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Investigation the nexus between CO₂ emissions, agricultural land, crop, and livestock production in Pakistan

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The ongoing adverse effects of climate change produced by carbon dioxide emissions have sparked global advocacy to face its adverse consequences with the utmost vigor. Pakistan's contribution to global emissions is less than 1% while it is among the most vulnerable countries facing threat of climate change. The sources of carbon dioxide (CO₂) emissions by particular nations must be understood to comprehend the procedures necessary to reduce emissions globally. This study is a contribution to empirics of the CO₂ emissions, gross domestic product, crop production index, livestock production index, population, agricultural land, land under cereal crop and agriculture value-added. This study considered annual data from 1961 to 2014 for the country of Pakistan. We performed an Autoregressive distributed lag (ARDL) bound testing approach to investigate the long-run and short-run association among all research variables. To check the stationarity of the study variables, we also employed Augmented Dickey-Fuller and Phillips-Perron (P.P.) tests. The outcomes of the long-run estimates indicate that the coefficients of agricultural land and land under cereal crop have a positive and significant relationship with CO₂ emissions, while the coefficients of crop production index have a negative and significant relationship with CO₂ emissions, respectively. The outcomes from short-run estimates show that the coefficients of crop production index and livestock production index are both positive and statistically significant, which implies that these variables are crucial in boosting carbon emissions. The error correction model value is also negative and statistically significant, indicating the deviation of CO₂ emissions to other variables from short-run to long-run equilibrium. According to the Pairwise Granger causality test, there is evidence of both unidirectional and bidirectional causation between the research variables. Based on the research outcomes, the government must carefully consider its regulations on agricultural and livestock production and embrace ecologically friendly techniques in the agriculture sector, which may minimize carbon emissions over time.

KEYWORDS

CO₂ emissions, livestock production index, agricultural land, ARDL model, granger causality, Pakistan

Introduction

Greenhouse gas (GHG) emissions and their impact on the external environment are causing severe concerns for businesses, industries and policymakers globally. Global warming is also being taken seriously by almost every country worldwide. Carbon dioxide (CO₂) emissions are one of the main contributors to global warming; thus, it has gained more attention from academicians (Appiah et al., 2017). Nearly 30 billion tonnes of CO₂ emissions are released into the atmosphere each year as a result of day-to-day human activities (Iwata and Okada 2014). The increasing threat of climate change and global warming, which is attributed to rising levels of greenhouse gases, has led to a strand of literature that examines the dynamics of various greenhouse gases (Churchill et al., 2020). Actually, our planet has continuously witnessed the changing of climate since the beginning of time, but especially in the last century, the increase in human activities has led to the shortening of the climate change period (Lott et al., 2017; Bakir et al., 2022). Researchers have investigated the impact and mechanism of agricultural GHG emissions and alternate ways to lessen its effect (Amuakwa-Mensah and Adom 2017; Alper and Onur 2016; Smith 2012). Global food security is being threatened by climate change. This concept increasingly demands human and environmental resources, which poses a severe threat to the social, economic and ecological sustainability of resource-poor developing areas such as South Asia (Bokhari et al., 2018; IPCC 2014; IPCC 2018). Previous scholars argued that the consequences of such weather and climate variability negatively affect these regions' environmental resources (Abid et al., 2016; Woods et al., 2017; Atif et al., 2018). Whereas these contextual settings' economic and social viabilities depend on the agricultural outputs, coordinated efforts are required to ensure agro-based economies' resilience.

The global livestock production is increasing rapidly as the demand for livestock products for human consumption increased. The livestock sector provides more than one-third of human protein needs and is a major provider of livelihood in almost all developing countries. Twenty-six percent of global land area is used for livestock production and forest lands are continuously being lost to such activities (Sakadevan and Nguyen 2017). About 60% of global biomass harvested annually to support all human activity is consumed by livestock industry, undermining the sustainability of allocating such large resource to the industry. It is a major contributor to human nutrition (protein) and health and provides a buffer against grain

shortage assuring food security to human population (Smith et al., 2013). A previous study conducted in Pakistan focused on the relationship between carbon dioxide emissions, crop production, livestock production and population growth. The results from the vector error correction model (VECM) indicated that crops production, livestock production and population growth have a negative effect in the long-run and positive influence in the short-run on carbon dioxide emissions in the study period (Rehman et al., 2021).

