acidification and air pollution (Leip et al., 2015). According to the IPCC sectoral division of livestock categories, GHG emissions from beef cattle are higher than those from pork and dairy products (Foong et al., 2022; Hörtenhuber et al., 2022; Xu et al., 2021). Specifically, animal-based GHG emissions are more noticeable in EU countries because of the prominent role of the beef cattle trade (Xu et al., 2021). Moreover, anaerobic decomposition of organic matter, such as solid and liquid animal manure, and slurry storage notably increase CH_4 emissions (Vac et al., 2013). Furthermore, the annual increase in NH_3 emissions from farming is 2.1%; specifically, there is a rise of 3.8% per annum from crop fields and 1.3% from livestock (Yang et al., 2023).

Approximately 60% of GHG emissions in the EU were contributed by Germany, France, the UK, Poland, and Spain, though this level declined by 2018 (Mielcarek-Bocheńska and Rzeźnik, 2021). From 2005 to 2019, the EU experienced a modest 2% to 3% decline in its GHG emissions from agriculture and is expected to decline more through 2030 (EEA, 2023; Murawska and Goryńska-Goldmann, 2023). A previous study by Harsányi et al. (2021) also reported a 3% decline in cumulative GHGs in Europe, which was driven mainly by reductions in CH_4 and N_2O, owing to the increased use of renewable energy and sustainable land use practices. The sectoral contribution of GHG emissions in previous research did not consider livestock-related emissions compared with crop production (Aguilera et al., 2021). However, emission considerations from all agricultural sectors, such as crop and livestock production and aquaculture, are crucial for holistic legitimization of policy actions related to GHG emissions (Flammini et al., 2021; Ridzuan et al., 2020). From a political standpoint, evaluating GHGs from the AFOLU sector contributes to discussions on the role of agriculture in mitigating climate change (Mielcarek-Bocheńska and Rzeźnik, 2021; Nabuurs et al., 2023). In this context, numerous databases and analyses have been created to address the present and future impacts of agricultural emissions on climate change, as well as to devise mitigation and adaptation strategies (Mohammed et al., 2020; Owen, 2020; van Zanten et al., 2023). For example, various policy options implemented in the AFOLU sector, such as carbon prices (Stepanyan et al., 2023), emission taxes and subsidies for carbon sequestration (Ollier and De Cara, 2024; Zakkour et al., 2024), are predicted to decrease net emissions by 129% by 2050. This reduction is expected to account for 12%–21% of the total anthropogenic GHGs (Henderson et al., 2021). Moreover, the EU Common Agricultural Policy (CAP) and the Green Deal (EUGD) account for nitrogen use efficiency (NUE) for mitigating emissions by minimizing fertilizer usage, reducing nitrogen runoff and enhancing crop uptake (Koukoutsi et al., 2023). Hence, successful EU policies aimed at decarbonizing the fossil fuel mix, promoting renewables, and enhancing energy efficiency have played crucial roles in this reduction (Bianco et al., 2024). Despite the implementation of extensive policies that target GHG emissions in the EU agriculture and livestock sectors, potential challenges remain due to the complexities of agricultural systems and farming practice diversity (Van Hoof, 2023). Moreover, carbon leakage, which refers to the displacement of carbon emissions from one place to another due to asymmetrical and stringent climate policies, as well as reduced energy demand in the EU, has led to the relocation of carbon intensive industries, contributing to higher global emissions (Jakob, 2021; Ostwald and Henders, 2014). Hence the trade balance between demand and supply is urgently needed to minimize the economic tradeoffs and carbon leakage (Clora and Yu, 2022). In this context, several studies evaluated the impact of climate change, energy usage, economic growth, and agriculture factors on agricultural emissions across the world (Table 1).

Many studies have been conducted to assess the trends of GHG emissions from the agricultural sector within EU member states; however, the links between agricultural GHG emissions and the output of the agricultural sector at both the EU-27 level and individual country scale remain an open question. On the other hand, many studies focused only on limited or single-sector emissions (e.g., crop or livestock), rather than providing an integrated, multisectoral analysis. Thus, a more comprehensive evaluation is still needed, along with a direct linkage to policy implementations such as the CAP and the European Green Deal.

To address these gaps, our research provides in-depth, country-specific analyses to evaluate the agricultural factors contributing to GHG emissions in both the short and long run across EU-27 countries. The objectives of this study are three-fold: (i) to monitor and analyze trends in GHG emissions (CO_2, CH_4, N_2O) from the agricultural sector in EU-27 countries between 1990 and 2021; (ii) to explore agricultural land use associated with GHG emissions using CORINE land cover/land use change (LCLU) detection; and (iii) to assess the short- and long-run dynamics of GHG emissions in EU-27 member states.

The detailed outputs for each country aim to inform sector-specific policy reforms by linking emission trends with agricultural land use changes. This research introduces a novel integration of ARDL modeling with remote sensing-based land use analysis, providing a benchmark for future country- and sector-specific environmental policies in the EU. Ultimately, this approach supports the transition to sustainable agricultural practices aligned with global climate targets and the Sustainable Development Goals (SDGs).

2. Methods

2.1. Data collection (GHS emissions and agricultural factors)

This study examines agricultural GHG emissions in the EU-27 countries. GHGs (CO_2, CH_4, N_2O) data were collected from the European Environmental Agency (EEA) agricultural emissions and projected emissions by EU Member State --- European Environment Agency (europa.eu). A time scale of 32 years (1990–2021) was selected based on data availability and ensuring a sufficient sample size for robust analysis. The significant agricultural factors data was acquired from World bank open data Indicators | Data and includes the following factors (Supplementary Table 1):

(a) *Agricultural land*: This includes arable lands, permanent crops, pastures, and other heterogeneous cultivated areas classified by land use in Km^2.
(b) *Agriculture, forestry, and fishing value added*: These values correspond to forestry, hunting, fishing, crop, and livestock production. The value added is the final output of a sector after accounting for all inputs and is measured in % of GDP.
(c) *Crop production*: This includes annual agricultural production relative to the base period of 2014–2016. Fodder crops were not included.
(d) *Livestock production index*: This includes milk, meat, and dairy products such as eggs, cheese, silk, honey, etc. This index was prepared by the Food and Agriculture Organization (FAO).
(e) *Total fisheries production*: This includes aquatic species in metric tons from subsistence, commercial, recreational, and industrial purposes. All mariculture and aquaculture were included.
(f) *Fertilizer consumption*: This is a measurement of plant nutrients used per unit of arable land. These include nitrogen, potassium, and phosphate. Animal and plant manure were excluded to focus on synthetic fertilizer use.
(g) *Forest area*: This area includes natural or planted trees with a minimum height of 5 m. Fruit plantations, garden trees, and agroforestry were not included.

The seven variables were selected due to their direct and indirect impacts on agricultural GHGs emissions in the EU-27. The selected factors are good representatives of GHGs emissions sources or sinks linked with land use, production intensity, and agricultural input. Moreover, agriculture value added better presents the economic efficiency and net contribution of agriculture, forestry, and fishing sectors to GDP rather than gross output in agriculture. Hence, the selected variables provide an appropriate and optimal sectoral perspective highly suitable for econometric modeling and relevant policy impacts.

2.2. Mann–Kendall trend and Sen's slope

The Mann–Kendall trend (Mann, 1945) and Sen's slope estimator (Sen, 1968) are applied to determine the monotonic trend of GHG (CO_2, CH_4, N_2O, and all GHG) emissions from the agricultural sector. A series of 32 years, from 1990 to 2021, is used to detect the trend and slope of agricultural emissions in 27 EU countries. The Mann–Kendall test and Sen's slope estimator aimed to evaluate the statistical significance and direction of emission trends, helping contextualize the cointegration results from econometric analysis. The nonparametric Mann–Kendall test, which is calculated from Eq. (1), assumes the null hypothesis (H_0) of no significant trend in the time series of GHG emissions, whereas the alternate hypothesis (H_a) assumes a significant ($p < 0.05$, $p < 0.001$) trend in GHG emissions.

$$MK = \sum_{i=j}^{n-1} \sum_{j=i+1}^{n} sgn\left(x_j - x_i\right), \tag{1}$$

where x_j and x_i represent the GHG emission values during the time/years i and j, respectively. The output of the M-K test is the Tau

Table 1
Comprehensive review of econometric analysis on GHGs emissions in world's major agricultural economies.

Region	Objective	Covariates & GHG	Time period	Findings	Policy implication	Reference
China	Evaluating the linear and non-linear effects of key agricultural variables on GHG emissions in China	CO_2 eq (million tons), agricultural land use, fertilizer input, energy usage, crop & livestock production index, fisheries production, agriculture value added (GDP %), forest area	1990–2020	Expansion in agricultural land use, high input of fertilizer and energy significantly increase emissions in the long run & vice versa. Livestock, crop, & fisheries production are sign for high emissions	Afforestation & Reforestation, agroforestry, shift to renewable energy, manure management, organic and precision farming, green economic growth needed	(Ahmed et al., 2025a)
Top 10 agricultural economies (India, China, Japan, Russia, USA, Brazil, Mexico, France, Turkey, Germany)	Evaluating key factors (surface temperature, water withdrawal, fertilizer input, economic growth, technological development) of agricultural GHGs emissions	Agricultural GHGs emissions (CO_2 eq), % of freshwater used in agriculture, Fertilizer input/ha, Annual Land surface temperature, GDP, Patents as technological factors.	1990–2020	Agricultural water usage and fertilizer input had significant impact on GHGs emissions in the long run but non- significant in short run. Surface temp and GDP had significant impact on both short & long run.	Country specific policy reforms with priority to mitigate climate change, efficient irrigation methods, conversion to wind and solar power, incentives and subsidies,	(Ahmed et al., 2025b)
Major agricultural economies (USA, Brazil, Argentina, Nigeria, India, China, Russia, Indonesia)	Evaluate the impact of climate change and agricultural input on agricultural soil emissions using econometric analysis	CO_2 eq (billion tons), Surface temperature, fertilizer input/ha, Crops & Livestock production index, agricultural land, energy use	1990–2020	Agricultural land use had no significant impact in the short and long run. Surface temperature & crop production causes high emissions in the long run with bidirectional relation	Country and sector specific policy reforms needed prioritizing climate change mitigation, adopting agroforestry, and manure management	(Ma et al., 2024)
EU 27 (collective)	Evaluate the role of crop residue (N_2O) and livestock emissions (CO_2) on total agricultural emissions through panel data econometrics.	% share of agricultural emissions in total GHGs emissions. N_2O from residue decomposition CO_2 from enteric fermentation.	2000–2020	Both plant residues and livestock emissions have a significant impact on agricultural emissions in the short run. N_2O residue emissions are more likely to contribute to total agricultural emissions in the long run.	More strategic policies needed to reform CAP for residue and livestock emissions. Country wise detailed analysis needed.	(Doğan and Kan, 2024)
Baltic region (Lithuania, Estonia, Latvia)	Analyze relationship b/w GHGs emissions & Gross value added (GVA) from agriculture. Testing EKC hypothesis curve	Agricultural CO_2 eq & GVA by agri.	1998–2019	Strong cointegration b/w GHGs emissions and GVA. EKC hypothesis partially supported Strong correlation in short run and weak in long run.	Need for sustainable agricultural strategies. More emphasizes should be on climate adaptation by CAP especially in Estonia & Latvia	(Makutėnienė et al., 2022)
Mediterranean & Western EU (France, Spain, Greece, Germany, UK, Bulgaria)	Analyze relationship b/w GHGs emissions and agricultural income Testing EKC hypothesis	Agricultural CO_2eq Agricultural income (net value added per capita), mechanization, labor force, organic farming adoption	1970–2014	Strong cointegration between net value added (NVA) and GHGs emissions. No EKC observed in Greece & Bulgaria. Mixed effects of CAP policy reforms.	Targeted policies are needed. CAP must focus on incentives for sustainable farming practices.	(Zafeiriou et al., 2018)
Mediterranean (France, Portugal, Spain)	Analyze relationship b/w GHGs emissions and agricultural income Testing EKC hypothesis	Agricultural CO_2eq & Net value added (NVA/capita)	1992–2014	Strong cointegration b/w NVA and CO2 emissions in Portugal and Spain with EKC proved but not in France	CAP reforms needed in France. Enhance short term emission reduction policies in Portugal. Subsidies for organic and precision farming.	(Zafeiriou and Azam, 2017)

τ value at the 90% to 95% level of significance in Eqs. (2) and (3). A positive Tau coefficient indicates an upward or increasing trend, whereas a negative coefficient indicates a downward or decreasing trend. Where:

$$\operatorname{sgn}\left(x_j - x_i\right), = \left\{ \begin{array}{ll} +1, & \left(x_j - x_i\right) > 0 \\ 0, & \left(x_j - x_i\right) = 0 \\ -1, & \left(x_j + x_i\right) < 0 \end{array} \right\} \tag{2}$$

$$\tau = \frac{2S}{n(n-1)} \tag{3}$$

The variance in MK is computed via Eq. (4).

$$\operatorname{Var}(\mathrm{MK}) = \frac{1}{18}\left[n(n-1)(2n+5)\sum_{p=1}^{q} t_p\left(t_p - 1\right)\left(2t_p + 5\right)\right] \tag{4}$$

Afterward, the coefficient of senses slope (SS) is used to measure the slope or rate of change per annum, as reflected by Eqs. (5) and (6).

$$SS = \frac{X_j - X_i}{j - i} \tag{5}$$

$$Q_i = \begin{cases} T_{(N+1)/2} & \text{if } N \text{ is odd} \\ \frac{1}{2}\left(T_{\frac{N}{2}} + T(N+2)/2\right) & \text{if } N \text{ is even} \end{cases} \tag{6}$$

2.3. *CORINE land cover (CLC) change detection*

The COoRdination of INformation on the Environment (CORINE) land cover (CLC) inventory is used to explore agricultural land use change detection to support the findings from econometric analysis. Aligned with the data source of GHG emissions, the CORINE land cover project was coordinated by the EEA under the framework of the EU Copernicus program (Gemitzi et al., 2021). The project was initiated in 1985 and aimed to standardize the land data of 33 EEAs and 6 cooperating countries. The spatial resolution of the dataset is 100 m, with a minimum land cover polygon of 25 ha (Büttner, 2014). The first decadal dataset of the inventory is available for the year 1990, preceding the years 2000, 2006, 2012, and 2018. The dataset is categorized into a hierarchical 3-level classification system with a total of 44 classes. Currently, the dataset was retrieved from the open-source cloud computing platform of the Google Earth Engine and processed in the Geographic Information System (GIS) environment via ArcGIS Pro for change detection analysis. In alignment with our covariates (agricultural factors), only land use classes related to agricultural and forest areas are considered (Supplementary Table 2). Agricultural land use classes include arable land, permanent crops, pastures and heterogeneous areas covering all kinds of crop production and pastureland for livestock. The forestland uses classes include broad leaves, coniferous, and mixed forests combined into only one class for analysis, providing a good indicator of carbon storage.

CLC inventory provides a broader thematic classification of agricultural land use at a higher spatial resolution comparative to other land cover datasets such as European Space Agency (ESA) Climate Change Initiative (CCI) land cover dataset. Currently, CLC provided with a detailed assessment of agricultural land use such as arable lands, permanent crops and pasturelands which are crucial to link with all types of agricultural GHGs emissions. Therefore, similarities in spatiotemporal resolution, hierarchical classification schemes, and detailed land use patterns make it a good choice for use in LCLU and GHG research (Arslan et al., 2021; Cruickshank et al., 2000; Gemitzi et al., 2021). Initially, the LCLU area for each class is computed, and the percentage is detected for the respective years. This step is followed by the categorical change detection procedure employed in ArcGIS Pro for examining "change only" in agricultural land use, which provides deeper insight and is comparable to the findings of the ARDL bound test.

2.4. *ARDL econometric model*

We employ an autoregressive distributive lag (ARDL) bound test model to analyze the relationships between agricultural GHG emissions and agricultural factors such as agricultural land use (Km^2), agriculture, forestry, and fishing value added (%GDP), crop production index, livestock production index, fisheries production index, fertilizer consumption (Kg/ha), and forest area (km^2). These variables were selected based on their established roles in influencing GHG emissions also reported in previous research (Ahmed et al., 2025a; Ma et al., 2024; Makutėnienė et al., 2022). Annual time series data from 1990 to 2021 is used to examine the relationships between the variables. Before the econometric ARDL model is implemented, all the variables are transformed into logarithmic forms to reduce skewness and ensure a normality in regression analysis (Supplementary Table 1).

Currently, ARDL econometric model is preferred over other methods such as structural equation modeling (SEM) or generalized method of moments (GMM) due to several methodological advantages. First, flexibility in lag structures for dependent and independent variables allowed us to evaluate the short and long run effects of agricultural factors, land use changes, and EU mitigation policies on GHGs emissions. Particularly, the model includes lagged variables to account for delayed effects of agricultural factors on GHG emissions. By regressing lag values of the independent variables (agricultural factors) against the dependent variable (GHG emissions), the lag length attribute supports the ARDL model in ascertaining the historical duration necessary to capture the residual effects. Moreover, it is also proven to perform robust for a limited or small sample size (1990 to 2021), allowing for both short and long run dynamics and equilibrium relationships in a single equation framework. The ARDL model demonstrates effectiveness regardless of the integration level of the time series data, whether at level (I (0)), first difference (I (1)), or a combination of both. Hence, the ability of ARDL to deal with endogeneity and heterogeneity in time series also makes it a valuable choice over other econometric techniques. The individual or own lag structure of each variable helps to accommodate the structural difference between the variables. Another significant feature of the ARDL model is Error Correction Mechanism (ECM). It evaluates the speed at which short-term deviations from equilibrium are corrected over time and presents the per year percentage at which short-term impacts progressively evolve into a fundamental basis for long-term effects. Hence, the ARDL findings provide an authentic insight into the reasons for agricultural emissions in EU effectively supporting its policy implications. Specifically, short run effects address the policy impacts while long run analysis explores the impact of structural changes. Therefore, the mentioned characteristics of ARDL prove to be more efficient, robust, and reliable modeling choice for examining the complex temporal relationship between agricultural GHGs emissions and corresponding factors. The following linear Eq. (7) describes the relationships between GHGs and agricultural factors:

$$\mathrm{GHG_t} = f\left(\mathrm{AL_t}, \mathrm{AVA_t}, \mathrm{CP_t}, \mathrm{LP_t}, \mathrm{FP_t}, \mathrm{FC_t}, \mathrm{FA_t}\right) \tag{7}$$

Log transformation is applied for efficient estimation via Eq. (8):

$$\begin{aligned} \mathrm{LGHG}_t = {} & \alpha_0 + \alpha_1 \mathrm{LAL}_t + \alpha_2 \mathrm{LAVA}_t + \alpha_3 \mathrm{LCP}_t + \alpha_4 \mathrm{LLP}_t \\ & + \alpha_5 \mathrm{LFP}_t + \alpha_6 \mathrm{LFC}_t + \alpha_7 \mathrm{LFA}_t + \varepsilon_t \end{aligned} \tag{8}$$

where $LGHG$ is the log of greenhouse gases as a response variable, $\mathrm{LAL_t}$ is the log of agricultural land, $\mathrm{LAVA_t}$ is the log of agricultural value added, $\mathrm{LCP_t}$ is the log of crop production, $\mathrm{LLP_t}$ is the log of livestock production, $\mathrm{LFP_t}$ is the log of fisheries production, $\mathrm{LFC_t}$ is the log of fertilizer consumption, and the $\mathrm{LFA_t}$ log of forest area. t represents the time series (1990–2021), and $\alpha_1, \alpha_2, \alpha_3$.. represents the long-term relationships between the variables.

2.4.1. *Unit root tests*

Before applying the ARDL model, unit root tests are conducted to assess the stationarity of the time series variables. Stationarity implies that the statistical properties of a time series, such as its mean and variance, remain constant over time (Qayyum et al., 2023). The ARDL approach is suitable for variables that are stationary at level **I(0)** or become stationary after first differencing **I(1)**, but it is not appropriate for variables that are integrated at the second difference **I(2)** or higher (Mohammed et al., 2024). Therefore, it is essential to apply unit root tests before cointegration analysis (Zhang et al., 2019). For instance, Tukhtamurodov et al. (2024) recommend to use more than one unit root tests to analyze the order of integration based on the sample size. Currently, our study used the Augmented Dickey–Fuller (ADF) test put forward by Dickey and Fuller (1981), the Dickey Fuller generalized least squares (DF-GLS) test by Elliott (1998), and the Phillips–Perron (P–P) test (Peter and Perron, 1988). After affirming the stationarity characteristics of the time series, we proceeded to estimate the ARDL bounds test for cointegration using the lag order chosen based on the minimum values of the Akaike information criterion (AIC). These criteria balance model fit and parsimony by penalizing excessive lag lengths to avoid overfitting. The optimal lag order is determined by estimating ARDL models with different lag structures and choosing the specification that minimizes the selected information criterion.

2.4.2. *ARDL bounds test*

The estimation procedure of the ARDL bounds test, initiated with Eq. (9), applied the Ordinary Least Squares (OLS) method and a bounds test (F-statistics) to analyze the joint significance of the coefficients of lagged level variables (Pesaran et al., 2001). The null hypothesis (H_0) of the ARDL bounds test states that no cointegration exists among variables (i.e., the coefficients of the lagged level variables = 0). The F-statistic is used to compare the critical values of the upper and lower bounds (Raihan, 2023). With F-statistics greater than upper critical bound, rejects the null hypothesis, indicating a significant long run cointegration among agricultural factors and GHGs emissions. On contrary, if F value falls below the lower bound, the H_0 is accepted. However, the result is inconclusive, if F value lies between the two bounds.

$$\begin{aligned}\Delta \mathrm{LGHG}_t &= \alpha_0 + \alpha_1 \mathrm{LGHG}_{t-1} + \alpha_2 \mathrm{LAL}_{t-1} + \alpha_3 \mathrm{LAVA}_{t-1} + \alpha_4 \mathrm{LCP}_{t-1} + \alpha_5 \mathrm{LLP}_{t-1} \\ &+ \alpha_6 \mathrm{LFP}_{t-1} + \alpha_7 \mathrm{LFC}_{t-1} + \alpha_8 \mathrm{LFA}_{t-1} + \sum_{i=1}^{q} \beta_1 \Delta \mathrm{LGHG}_{t-i} + \sum_{i=1}^{q} \beta_2 \Delta \mathrm{LAL}_{t-i} \\ &+ \sum_{i=1}^{q} \beta_3 \Delta \mathrm{LAVA}_{t-i} + \sum_{i=1}^{q} \beta_4 \Delta \mathrm{LCP}_{t-i} + \sum_{i=1}^{q} \beta_5 \Delta \mathrm{LLP}_{t-i} + \sum_{i=1}^{q} \beta_6 \Delta \mathrm{LFP}_{t-i} \\ &+ \sum_{i=1}^{q} \beta_7 \Delta \mathrm{LFC}_{t-i} + \sum_{i=1}^{q} \beta_8 \Delta \mathrm{LFA}_{t-i} + \varepsilon_t \end{aligned} \tag{9}$$

After the long run coefficients estimations, short-run dynamics are established using an Error Correction Model (ECM), an essential part ARDL framework (Engle and Granger, 1987). The ECM quantify the speed at which dependent variable (GHGs emissions) returns to equilibrium following a short run disturbance. A lagged error correction term (ECM_{t-1}) is introduced in the ARDL Eq. (10), representing the residuals from the long-run relationship, and θ presents the speed of adjustment. A statistically significant negative coefficient of ECM_{t-1} presents the adjustment of variables towards long run equilibrium (Ben Abdallah, 2024). It also explains short-run fluctuations in the dependent variable (GHGs emissions) in response to changes in the explanatory variables (agricultural factors). Hence, the ECM's significant and negative value also supports the robustness of the short-term dynamics influencing GHG emissions.