Mainly, there are a lot of misconceptions about how agricultural development technologies and climate change may influence crop production capacity as well as operational procedures or driving mechanisms (Zhang and Huang 2013; Tao and Zhang 2013). Agriculture, forestry and land use directly accounts for 18.4% of greenhouse gas emissions while the energy sector generates 73.2% of greenhouse gas emissions in Pakistan. According to the Intended Nationally determined Contribution (INDC), Pakistan's total greenhouse gas emissions have increased by 123% in 21 years from 1994 to 2015. Despite being a low producer of CO₂ emissions (0.2 million metric tons), Pakistan has been one of the most adversely affected countries by global warming. Unfortunately, to address this problem, Pakistan has not taken any significant actions (Smadja et al., 2015). This incurs enormous costs due to property and infrastructure damage, decreased agricultural production, and the cost of rehabilitating regions adversely affected by natural calamities due to frequent climatic disasters. Comparing with other sector like commercial building operations which indicates the most significant potential in cost-effective emission reduction, is essential to be discussed. Previous research conducted in China and the United State (U.S.) investigated the carbon neutrality pathway of the commercial building operations. The results indicated that CO₂ abatement efficiency in China was 1.1–1.9 times that of the U.S., although CO₂ abatement in China and the U.S. in 2001–2018 was very similar (Zhang et al., 2022a). In the same context, to further conduct deep decarbonization and carbon neutrality, strategies of building integrated power generation, building electricity decarbonization and building energy efficiency can achieve 34.3, 29.7 and 22.5% of carbon abatement in China and 31%, 45.4% and 10.2 of carbon abatement in the U.S., respectively (Zhang et al., 2022b). Another study conducted in 16 economies investigated that the carbon intensity will decreased by an average of 1.42 and 2.93% per year in the periods of 2000–2010 and 2010–2019, respectively (Xiang et al., 2022). The study evaluated the carbon emission intensity of global commercial operations

TABLE 1 Data elaboration and sources.

Variables	Abbreviation	Unit of measurement	Source
Carbon dioxide emission	CO ₂	kilotons	FAOSTAT (2021)
Gross domestic product	GDP	Current US \$	WDI (2021)
Crop production index	CPI	(2004–2006 = 100)	WDI (2021)
Livestock production index	LPI	(2004–2006 = 100)	WDI (2021)
Population	POP	Total	WDI (2021)
Agricultural land	AL	Square kilometre	WDI (2021)
Land under cereal crop	LCC	Hectares	WDI (2021)
Agriculture value-added	AVA	Percentage of GDP	WDI (2021)

TABLE 2 Descriptive statistics analysis for all variables.

Variables	LnCO ₂	LnGDP	LnCPI	LnLPI	LnPOP	LnAL	LnLCC	LnAVA
Mean	10.88533	24.21358	4.038919	3.908579	18.37950	12.80024	16.22058	3.290421
Median	10.92998	24.30179	4.121966	3.892334	18.41972	12.79536	16.24839	3.222102
Maximum	12.02154	26.22191	4.753504	4.926166	19.03881	12.86123	16.45170	3.746831
Minimum	9.592673	22.12312	3.003204	2.987700	17.64382	12.77156	15.87711	3.006656
Std. Dev	0.801811	1.193248	0.509219	0.628206	0.432642	0.019460	0.152553	0.196416
Skewness	0.002686	-0.087221	-0.337403	0.093472	-0.143703	0.726173	-0.548516	0.734181
Kurtosis	1.510778	1.953711	1.904573	1.560034	1.696689	3.307942	2.226820	2.385217
Jarque-Bera	4.990073	2.531587	3.724483	4.744013	4.007751	4.959305	4.052896	5.701605
Probability	0.082493	0.282015	0.155324	0.093293	0.134812	0.083772	0.131803	0.057798
Observations	54	54	54	54	54	54	54	54

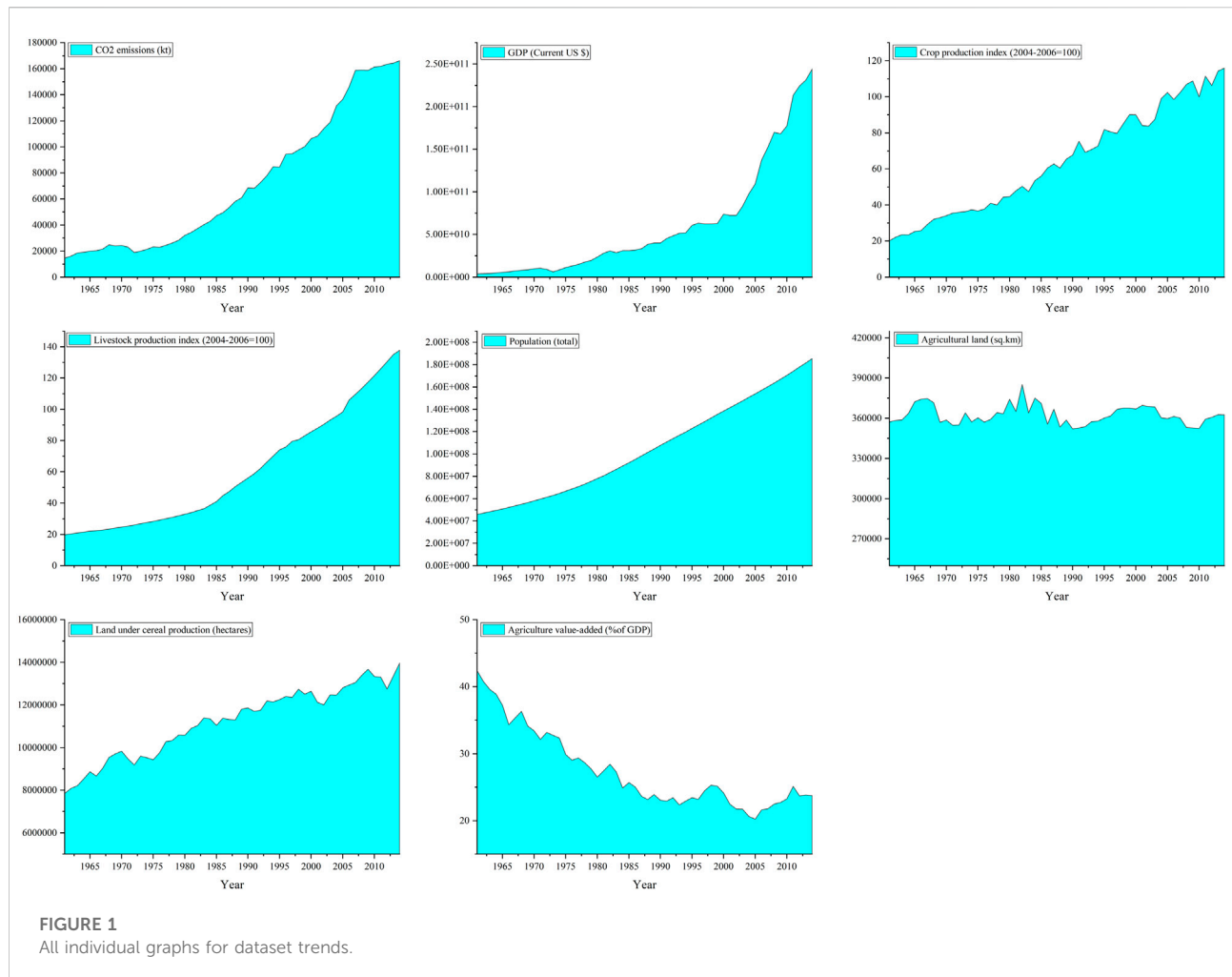
TABLE 3 Correlation statistics.

Variables	LnCO ₂	LnGDP	LnCPI	LnLPI	LnPOP	LnAL	LnLCC	LnAVA
LnCO ₂	1.000000							
LnGDP	0.978197	1.000000						
LnCPI	0.977695	0.982293	1.000000					
LnLPI	0.993391	0.979114	0.978507	1.000000				
LnPOP	0.988421	0.989156	0.992583	0.992774	1.000000			
LnAL	-0.148334	-0.139380	-0.156511	-0.175964	-0.150796	1.000000		
LnLCC	0.956098	0.973567	0.984454	0.949377	0.973312	-0.118678	1.000000	
LnAVA	-0.884455	-0.897413	-0.930436	-0.872307	-0.914255	0.140070	-0.930411	1.000000

continued to decline from 2000 to 2019, and trend was more significant.