$$\begin{aligned}\Delta \mathrm{LGHG}_t &= \alpha_0 + \alpha_1 \mathrm{LGHG}_{t-1} + \alpha_2 \mathrm{LAL}_{t-1} + \alpha_3 \mathrm{LAVA}_{t-1} + \alpha_4 \mathrm{LCP}_{t-1} + \alpha_5 \mathrm{LLP}_{t-1} \\ &+ \alpha_6 \mathrm{LFP}_{t-1} + \alpha_7 \mathrm{LFC}_{t-1} + \alpha_8 \mathrm{LFA}_{t-1} + \sum_{i=1}^{q} \beta_1 \Delta \mathrm{LGHG}_{t-i} + \sum_{i=1}^{q} \beta_2 \Delta \mathrm{LAL}_{t-i} \\ &+ \sum_{i=1}^{q} \beta_3 \Delta \mathrm{LAVA}_{t-i} + \sum_{i=1}^{q} \beta_4 \Delta \mathrm{LCP}_{t-i} + \sum_{i=1}^{q} \beta_5 \Delta \mathrm{LLP}_{t-i} + \sum_{i=1}^{q} \beta_6 \Delta \mathrm{LFP}_{t-i} \\ &+ \sum_{i=1}^{q} \beta_7 \Delta \mathrm{LFC}_{t-i} + \sum_{i=1}^{q} \beta_8 \Delta \mathrm{LFA}_{t-i} + \theta \mathrm{ECM}_{t-1} + \varepsilon_t \end{aligned} \tag{10}$$

where the speed of adjustment is depicted by θ and the first lag of the error term is illustrated by ECM_{t-1}, which signifies the error correction model. The estimated value of the ECM is often between 0 and 1. The ECM's significant and negative value supports the robustness of the short-term dynamics influencing GHG emissions.

2.5. *Granger causality test*

This study applied the pairwise panel Granger (1969) causality test to determine whether one time series can predict another. The utility of the Granger causality test lies in its ability to analyze complex time series data and uncover potential predictive relationships. By identifying such predictive relationships, policymakers and analysts can better anticipate economic trends and implement informed strategies. The method offers several advantages compared to alternative time-series assessments. An important benefit of this test is its capacity to analyze many lags whereas disregarding higher-order lags. A time series Y is considered to be "Granger-cause" an additional time series X if it can assist in forecasting the impending pattern of X. The coefficients can be estimated by means of the OLS test, and the Granger causality between X and Y can be identified using F tests. The time series for this pair of variables is conveyed as X_t and Y_t, where X_t and Y_t characterize their estimates at time t. The bivariate autoregressive models can include X_t and Y_t presented in the following equations:

$$X_t = \beta_1 \sum_{i=1}^{n} \alpha_i Y_{t-1} + \sum_{i=1}^{n} \mu_i X_{t-1} + e_t \tag{11}$$

$$Y_t = \beta_2 \sum_{i=1}^{n} \Omega_i Y_{t-1} + \sum_{i=1}^{n} \infty_i X_{t-1} + u_t \tag{12}$$

where "n" is lag number while β_1, β_2, α_i, Ω_i, μ_i, and ∞_i were used for estimate. Besides, "e_t" and "u_t" denote the residual aspects.

3. Results

3.1. *An outlook of GHG emissions from the agricultural sector within the EU-27 from 1990 to 2021*

Within EU-27, GHG emissions from the agricultural sector vary among countries. The data presented in Fig. 1 reveal that the highest emissions were recorded in France (FR) and Germany (DE), with values of 66.2 kt CO_2eq and 56.3 kt CO_2eq, respectively. Mann–Kendall analysis revealed a significant ($p < 0.0001$) declining trend for all GHG emissions, with a Sen's slope of −2190 kt CO_2eq/year in the EU 27 countries. Countries such as Austria, Belgium, and the Netherlands in Western Europe and Greece, Italy, and Malta in Southern Europe showed significant decreases. The Sen's slope ranged from −249.9 kt CO_2 eq/year in France to −1.1 kt CO_2 eq/year in Malta.

Other countries, such as Cyprus, Finland, Poland, Portugal, and Slovenia, also experienced significant ($p < 0.05$) declining trends in total GHG emissions. Significant declines in CH_4 emissions were observed in most EU-27 countries; however, Cyprus, Ireland, and Luxembourg exhibited a non-significant increase. Similarly, the majority of EU-27 countries recorded a significant reduction in N_2O emissions, while increased emissions were recorded in Bulgaria, Czechia, Estonia ($p < 0.05$), Finland ($p < 0.05$), Latvia ($p < 0.05$), and Lithuania ($p < 0.05$) (Supplementary Table 3). CO_2 emissions significantly ($p < 0.0001$) decreased only in Poland and Slovenia from Eastern Europe; Cyprus, Greece, and Italy from southern Europe; Denmark, Finland, and Sweden from Northern Europe; and only the Netherland from Western Europe (Fig. 2, Supplementary Table 3). A few countries, such as Estonia, Hungary, Ireland, Latvia, and Spain, experienced a non-significant increasing trend in total GHG emissions (CO_2, CH_4, and N_2O). Interestingly, Hungary exhibited an unusual trend, with

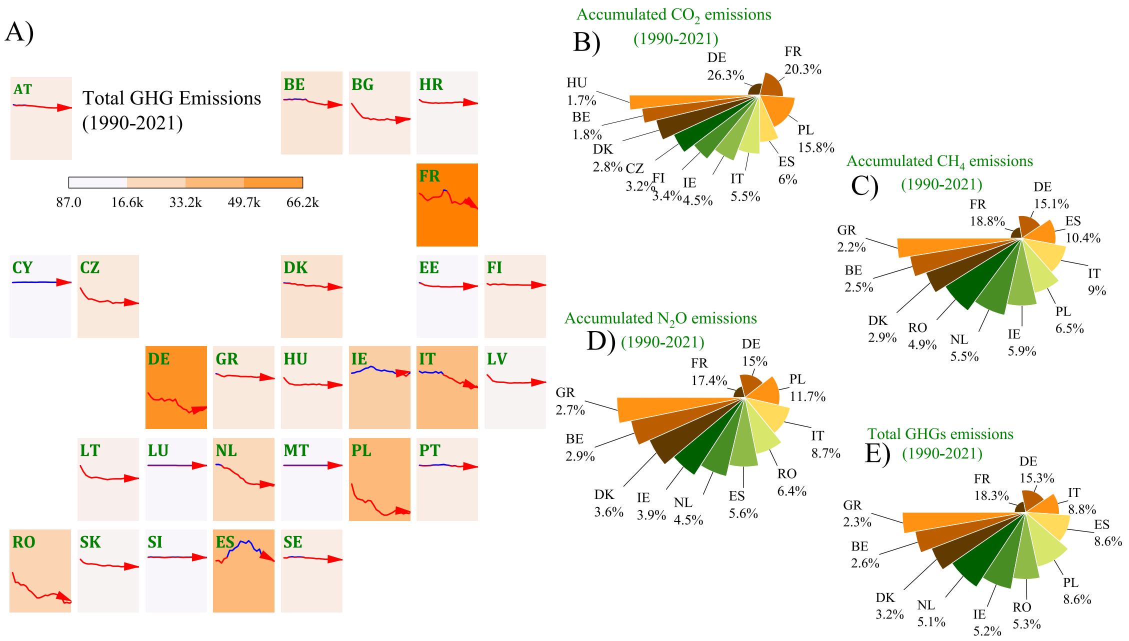


Fig. 1. (A) Analysis of changes in total GHG emissions compared with the baseline (emission in 1990) from each EU-27 member state in the agricultural sector (1990–2020): arrows show the trend, red color represents a decrease in emissions compared with the baseline, blue color represents an increase in values compared with the baseline, and the intensity of orange color represents higher emissions of the member state based on 2021 emission data. (B) Leading 11 EU-27 countries by cumulative CO_2 emissions in agriculture (1990–2021). (C) Leading 11 EU-27 countries by cumulative CH_4 emissions in agriculture (1990–2021). (D) Leading 11 EU-27 countries by cumulative N_2O emissions in agriculture (1990–2021). (E) Leading 11 EU-27 countries by cumulative GHG emissions in agriculture (1990–2021). (Austria (AT), Belgium (BE), Bulgaria (BG), Croatia (HR), Cyprus (CY), Czechia (CZ), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Germany (DE), Greece (GR) (Eurostat: EL), Hungary (HU), Ireland (IE), Italy (IT), Latvia (LV), Lithuania (LT), Luxembourg (LU), Malta (MT), Netherlands (NL), Poland (PL), Portugal (PT), Romania (RO), Slovakia (SK), Slovenia (SI), Spain (ES), Sweden (SE), and European Union (EU)).

significant CH_4 reductions (−31.505 kt CO_2 eq/year, $p < 0.05$), but increases in both CO_2 (3.204 kt CO_2 eq/year, $p < 0.05$) and N_2O (37.312 kt CO_2 eq/year, $p < 0.05$) emissions.

Overall, 20 out of 27 EU-27 member states presented a significant ($p < 0.05$, $p < 0.001$) declining trend in total GHG emissions from the agricultural sector over 32 years (Supplementary Table3). Interestingly, all countries—except Cyprus (+18%), Ireland (+16%), and Spain (+4%)—exhibited a percentage decrease in GHG emissions compared with the baseline year (i.e., 1990), with the greatest declines recorded in Slovakia (−60%), Latvia (−55%), and Lithuania (−52%) (Supplementary Table 4). This decline aligns with EU-wide goals for reducing agricultural emissions.

3.2. *Agricultural land use change detection within the EU-27 (1990–2018)*

Agricultural land use statistics derived from the CORINE land cover inventory for EU-27 countries revealed that agricultural land in the EU-27 increased from 183.9 million hectares (Mha) in 1990 to 184.2 Mha in 2018, reflecting a 0.08% net gain. Change detection analysis for the first decade (1990–2000) showed an increase in total agricultural land use from 44.6% to 45.7%, followed by a decline to 45.1% in 2006 and to 44.7% in both 2012 and 2018 (Fig. 3, Supplementary Table 5). Overall, total agricultural land use experienced a net gain of 0.3 Mha from 1990 to 2018.

A detailed assessment of different agricultural land use types based on the standard CLC inventory (Fig. 4, Supplementary Table 5) revealed that the highest proportion of agricultural land use was shared by non-irrigated arable land, which increased from 96.25 million hectares (Mha) (52.3%) in 1990 to 96.53 Mha (53.48%) in 2018, with a net gain of 2.27 Mha (1.14%). Pastureland use increased from 29.7 Mha (16.2%) in 1990 to 32.3 Mha in 2018 (17.5%) with a net gain of 2.64Mha (1.4%). A change detection analysis revealed a conversion of 2.5 Mha of pastureland to non-irrigated arable land over three decades suggesting the intensification of agricultural activities (Fig. 4A, Supplementary Table 6). Permanently irrigated arable land also experienced a net gain of 1.14Mha (0.62%), followed by a 1.2Mha (0.66%) gain from permanent crops of fruit trees (0.22%) and olive groves (0.44%) (Fig. 4B-G).

Heterogeneous agricultural areas comprising of annual permanent crops, complex cultivation patterns and agricultural land with natural vegetation experienced a net loss of 7.2Mha (3.93%) over three decades (Fig. 4G). Change detection indicated that 1.1Mha of heterogeneous agricultural land converted into irrigated and non-irrigated arable land, also signifying increased food demand contributing to higher CO_2 emissions from agricultural soils (Fig. 4A-1). Forestland use in 1990 was identified as 87.8Mha (21.3%) of total EU land use (excluding the forest area of Sweden and Finland), which increased to 136Mha (33.2%) in the year 2018 with a net gain of 12% (Fig. 4G). CLC change detection from 2000 to 2018 revealed a 1.2% increase in forestland area due to smart climate policies such as afforestation and agroforestry. The increase in forest land use significantly contributes to carbon flux and reducing GHG emissions.

3.3. *Empirical results of the ARDL bound test*

The outcomes of the summary statistics (Supplementary Table 7) presented the central tendency and normality tests (skewness, probability, kurtosis, and Jarque–Bera) of all the variables. The closer mean and median values and skewness near zero clearly imply that all the variables adhere to normality except for crop production, which has a negatively skewed (−0.33) distribution. The empirical findings of kurtosis (less than 3) indicated that all the series are platykurtic. Additionally, the smaller values of the Jarque–Bera probability revealed the normal distribution of the dataset.

Before conducting ARDL analysis, the findings of unit root testing via Augmented Dickey–Fuller (ADF), Dickey–Fuller generalized least squares (DF-GLS), and Phillips–Perron (P–P) (Supplementary Table 8) revealed that although some of the variables were nonstationary at

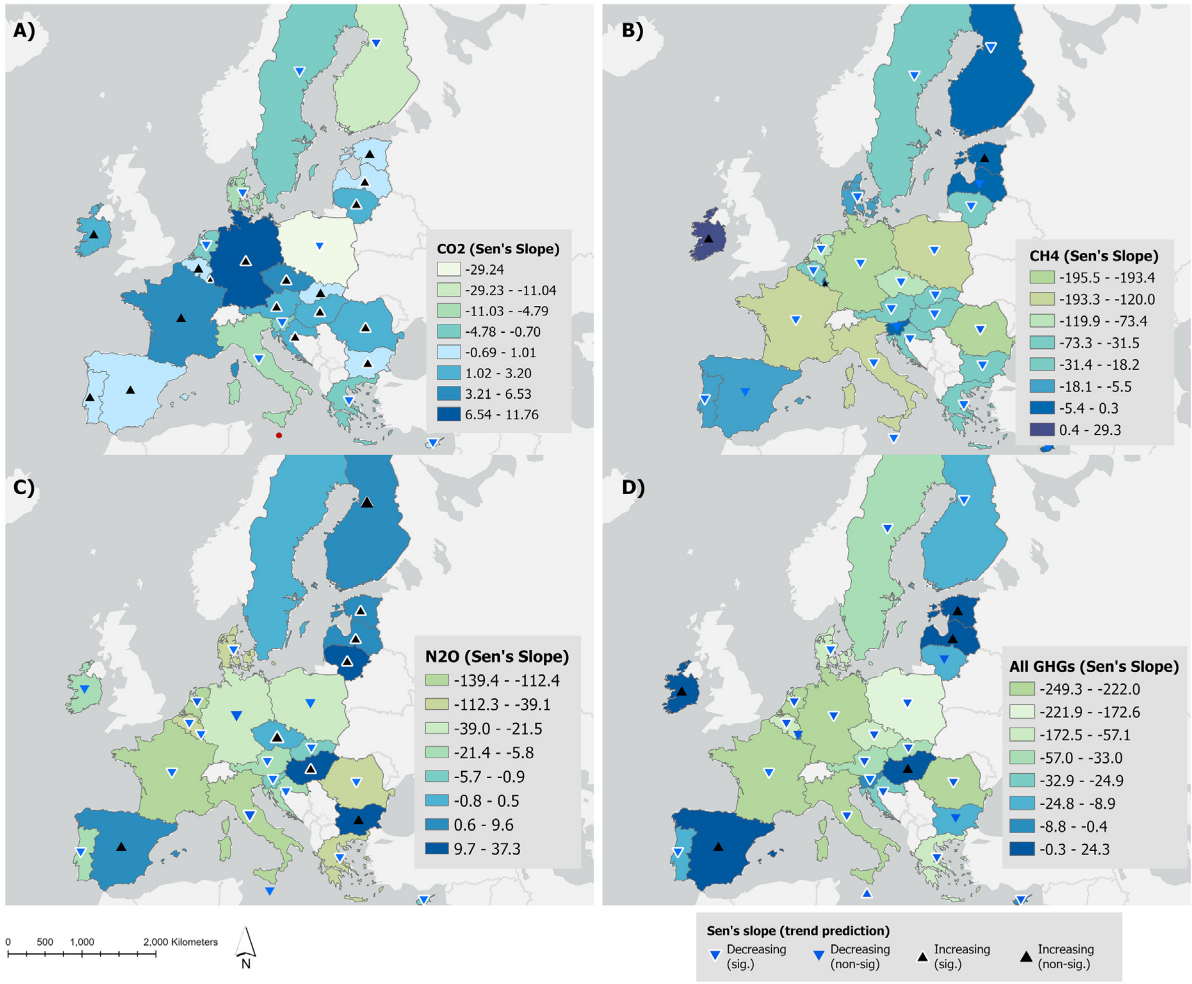


Fig. 2. Man-Kendall trend and Sen's slope analysis of GHGs emissions from agricultural sector within EU-27 member states from 1990 to 2021: (A) CO_2 emissions from agricultural sector (1990–2021), (B) CH_4 emissions from agricultural sector (1990–2021), (C) N_2O emissions from agricultural sector (1990–2021), (D) Total GHG emissions from agricultural sector (1990–2021).

Table 2
ARDL long and short-run results: dependent variable LGHG.

Variables	Long-run			Short-run		
	Coefficient	*t*-Statistic	p-value	Coefficient	*t*-Statistic	p-value
LAL	0.145806	0.419978	0.6805	−0.070569	−0.509679	0.6177
LAVA	0.049310	0.885465	0.3899	0.071083**	2.754353	0.0148
LCP	0.204672*	1.782752	0.0949	0.060431***	3.288927	0.0050
LLP	0.058589	0.275980	0.7863	0.002233	0.039696	0.9689
LFP	0.064012	1.083912	0.2955	0.037519*	2.016980	0.0620
LFC	0.122976	1.638666	0.1221	0.026441	1.484384	0.1584
LFA	−0.186571	−0.624863	0.5415	−0.120503	−1.466726	0.1631
C	10.58580	1.302190	0.2125	–	–	–
ECM (−1)	–	–	–	−0.574806***	−9.249644	0.000
R^2	0.9217					
Adjusted R^2	0.8979					

LAL = Agricultural land (sq.km), LAVA = Agriculture, forestry, and fishing, value added (% of GDP), LCP = Crop production (Index), LLP = Livestock production (index), LFP = Total fisheries production (metric tons), LFC = Fertilizers consumption (Kg/ha), LFA = Forest area (Km^2)

level **I(0)** for some tests, all the variables became stationary at the first difference **I(1)** in three-unit root tests. Hence, the findings of unit root tests indicated that the series is suitable for employing the ARDL model. The ARDL bounds test results explored the cointegration links among the variables (Supplementary Table 9). The existence of a long-term association between the parameters was confirmed when the estimated F-test value exceeded both the lower and upper bounds. Our findings indicated that the F-statistic value (6.20) exceeded the critical upper bounds at the 10%, 5%, 2.5%, and 1% significance levels for both the **I(0)** and **I(1)** cases. This leads to the rejection of the null hypothesis and suggests the presence of long-run cointegration relationships among the covariates (agricultural factors).

3.3.1. ARDL estimations for EU-27: Long- and short-run analysis

The results of the ARDL long- and short-run analyses revealed dynamic relationships between agricultural factors and GHG emissions (Table 2). The estimated long-run coefficient for agricultural land (LAL) was positive (0.1458,p = 0.6805), while the short-run coefficient was

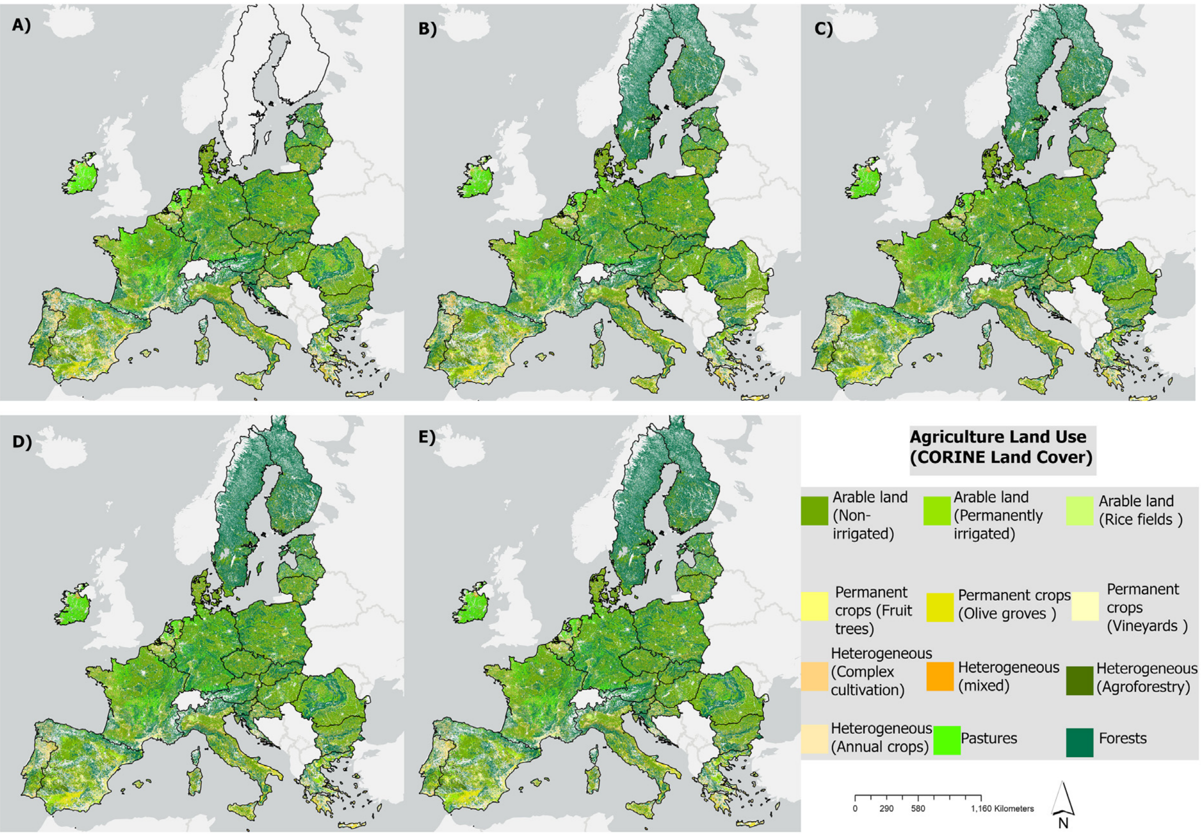


Fig. 3. Agricultural land use pattern from CORINE Land Cover: (A) 1990, (B) 2000, (C) 2006, (D) 2012, (E) 2018.

negative (−0.0706,$p = 0.6177$), though both were statistically insignificant. This suggests that a 1% increase in agricultural land could lead to a 0.07% reduction in agricultural GHG emissions in the short run, but an expected 0.15% increase in the long run. These opposing effects may indicate that short-term land-use expansion includes practices like crop rotation, which initially reduce emissions but eventually contribute to higher emissions as land intensification progresses (Table 2).

Furthermore, the positive coefficients of other variables, such as value-added agriculture (LAVA), crop and livestock (LCP and LLP) production, fisheries production (LFP), and fertilizer consumption (LFC), are linked with increased emissions of GHGs both in the short and long run. It clearly indicates that high GHGs emissions in EU27 are attributed to intensive agricultural expansion for high demand of cereals and animal feed. Notably, a significant ($p < 0.05$) positive coefficient of LCP revealed a 0.2% increase in GHG emissions in the long run and a 0.06% increase in the short run. Moreover, fisheries production revealed a significant 0.03% increase in GHG emissions in the short run and a 0.06% nonsignificant increase in the long run. In contrast, the negative coefficient for forest area (LFA) suggests a mitigating role in emissions, with values of −0.1205 ($p = 0.1631$) in the short run and −0.1866 ($p = 0.5415$) in the long run. While not statistically significant, these estimates support the carbon-sequestering function of forests in offsetting emissions from intensive agricultural activities (Table 2).

The error correction model (ECM) in the short-run analysis is important in time series modeling, as it provides a deeper understanding of long-run dynamics by quantifying the forces that drive the system back towards equilibrium via adjustment coefficients. The negative coefficient of the ECM (−0.5748) is statistically significant at the 1% level ($p < 0.001$), implying that short-run deviations from the long-run equilibrium are corrected annually by approximately 57.5%. The R^2 and adjusted R^2 values of 0.9217 and 0.8979 from the long-run estimation indicate a strong model fit and suggest that around 90% of the variability in GHG emissions is explained by the included agricultural factors (Table 2).

The diagnostic inspection of the ARDL model proved the consistency and reliability of the model's output (Supplementary Table 10). The Jarque–Bera statistic and p value suggested that the residuals exhibited a normal distribution, followed by the Breusch–Godfrey Lagrange multiplier (LM) test, revealing no serial correlation. The Breusch–Pagan–Godfrey test for heteroskedasticity revealed that the data do not exhibit heteroscedasticity. The Ramsey RESET test also confirmed the model. Furthermore, the cumulative sum of recursive residuals (CUSUM) and cumulative sum of squares of recursive residuals (CUSUMSQ) signified ($p < 0.05$) the stability of the model (Supplementary Fig. 1).

3.3.2. *ARDL long-run and short-run estimations for EU-27 member states*

Countrywide, detailed ARDL long- and short-run estimations provide a more profound understanding of sectoral GHG emissions over a specific time frame (Fig. 5, Supplementary Table 11). Countries including Belgium, Finland, Greece, Latvia, Poland, and Spain demonstrated a significant increase ($p < 0.05$, $p < 0.01$) in GHG emissions in the long run, ranging from a minimum of 0.36% in Finland to a maximum of 1.83% in Spain, associated with a 1% increase in agricultural land (LAL). Sen's slope analysis also revealed an increasing trend in CO_2 emissions in Belgium, Latvia, and Spain. In contrast, several countries—such as Germany, Hungary, Ireland, Portugal, and Romania—showed significant short-run increases in GHG emissions ($p < 0.05$, $p < 0.01$) (Fig. 5A). These short-run rises in GHG emissions are attributed to high fertilizer input and intensive livestock farming. Additionally, land-use conversion from pasture to arable land, as well as deforestation for agricultural expansion, as identified through CORINE change detection, also contributed to this trend.

Moreover, a 1% increase in agriculture, forestry, and fishing value added (LAVA) significantly ($p < 0.05$, $p < 0.01$) increased long-run

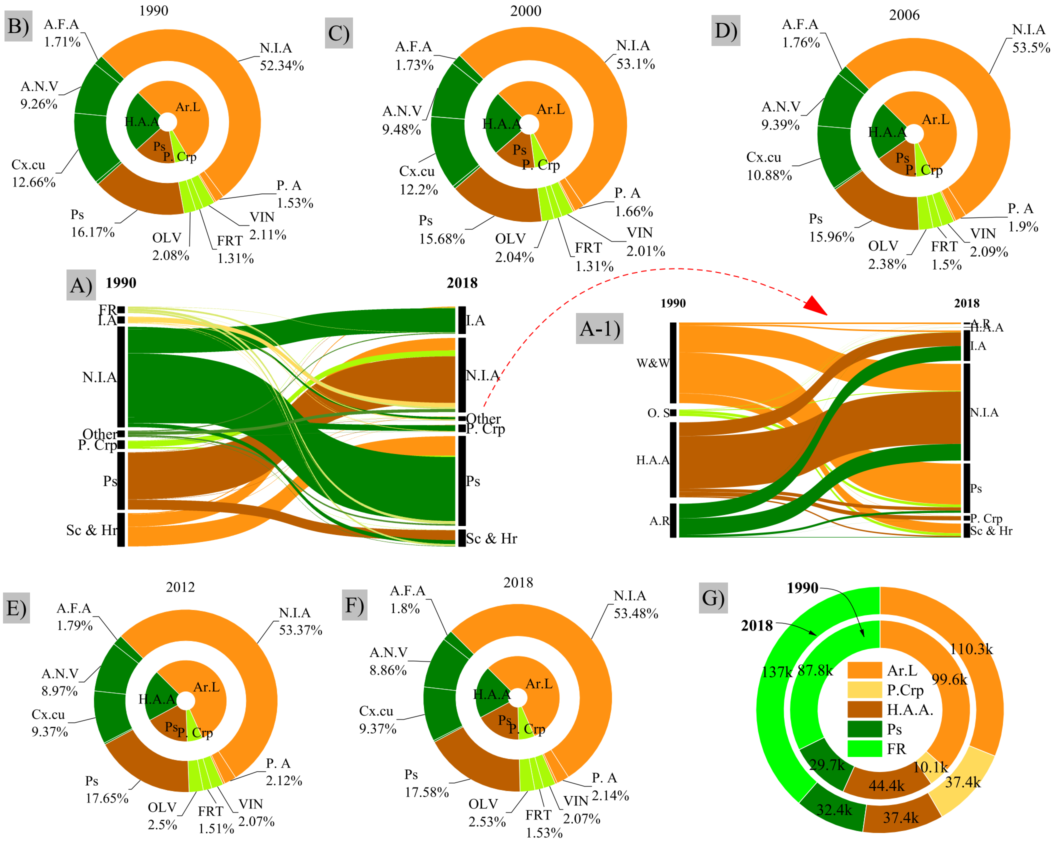
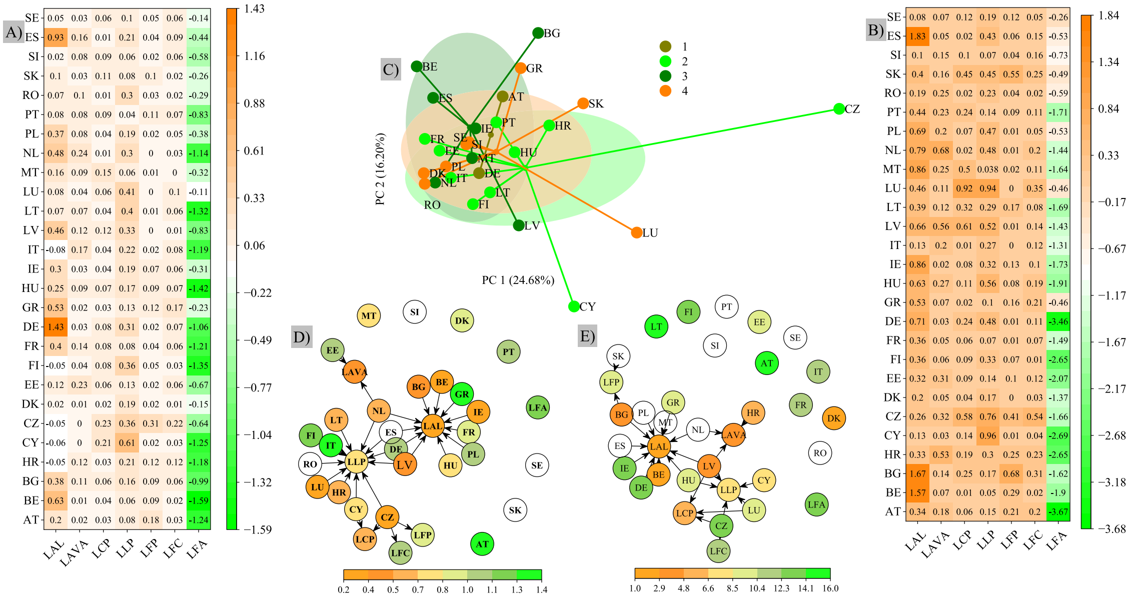


Fig. 4. Transformation of agricultural land use pattern within EU-27 based on CORINE Land Cover from 1990 to 2018: (A) Alluvial chart of agricultural land changes from 1990 to 2018, (A-1) Detailed view of "other" group changes, (B) Agricultural land percentage in 1990, (C) Agricultural land percentage in 2000, (D) Agricultural land percentage in 2006, (E) Agricultural land percentage in 2012, (F) Agricultural land percentage in 2018, (G) Comparison of main agricultural land areas in EU-27 between 1990 and 2018. (Scrub and/or herbaceous (Sc & Hr), Permanent crops (P. Crp), Pastures (Ps), Non irrigated arable (N.I.A), Irrigated arable (I.A), Wetlands & water (W&W), Open spaces (O. S), Heterogeneous agricultural areas (H.A.A), Forests (FR), Arable rice (A.R.), Arable land (Ar.L), Permanently irrigated land (P. A), Vineyards (VIN), Fruit trees (FRT), Olive groves (OLV), Pastures (Ps), Annual crops (An. Crp), Complex cultivation (Cx.cu), Agriculture and natural vegetation (A.N.V), Agro-forestry areas (A.F.A)).



A)

	LAL	LAVA	LCP	LLP	LFP	LFC	LFA
SE	0.05	0.03	0.06	0.1	0.05	0.06	-0.14
ES	0.93	0.16	0.01	0.21	0.04	0.09	-0.44
SI	0.02	0.08	0.09	0.06	0.02	0.06	-0.58
SK	0.1	0.03	0.11	0.08	0.1	0.02	-0.26
RO	0.07	0.1	0.01	0.3	0.03	0.02	-0.29
PT	0.08	0.08	0.09	0.04	0.11	0.07	-0.83
PL	0.37	0.08	0.04	0.19	0.02	0.05	-0.38
NL	0.48	0.24	0.01	0.3	0	0.03	-1.14
MT	0.16	0.09	0.15	0.06	0.01	0	-0.32
LU	0.08	0.04	0.06	0.41	0	0.1	-0.11
LT	0.07	0.07	0.04	0.4	0.01	0.06	-1.32
LV	0.46	0.12	0.12	0.33	0	0.01	-0.83
IT	-0.08	0.17	0.04	0.22	0.02	0.08	-1.19
IE	0.3	0.03	0.04	0.19	0.07	0.06	-0.31
HU	0.25	0.09	0.07	0.17	0.09	0.07	-1.42
GR	0.53	0.02	0.03	0.13	0.12	0.17	-0.23
DE	1.43	0.03	0.08	0.31	0.02	0.07	-1.06
FR	0.4	0.14	0.08	0.08	0.04	0.06	-1.21
FI	-0.05	0.04	0.08	0.36	0.05	0.03	-1.35
EE	0.12	0.23	0.06	0.13	0.02	0.06	-0.67
DK	0.02	0.01	0.02	0.19	0.02	0.01	-0.15
CZ	-0.05	0	0.23	0.36	0.31	0.22	-0.64
CY	-0.06	0	0.21	0.61	0.02	0.03	-1.25
HR	-0.05	0.12	0.03	0.21	0.12	0.12	-1.18
BG	0.38	0.11	0.06	0.16	0.09	0.06	-0.99
BE	0.63	0.01	0.04	0.06	0.09	0.02	-1.59
AT	0.2	0.02	0.03	0.08	0.18	0.03	-1.24

B)

	LAL	LAVA	LCP	LLP	LFP	LFC	LFA
SE	0.08	0.07	0.12	0.19	0.12	0.05	-0.26
ES	1.83	0.05	0.02	0.43	0.06	0.15	-0.53
SI	0.1	0.15	0.1	0.07	0.04	0.16	-0.73
SK	0.4	0.16	0.45	0.45	0.55	0.25	-0.49
RO	0.19	0.25	0.02	0.23	0.04	0.02	-0.59
PT	0.44	0.23	0.24	0.14	0.09	0.11	-1.71
PL	0.69	0.2	0.07	0.47	0.01	0.05	-0.53
NL	0.79	0.68	0.02	0.48	0.01	0.2	-1.44
MT	0.86	0.25	0.5	0.038	0.02	0.11	-1.64
LU	0.46	0.11	0.92	0.94	0	0.35	-0.46
LT	0.39	0.12	0.32	0.29	0.17	0.08	-1.69
LV	0.66	0.56	0.61	0.52	0.01	0.14	-1.43
IT	0.13	0.2	0.01	0.27	0	0.12	-1.31
IE	0.86	0.02	0.08	0.32	0.13	0.1	-1.73
HU	0.63	0.27	0.11	0.56	0.08	0.19	-1.91
GR	0.53	0.07	0.02	0.1	0.16	0.21	-0.46
DE	0.71	0.03	0.24	0.48	0.01	0.11	-3.46
FR	0.36	0.05	0.06	0.07	0.01	0.07	-1.49
FI	0.36	0.06	0.09	0.33	0.07	0.01	-2.65
EE	0.32	0.31	0.09	0.14	0.1	0.12	-2.07
DK	0.2	0.05	0.04	0.17	0	0.03	-1.37
CZ	0.26	0.32	0.58	0.76	0.41	0.54	-1.66
CY	0.13	0.03	0.14	0.96	0.01	0.04	-2.69
HR	0.33	0.53	0.19	0.3	0.25	0.23	-2.65
BG	1.67	0.14	0.25	0.17	0.68	0.31	-1.62
BE	1.57	0.07	0.01	0.05	0.29	0.02	-1.9
AT	0.34	0.18	0.06	0.15	0.21	0.2	-3.67

Fig. 5. Results of the ARDL model applied at the member state level for the EU-27, where the dependent variable is the log of greenhouse gas emissions (LGHG). The figure presents the short-run (A) and long-run (B) impacts of the model. Additionally, panel (C) shows the K-means clustering of EU-27 member states based on the ARDL output in the short and long run. Panel (D) visualizes a network plot based on the incidence matrix using the Fruchterman-Reingold layout method for the short-run, while panel (E) presents the same network plot for the long-run analysis. (Austria (AT), Belgium (BE), Bulgaria (BG), Croatia (HR), Cyprus (CY), Czechia (CZ), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Germany (DE), Greece (GR) (Eurostat: EL), Hungary (HU), Ireland (IE), Italy (IT), Latvia (LV), Lithuania (LT), Luxembourg (LU), Malta (MT), Netherlands (NL), Poland (PL), Portugal (PT), Romania (RO), Slovakia (SK), Slovenia (SI), Spain (ES), Sweden (SE), and European Union (EU); LAL = Agricultural land (sq.km), LAVA = Agriculture, forestry, and fishing, value added (% of GDP), LCP = Crop production (Index), LLP = Livestock production (index), LFP = Total fisheries production (metric tons).).

GHG emissions by 0.05% in Denmark and up to 0.68% in the Netherlands (Fig. 5B). Germany and Portugal were identified as significant ($p < 0.05$, $p < 0.01$) long-run contributors to GHG emissions due to a 1% growth in crop production (LCP), which was also associated with a significant increasing trend in CO_2 emissions, confirmed by Sen's slope values of 11.75 for Germany and 0.07 for Portugal (Supplementary Table 3).

Furthermore, countries such as Cyprus, Finland, Germany, Hungary, Ireland, Italy, Latvia, the Netherlands, Poland, and Spain significantly contributed to long-run GHG emissions through livestock production (LLP), primarily associated with high CH_4 and N_2O emissions. Similarly, fisheries production contributed significantly to long-run GHG emissions in seven EU countries: Austria, Greece, Hungary, Italy, Poland, Portugal, and Spain. Conversely, a 1% expansion in forestland area significantly ($p < 0.05$, $p < 0.01$) reduced GHG emissions—by a minimum of 0.04% in Greece and Luxembourg, and by a maximum of 3.67% in Austria, and 2.6% in both Cyprus and Finland.

Lastly, the K-means clustering of EU-27 member states, based on the ARDL output in the short and long run, revealed four distinct groups: (AT, DE) as one group, (HR, CY, CZ, EE, FI, FR, HU, IT, LT, PT) as a separate group, (BE, BG, IE, LV, MT, NL, ES) in group three, and the final group comprised of (DK, GR, LU, PL, RO, SK, SI, SE) (Fig. 5-C). However, the network plot based on the incidence matrix depicted in Fig. 5-D & E.

3.4. Granger-causality test for the causal relationships between the variables

This study performed a pairwise Granger causality test to investigate the causal relationship involving the variables for more precision in policy recommendations. The synopsis of pairwise Granger causality is shown with the causality direction between the variables (Table 3), for instance, unidirectional causality from left to right (→), bidirectional causality (↔) when both variables cause each other, and no causality (≠). The null hypothesis (H_0) states that the variables do not Granger-cause each other. The pairwise Granger causality assessment exposes unidirectional causality from agricultural land (LAL), agricultural value added (LAVA), crop and livestock production (LCP, LLP), and fertilizer consumption (LFC) to GHG emissions (LGHG) (Table 3). Moreover, the results also indicate unidirectional causality from agricultural land (LAL) to agricultural value added (LAVA), crop production (LCP), and fertilizer consumption (LFC). Additionally, unidirectional causality also detected from crops, livestock, and fisheries production (LCP, LLP, LFP), fertilizer consumption (LFC), and forest area (LFA) to agricultural value added (LAVA). Besides, there is also a unidirectional causality that appeared from fertilizer consumption (LFC) to crop production (LCP). Furthermore, the Granger causality analysis revealed bidirectional causality between forest area (LFA) and agricultural land (LAL), indicating that both variables mutually influence each other (Table 3).

4. Discussion

4.1. Spatial variability in agricultural GHGs emission trends and causes in EU-27

The agricultural sector is a high-potential source and sink of GHGs, including CO_2, CH_4, and N_2O, with 24% of total anthropogenic emissions subject to mechanization and land management practices (Foong et al., 2022; Jantke et al., 2020; Lenka et al., 2015). Therefore, understanding the structure and dynamics of agricultural emissions is extremely important (Genstwa and Zmyślona, 2024). Agricultural land use changes are directly and indirectly linked to sectoral GHG emissions, such as crop and livestock production, and agricultural inputs. Compared with fossil fuels, land use emissions are more complex and challenging to examine and mitigate (Hong et al., 2021; Qin et al., 2024). This is because land-use emissions are influenced by complex spatiotemporal factors, such as seasonal variations and localized practices, making them harder to monitor and mitigate. Most importantly, stabilizing agricultural emissions is crucial for mitigating climate change and ensuring food security (Carlson et al., 2017).

The EU agriculture sector contributes 12% to 15% of total GHGs emissions and showed a highly significant ($p < 0.0001$) decline in all GHGs emissions with Tau = −0.77 and SS = −2190 (Supplementary Table 3). Other regions of the world such as East and South Asia contributed 15% to 30% of global agricultural GHGs emissions, mainly from livestock intensification, rice cultivation, and overuse of synthetic fertilizers, especially in India and China (M. (Pathak et al., 2022)). Similarly, Sub-Saharan Africa and Latin America also contributed high in agricultural GHGs emissions due to livestock growth, enteric fermentation, deforestation, and land conversions (FAO, 2020; Rodrigues et al., 2022). Consistent with our findings, previous scientific reports have demonstrated that GHG emissions from the agricultural sector in the EU 27 significantly decreased from 1990 to 2016, except in Iceland and Spain (Mohammed et al., 2020). Our extended trend analysis (1990 to 2021) also revealed Spain to be a non-reducer EU country along with Estonia, Hungary, Ireland, and Latvia (Fig. 1, Supplementary Table 3). Several agricultural factors are previously identified in literature contributing to high emissions in central and mediterranean EU countries (Aguilera et al., 2021). For example, mineral fertilizers and cattle slurry were significantly reported for increased N_2O emissions due to ammonia volatilization in Spain (Martin-Gorriz et al., 2021; Melián-Navarro and Ruiz-Canales, 2020). Moreover, improper irrigation management such as desalinated sea water increased the energy demand and consumption leading to high GHGs emissions in southeastern parts of Spain (Martin-Gorriz et al., 2014; Aguilera et al., 2021). In the decade from 2010 to 2019, Ireland, Denmark, and Lithuania were the largest emitters of GHGs from agriculture, whereas Malta, Cyprus, and Luxembourg had the lowest GHG emissions from this sector (Murawska and Goryńska-Goldmann, 2023). However, currently, France, Germany, Italy, the Netherlands, Romania, and Poland registered the most significant ($p < 0.001$) reductions in all GHG emissions, with steeper negative Sen slopes (Figs. 1 and 2, Supplementary Table 3). These findings are supported by French policies aimed at decreasing the use of high-carbon energy (Pellerin et al., 2017) and voluntary actions by German farmers (Jantke et al., 2020). Overall, France and Germany showed significant reductions due to policies promoting renewable energy and sustainable agriculture (Ma et al., 2021), while Poland benefited from economic transformation (Zegar, 2021). Moreover, the expansion of renewable energy production in the Netherlands (Batini, 2021), and the dismantling of large state-owned farms, trade liberalization, new investments, and economic transformation in Poland Genstwa and Zmyślona (2024) have also led to reductions in GHG emissions in these countries.

4.2. Spatial dynamics in ARDL cointegration patterns and GHG mitigation across EU-27

Spatial variability in emissions trends is linked to agricultural land use changes and other factors affecting the GHGs emissions in the long and short run. For example, land use change analysis from CLC indicated a 0.08% expansion of agricultural land use since 1990 (Figs. 3 and 4; Supplementary Table 5). This finding is consistent with the cointegration findings of increased GHG emissions of 0.15% in the long run but a 0.07% decline in the short run (Table 2). The decadal land use change fluctuations in agricultural land use are related to short-term declines. The initial expansion of agricultural land was accompanied mostly by maximum crop growth and carbon sequestration, resulting in less GHG emissions in the short run but ultimately increasing them in the long run. The nomenclature of agricultural land use is under huge pressure of abandonment with a net loss of 5.6 million hectares by the year 2030. Among the major contributors of agricultural land loss, will include Spain, Poland, France, UK, Italy, and Germany (Perpiña

Table 3
The results of the pairwise Granger causality test recommending sectoral policies implications.

Null hypothesis (H_0)	F-statistic	Decision on H_0	Causality direction	Policy recommendation
LAL ≠ LGHG	6.266047***	✘	LAL → LGHG	Strict land use planning focusing land zoning, Conserving carbon rich soil such as peatlands & wetlands, Promote agroforestry & crop rotation,
LGHG ≠ LAL	2.50809	✔		
LAVA ≠ LGHG	3.30994*	✘	LAVA → LGHG	Invest & promote in low emission technology such as precision agriculture, Improving resource efficiency for climate smart productivity,
LGHG ≠ LAVA	0.73013	✔		
LCP ≠ LGHG	5.63261***	✘	LCP → LGHG	Agricultural land shifting to low emission cultivation, Promote climate resilient crops, Improving nitrogen use efficiency,
LGHG ≠ LCP	1.53388	✔		
LLP ≠ LGHG	6.44745***	✘	LLP → LGHG	Manure management, Rotational grazing, More focus on F2F strategies, Introducing livestock emission caps,
LGHG ≠ LLP	1.46539	✔		
LFP ≠ LGHG	1.51129	✔	LFP ≠ LGHG	——————-
LGHG ≠ LFP	1.50748	✔		
LFC ≠ LGHG	5.90734***	✘	LFC → LGHG	Integrated nutrient management, Regulating synthetic fertilizer's application, Incentives on organic fertilization,
LGHG ≠ LFC	1.40292	✔		
LFA ≠ LGHG	0.41726	✔	LFA ≠ LGHG	———————
LGHG ≠ LFA	1.58973	✔		
LAVA ≠ LAL	1.83161	✔	LAL → LAVA	Increased agricultural land led to increased agricultural value added, Preventing land use expansion, Yield optimization through smart farming
LAL ≠ LAVA	5.73036***	✘		
LCP ≠ LAL	0.11819	✔	LAL → LCP	Sustainable land use intensification, Promote high yield varieties,
LAL ≠ LCP	4.34607**	✘		
LLP ≠ LAL	1.11993	✔	LLP ≠ LAL	———————-
LAL ≠ LLP	0.96958	✔		
LFP ≠ LAL	0.56325	✔	LFP ≠ LAL	——————
LAL ≠ LFP	1.86709	✔		

(*continued on next page*)

Table 3 (*continued*).

Null hypothesis (H_0)	F-statistic	Decision on H_0	Causality direction	Policy recommendation
LFC ≠ LAL	1.88874	✔	LAL → LFC	Sustainable land use intensification, Promote high yield varieties, Promote organic fertilization
LAL ≠ LFC	4.03869**	✘		
LFA ≠ LAL	6.05413***	✘	LFA ↔ LAL	Focus on LULUCF regulation, Protecting conversion of forest land use to agriculture, Promoting afforestation & reforestation
LAL ≠ LFA	5.98303***	✘		
LCP ≠ LAVA	5.84946***	✘	LCP → LAVA	Crop, livestock, fisheries production, & fertilizers consumption led to agriculture value addition, Integrated monitoring system for crops, livestock, and fisheries, Linking agricultural subsidies to emission intensity
LAVA ≠ LCP	0.81664	✔		
LLP ≠ LAVA	5.73698***	✘	LLP → LAVA	
LAVA ≠ LLP	0.44479	✔		
LFP ≠ LAVA	4.43523**	✘	LFP → LAVA	
LAVA ≠ LFP	1.51094	✔		
LFC ≠ LAVA	4.09518**	✘	LFC → LAVA	
LAVA ≠ LFC	2.44438	✔		
LFA ≠ LAVA	5.54856***	✘	LFA → LAVA	Focus on LULUCF regulation, Protecting conversion of forest land use to agriculture, Promoting afforestation & reforestation
LAVA ≠ LFA	2.35379	✔		
LLP ≠ LCP	0.46590	✔	LLP ≠ LCP	——
LCP ≠ LLP	1.70185	✔		
LFP ≠ LCP	0.30015	✔	LFP ≠ LCP	——
LCP ≠ LFP	0.40164	✔		
LFC ≠ LCP	4.04720**	✘	LFC → LCP	Focus on CAP (2023) & F2F strategy, Emission taxes on synthetic fertilizers, Incentives on organic farming,
LCP ≠ LFC	1.60391	✔		
LFA ≠ LCP	0.12309	✔	LFA ≠ LCP	——
LCP ≠ LFA	0.19705	✔		
LFP ≠ LLP	0.77544	✔	LFP ≠ LLP	——
LLP ≠ LFP	2.58639	✔		
LFC ≠ LLP	0.81602	✔	LFC ≠ LLP	——
LLP ≠ LFC	0.80237	✔		
LFA ≠ LLP	1.76353	✔	LFA ≠ LLP	——
LLP ≠ LFA	1.43600	✔		
LFC ≠ LFP	0.69873	✔	LFC ≠ LFP	——
LFP ≠ LFC	2.47608	✔		
LFA ≠ LFP	1.08821	✔	LFA ≠ LFP	——
LFP ≠ LFA	1.86593	✔		
LFA ≠ LFC	0.22451	✔	LFA ≠ LFC	——
LFC ≠ LFA	1.05790	✔		

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

Castillo et al., 2018). It will be compensated with integrated land use such as Agro-livestock forestry schemes contributing to more carbon sequestration but with high economic trade-offs between food security and environmental sustainability (Strapasson et al., 2020; van Meijl et al., 2006). However, integrated farming system is reported to improve the economic returns with environmental quality outside the EU (Alemayehu et al., 2017). For instance, Xu et al. (2014) also developed a spatially explicit tradeoff model emphasizing the role of payment policies for shifting agricultural land use with high ecosystem service value. The recent agricultural outlook summary of the EU also reported a shift in dietary pattern of EU consumer from livestock towards plant protein, and stable dairy consumption. It would be responsible for major internal changes in agricultural land use such as conversion from cereal to protein crops (soybean, oil seeds, and pulses) (EC, 2024). For instance, simulations of future agricultural land use of EU suggested a technical decline of 123 $MtCO_2$ eq/yr up to 2050 due to dietary change, integrated agricultural pattern, and intensified production (high yield/acre). However, it could potentially affect the food prices and supply, especially in livestock dependent rural economies (Strapasson et al., 2020).

Production-based agricultural emissions are highly linked to global GHG emissions (Foong et al., 2022). The total GHG emissions from the food system were approximately 16 Gt CO_2eq/yr in 2018, with three-quarters generated within the farm gate or in pre- and postproduction activities (Tubiello et al., 2021). CO_2 emissions were highest from pre- and postproduction processes, whereas CH_4 and N_2O emissions were highest from farm gate activities (Tubiello et al., 2022). In Germany and France, LAL, LAVA, LFP, and LFC did not exhibit any significant cointegration with GHG emissions in the long run (Fig. 5, Supplementary Table 11). It implies the effectiveness of smart agricultural policies. For example, in terms of smart production, better management of nitrogen fertilizers and organic farming with incentive policies has effectively reduced GHG emissions in these countries (Black et al., 2021; Kernecker et al., 2020; Széles et al., 2024). France's agricultural Policies and Measures (PaMs) primarily target land use and soil management, with a strong emphasis on reducing nitrogen application. This aligns with the French National Low Carbon Strategy, which aims to cut nitrogen fertilizer use and promote organic farming (German et al., 2021). Long run estimations revealed that Austria, Greece, Hungary, Italy, Poland, Portugal, and Spain also need implementation of such policies to reduce LFC-based GHG emissions (Supplementary Table 12).

Furthermore, Germany demonstrated the highest 0.48% increase in GHG emissions in the long run, with a 1% increase in LLP, followed by a 0.24% increase in per-percent LCP. Similarly, Denmark also revealed 0.19% significant rise in GHGs emissions in the short run, with 1% increase in LLP. This might be attributed to enteric CH_4 and N_2O emissions in the Denmark due to the country's high livestock density (German et al., 2021).

Other countries, such as Cyprus, Finland, Hungary, Ireland, Italy, Latvia, the Netherlands, Poland, and Spain, also exhibited significant cointegration between LLP and GHGs in the long run (Fig. 5, Supplementary Table 11 & 12). Specifically, enteric fermentation and anaerobic wastes remain the largest contributors to CH_4 and CO_2 emissions from LLP (Petrescu et al., 2020). In Latvia, agriculture sector contributed 22% of total GHGs emissions by 2019 which is expected to rise by 2040 mainly due to N_2O emissions from soils and CH_4 emissions from manure management (Ratniece et al., 2017). Hence, key target policy areas in such countries include soil and nutrient management, minimizing fertilizers use and livestock reduction (German et al., 2021). However, an approximately 31% to 35% decline was observed in both emissions attributed to structural economic changes and the energy policies of the EU Emissions Trading System (ETS) (Simionescu et al., 2022; Petrescu et al., 2020).

Similarly, LFP exhibited long run cointegration with GHG emissions in seven EU countries, including Belgium, Finland, Greece, Ireland, Portugal, Slovakia, and Sweden. High fuel consumption by fishing vessels, onboard processing and transportation, and energy intensive fishing policies mainly contributed to a global 179 Mt of CO_2eq in 2011 (Parker et al., 2018). Several EU countries such as Scottland and Sweden focused on multiple regulatory measures such as Common Fisheries Policies (CFP) to promote low carbon fishing integrating fuel taxes and high economic returns (Bastardie et al., 2022; Waldo and Paulrud, 2017).

Hence, our findings reveal a gap between policies and GHG emissions in the long run, identifying the need for more targeted implementation in several sectors, particularly in agriculture value added (LAVA), livestock (LLP), fisheries (LFP), and fertilizers consumption (LFC). Additionally, EU member states aim to reduce 55% of agricultural GHG emissions, balancing offsets by carbon sequestration in forests (Matthews, 2023). This is validated by our findings of a 0.12% GHGs reduction in the short run and a 0.18% reduction in the long run, with a 1% increase in forest area (Figs. 3, and 5). Moreover, CLC change detection also showed a 1.2% increase in forest area in the EU-27 contributing to 7.5% decline in GHGs emissions in the same time span. The standing Biomass, forest soil and wood products act a significant carbon sinker up taking around 435 $MtCO_2$eq/year (Pilli et al., 2022; Strapasson et al., 2020). Moreover, harvested biomass is used as a bioenergy, substituting fossil fuels consumption and reducing the GHGs emissions (Korosuo et al., 2023). However, sustainable forest management policies are still crucial to prevent future carbon emissions.

4.3. Past and current agroclimatic policies in the EU, assessing their effectiveness and suggested improvements

Overall, the significant decline in total GHG emissions by 20 EU countries reflects the implementation of the EU's CAP, which broadly addresses the sustainable management of natural resources and viable food production (Cuadros-Casanova et al., 2023; Kowas, 2022). The CAP initiated in 1960's has undergone several transformations from Agro-environmental and socioeconomic perspectives. Initially, it was designed for a self-sufficient agrifood system with minimal climate focus (Giuliani and Baron, 2025). Enlargement of the EU, rising production, and global trade pressure initiated the need for policy reforms, including MacSharry reforms in 1992 starting a focus on rural development. It was followed by the EU Agenda 2000 and Fischler reform (2003) focusing modulation and cross compliance (Burrell, 2009). Hence, lowering the production incentives and less fertilizer usage brought a significant decline in EU GHGs emissions especially CH_4 and N_2O. However, Vlontzos and Pardalos (2017) suggested the need for further improvements in agricultural emissions. To achieve less than 2 °C of global warming (Wei et al., 2021), CAP reforms from 2014–2022 and new CAP 2023–2027 established a legislative setup for agricultural emissions in the EU that involves direct assistance to farmers and mandatory environmental initiatives, voluntary perks under pillar I, and long term rural development under pillar II (Cagliero et al., 2021; Eskander and Fankhauser, 2020; Pe'er et al., 2019). Hence, the green transition of new CAP (2023-27) supports European green deal targets of combating GHGs emissions, farm to fork strategy, and biodiversity conservation supporting the farmers towards climate smart and sustainable agriculture in EU-27 (Sotte and Vergamini, 2025). Incentives based voluntary policies such as Agri-environmental schemes under CAP pillar II, eco schemes, carbon farming initiatives and mandatory (legally binding) policies such as cross compliance, LULUCF regulations, and Effort Sharing Regulations (ESR) played a key role in mitigating GHGs emissions in EU-27 (Table 4). Table 5 provides a comprehensive review of all EU agroclimatic policies with key goals, strategies for reducing GHGs emissions, economic trade off, and suggested improvements for practical implications in EU-27 (see Table 5).

Table 4
ARDL long and short-run results: dependent variable LGHG.

Variables	Long-run			Short-run		
	Coefficient	*t*-Statistic	p-value	Coefficient	*t*-Statistic	p-value
LAL	0.145806	0.419978	0.6805	−0.070569	−0.509679	0.6177
LAVA	0.049310	0.885465	0.3899	0.071083**	2.754353	0.0148
LCP	0.204672*	1.782752	0.0949	0.060431***	3.288927	0.0050
LLP	0.058589	0.275980	0.7863	0.002233	0.039696	0.9689
LFP	0.064012	1.083912	0.2955	0.037519*	2.016980	0.0620
LFC	0.122976	1.638666	0.1221	0.026441	1.484384	0.1584
LFA	−0.186571	−0.624863	0.5415	−0.120503	−1.466726	0.1631
C	10.58580	1.302190	0.2125	–	–	–
ECM (−1)	–	–	–	−0.574806***	−9.249644	0.000
R^2	0.9217					
Adjusted R^2	0.8979					

LAL = Agricultural land (sq.km), LAVA = Agriculture, forestry, and fishing, value added (% of GDP), LCP = Crop production (Index), LLP = Livestock production (index), LFP = Total fisheries production (metric tons), LFC = Fertilizers consumption (Kg/ha), LFA = Forest area (Km^2)

The changing demographics in the EU, especially an aging population, have a bigger impact on eating habits and household food choices (Perez-Cueto et al., 2022). For example, in northwestern Europe, people are more likely to support a sustainable agri-food system and see reducing meat consumption as part of a healthy lifestyle compared to eastern and southern Europe (de Boer and Aiking, 2022). Hence, dietary shift towards plant-based food cut ammonia emissions by 33% and help to achieve the emission target of EU green deal by 2050 (Himics et al., 2022). Shifting European diets towards EAT-Lancet recommendations reduced animal-based production. However, it leads to income losses (up to 34%) in livestock-heavy regions like Germany, while benefiting vegetable farms (+30%), requiring structural support for impacted farmers (Rieger et al., 2023).

The EU food system is impacted by mentioned (Table 4) agro-climatic policies and regulations such as agricultural subsidies (Heyl et al., 2022). CAP payments constitute the largest expense in the EU budget (Kortleve et al., 2024) but are not effective in transforming agricultural systems or reducing GHG emissions in the long term (Heyl et al., 2022). This is particularly because CAP pre-reforms (before 2013) supported high-emissions livestock farming through mechanisms such as livestock commodity support, direct payments, and explicit support for the production and consumption of livestock products (Baldock and Mottershead, 2017; Kortleve et al., 2024). For example, Gołasa et al. (2021) and Li et al. (2023) reported that LLP and animal-based food were the dominant sources of GHGs emissions compared with energy-related emissions. However, the new reforms in CAP (2023-27) introduced green architecture emphasizing stronger environmental goals strengthening pillar II of rural development (Pe'er et al., 2019).

Despite broader policy discussions, empirical findings from granger causality test suggest sector specific polices (Table 3) for practical implementation in identified EU member states from ARDL long and short run cointegration (Supplementary Table 12). Our previous discussion also provides examples of member states adopting key policies mitigating the agricultural emissions. For example, GHGs emissions in Finland, Portugal, Sweden, Germany, Hungary, Ireland, Italy, Latvia, Netherland, Poland, and Spain are significantly cointegrated with crop and livestock production and need stronger policy implications on soil and manure management, nitrification inhibitors, and green ammonia fertilization for cross sector and cost-effective mitigation (German et al., 2021; Sponagel et al., 2025). For instance, Jantke et al. (2020) also noted that the implementation of fertilizer regulations, which obligate the reduction in phosphates, nitrates, and ammonia release into the environment, contributed to reductions in agricultural emissions. Moreover, despite high abatement marginal costs, nitrogen taxation can be an efficient way to reduce LFC-based GHG emissions (Henseler et al., 2020). Emission taxes are supposed to be a potential tool with agroclimatic framework but inevitably increase the production costs and food price (Stevanović et al., 2017). Other significant impacts include shifts in agricultural land use, and loss of income for small land holders, exacerbating the food insecurity (Fujimori et al., 2022; Tombe and Winter, 0000). Therefore, such kinds of mitigation policies must be supported with alternative socioeconomic incentives offered under voluntary carbon markets to balance between environmental sustainability and economic viability.

Nevertheless, livestock GHG emissions in Europe could be reduced by up to 60% through mitigation opportunities (Goodland, 2014) such as reducing the livestock number and consumption taxes (Jansson and Säll, 2018). Previously, a hypothetical policy-based scenario proposed by Fellmann et al. (2018) demonstrated that technological and management-based solutions, such as anaerobic digestion and precision farming, play crucial roles in reducing agricultural emissions in EU countries. Moreover, the regulation of animal-based production and consumption is needed to facilitate GHG mitigation procedures (Guyomard et al., 2021). Ultimately, the detailed investigations of this research lay the groundwork for suggesting more tailored policies aimed at mitigating GHG emissions across the EU-27 member states, fostering sustainable agricultural practices, and addressing the multifaceted challenges posed by climate change in the agricultural sector. Hence, future policies should focus on promoting renewable energy in agriculture, reducing subsidies for high-emission practices, and incentivizing sustainable land-use changes.

5. Limitations

Our research provides a solid foundation for formulating sector specific policies for mitigating GHG emissions in EU-27 countries. Despite a detailed assessment of agricultural emissions, land use changes and cointegration with agricultural factors, this study is bound to some limitations. First, there is a possibility of inconsistencies in data due to spatial heterogeneity of agricultural systems and emission trends among the member states which might affect the results.

Granger causality may not fully provide a true directive relationship by overlooking underlying structural factors. For example, it shows that livestock production or fertilizers consumption led to GHGs emissions but does not account for subsidy driven intensification or other policy induced factors, type of soil or crop variety etc. Therefore, a granular scale analysis is recommended in future including more factors such as incorporating sub-sectoral breakdown. Moreover, inclusion of other variables, such as enteric fermentation, manure management, and crop-specific production, can also provide a more detailed assessment. Hence, we suggest a scenario-based modeling approach to project future emissions under different policies and technological adoptions. This study also does not account for the role of socioeconomic drivers and technological advancements in agriculture in shaping emissions trends and recommended in future research. Furthermore, ARDL is assumed to be a strong econometric model providing both short and long-run relationship analysis, but the absence of structural breaks or nonlinearities might cause a few uncertainties. Other external factors

Table 5
An overview of EU-27 agroclimatic policy strategies for reducing GHG emissions.

Policy Name	Year Introduced	Duration	Main Goals	Target Group	Key strategies for mitigating GHGs emissions	Economic Trade-offs/ potential risks	Suggested Improvements	Reference
CAP Reform (1992-MacSharry)	1992	1992–2003	Direct payment, Agro-environmental measures	Farmers & Agri-businesses	Cutting support prices for cereals, Direct payment to farmers, less climate focus	Over production, encouraging high emissions and market distortions,	Shift to decoupled payments (based on farm size not production)	(Burrell, 2009)
Fischler Reform (2003)	2003	2003–2013	Decoupled single farm payments, cross compliance & compulsory modulation	Farmers & Agri-businesses	Subsidies shift from production to income support reduced over production and CH_4 emissions. Agri-env schemes mitigate CO_2 and N_2O emissions, less climate focus	Variability in income due to decoupling, Less incentive for Agri-environment schemes, imbalance b/w financial support and sustainable practices,	Decoupling & cross compliance need to be improved by strengthening climate protection, penalties for rule breaking, More focused support on Pillar II	(Burrell, 2009)
CAP (2013-22)	2013	2014–2022	Decoupled single farm payments, cross compliance & compulsory modulation, Agro-environment measures	Farmers & Agri-businesses	Greening direct payments, agroforestry, organic farming & cover cropping reduce fertilizers emissions	Variability in income due to decoupling, Less incentive for Agri-environment schemes, Ignored livestock sector,	Subsidies cut for farmers supporting high livestock emissions, promoting crop diversity and cover cropping, focus on soil management	Navarro and López-Bao (2018)
CAP (2023-27)	2023	2023–2027	Eco schemes, Conditionality, carbon farming, reducing livestock emissions, Precision agriculture & voluntary adjustments	Farmers & Agri-businesses	Direct payments, eco schemes (30% budget) of agroforestry & cover cropping, peatlands & grasslands restoration, carbon farming and renewable energy support improved carbon sink and less agricultural emissions	Eco schemes & conditionality may cause less profit to small land holders,	Advancing agroecological practice, Certified carbon credit framework, Protecting carbon sinks, promoting eco schemes & strict conditionality Strong financial and technical support is needed for smallholders.	(Sotte and Vergamini, 2025)
European Green Deal	2019	2019–2050	Achieve climate neutrality (by 2050), reducing 55% GHGs by 2030, sustainable agriculture, biodiversity conservation	Agriculture, Livestock, Industry, & waste	Reduction of pesticide (50%) & fertilizers use (20%), reducing livestock, control CH_4 and N_2O emissions,	10 to 15% yield reduction, high-cost burdens on livestock farmers, Reduction in farm income, Less funding in Agri technology,	Promote voluntary CAP eco schemes, organic farming, targeted regional support for farmers, more focus on carbon schemes, enhancing green deal funds, promote low carbon aquaculture & sustainable marine production	(Jongeneel et al., 2021)
Farm to Fork Strategy (F2F)	2020	2020–2030	Reduce agricultural emissions by reducing fertilizers use & promoting renewable energy sources, improving organic farming	Farmers, Food businesses, producers, processors, & consumers	Incentives on organic farming, nutrient management, eco schemes, agroforestry, cover cropping, peatlands & grasslands restoration, carbon farming, livestock management	Lower organic yield, Carbon leakage, high food price,	Investment in farm innovation, Carbon Border Adjustment Taxation on synthetic fertilizers	(Wesseler, 2022)

(*continued on next page*)

Table 5 (*continued*).

Policy Name	Year Introduced	Duration	Main Goals	Target Group	Key strategies for mitigating GHGs emissions	Economic Trade-offs/ potential risks	Suggested Improvements	Reference
LULUCF Regulation	2018 (Revised 2023)	2018–2030	Achieve net carbon removals of 310 $MtCO_2eq$ by 2030, 55% reduction in GHGs emissions	Forestry and land managers in EU member states	Improved forest management (reforestation & afforestation), Restoration of peatlands & wetlands, Grassland management, Promote carbon farming, Afforestation, peatland restoration, soil carbon monitoring.	Competition between the demand of bioenergy & carbon storage, Land management cost, Natural disasters such as forest fires disturb the balance	Integrate croplands, wetlands, peatlands for carbon storage and GHGs mitigation, Avoid peatland drainage Wetlands & Peatlands conservation	(Romppanen, 2020)
Effort Sharing Regulation (ESR)	2018	2021–2030	Binding national GHGs emissions targets for non-Emission Trading System (ETS) sectors including Agriculture, Transport, Building, waste management	EU member states	Independent binding emissions targets by each member state, Flexible use of LULUCF credits for cost effective solution, Sectoral focus of GHGs mitigation, e.g., manure management and fertilizers reduction in the Agri sector, Implementing National Action Plans,	Regional disparities among EU states due to income differences and size of sub-sectors, e.g., Eastern EU states bear high costs due to larger agriculture sector, Less income states cannot meet target	Increased funding support for low-income states, Agriculture-specific sub-targets recommended for CH_4 & N_2O mitigation, Penalties for non-compliance, Subsidies for target achievers	(Peeters and Athanasiadou, 2020)

such as climatic variabilities or policy changes may also influence the generalizability of the model.

6. Conclusion

Understanding agricultural GHGs (CO_2, N_2O, and CH_4) emissions originating from various factors is crucial to achieving future policy goals of EU-27. This study evaluates the complex relationship between agricultural factors such as land use, crops, livestock, and fisheries production, fertilizers consumption, agriculture value added, and GHG emissions among member states of EU-27, offering robust econometric evidence to inform future climate-resilient policy interventions. Study findings from ARDL analysis reveal that agriculture value added, livestock, and fisheries production followed by fertilizer consumption have significant long term cointegration in many of the EU member states. It suggests the implementation of strict CAP and EU green deal guidelines to be followed to achieve climate neutrality in near future. Sector specific policy recommendations such as sustainable land use planning to prevent land use conversions, conserving rich carbon soil, investments in low emission technologies, improving nitrogen use efficiency, introducing livestock emission caps, promoting F2F strategies, integrated nutrient management, yield optimization, incentives on organic fertilization, integrated monitoring system for crops, livestock and fisheries are urgently needed at national scale. Such research must be promoted to assist policy makers and agribusinesses at a high spatiotemporal resolution for climate change mitigation and achieving UN defined SDGs.

CRediT authorship contribution statement

Safwan Mohammed: Writing – review & editing, Visualization, Validation, Conceptualization. **Asif Raihan:** Formal analysis. **Sana Arshad:** Writing – original draft, Visualization. **Behnam Ata:** Writing – review & editing. **Akasairi Ocwa:** Writing – review & editing. **Main Al-Dalahmeh:** Writing – review & editing. **Endre Harsanyi:** Writing – review & editing, Methodology.

Declaration of competing interest

None.

Acknowledgment

The authors would like to thank the University of Debrecen and its Program for Scientific Publications for funding open access. The first author also acknowledges support from Hungary's National Research, Development, and Innovation Fund through Project No. TKP2021-NKTA-32, financed under the TKP2021-NKTA funding scheme.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resenv.2025.100239.

Data availability

Available online.

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