Among the developing countries of South Asia, Pakistan's economy is growing rapidly, and it is expected that Pakistan's economic growth will continue with the same trend in the

future (Aftab et al., 2021). Pakistan's economy depends mainly on agriculture, and agriculture is the main dominant sector of the country. Still, due to the rapid growth of the industrial sector in Pakistan, agricultural land is declining. Besides this, rapid growth in population



causes deforestation; Pakistan is the top-ranked country in Asian countries that faces deforestation. Pakistan is one of several countries in the world that are currently at risk from climate change. The nation is experiencing sweltering summer and freezing winter. Meteorological variables monitor resource availability and manage the necessary fundamental growth processes. Because of this, agriculture is very susceptible to climate change. Nonetheless, the phenomena and patterns underlying this fact are vague and ambiguous (Tao and Zhang 2013; Tao et al., 2014; Wilcox and Makowski 2014). In Pakistan, CO₂ emission occupies the maximum share (60 percent) among all the greenhouse gases (Khan et al., 2004). CO₂ emission in Pakistan was noted to be 32,067 kilotons (kt) in 1980 (World Development Indicator), while the trend increased by 8 percent to 10 percent per annum. The total emission of

CO₂ has increased to 158,000 kilotons (kt) since 2014. A study by (Lin and Raza 2020) narrated that over the last few decades, due to extraordinary population growth, agricultural productivity, energy demand and economic growth have solved the problem of food security. However, it exponentially increased the CO₂ emissions in the country. Pakistan's agriculture is a pathway for rural development and earning for rural areas. Directly or indirectly, about 70% of the rural population is involved in the agricultural industry, and agriculture accounts for more than 21% share of Pakistan's GDP (Ahmed et al., 2018; Koondhar et al., 2018). With the intention of raising food production, Pakistani farmers apply fertilizer excessively. Due to over-fertilization, traditional ways of growing food and increasing food production efficiency result in decreased soil fertility, contaminated subsurface water, and higher production cost.

TABLE 4 Results of unit root testing.

Model	ADF at level		ADF at 1st diff		P.P. at level		P.P. at 1st diff	
	t-statistics	p-value [lag]	t-statistics	p-value [lag]	Adj. t-statistics	p-value [Bandwidth]	Adj. t-statistics	p-value [Bandwidth]
Intercept								
<i>LnCO₂</i>	-0.637751	0.8528 [1]	-5.915923	0.0000 [0]	-0.809440	0.8082 [3]	-5.928838	0.0000 [2]
<i>LnGDP</i>	-0.512237	0.8803 [0]	-6.128411	0.0000 [0]	-0.501008	0.8825 [6]	-6.117041	0.0000 [8]
<i>LnCPI</i>	-2.208684	0.2061 [8]	-2.441000	0.1363 [4]	-4.414755	0.0008 [29]	-10.02799	0.0000 [13]
<i>LnLPI</i>	-0.330422	0.9127 [2]	-2.110834	0.2414 [1]	0.600337	0.9885 [5]	-3.569189	0.0098 [3]
<i>LnPOP</i>	-2.166760	0.2207 [4]	-1.862027	0.3465 [10]	-2.225562	0.1999 [5]	-0.655558	0.8485 [5]
<i>LnAL</i>	-5.034311	0.0002 [10]	-4.206926	0.0019 [10]	-4.149930	0.0018 [4]	-11.66262	0.0000 [3]
<i>LnLCC</i>	-1.845078	0.3552 [0]	-7.310103	0.0000 [0]	-2.177064	0.2168 [6]	-7.399540	0.0000 [4]
<i>LnAVA</i>	-2.617304	0.0959 [0]	-6.708506	0.0000 [0]	-2.720270	0.0773 [2]	-6.708506	0.0000 [0]
Trend and Intercept								
<i>LnC O₂</i>	-2.107644	0.5292 [2]	-2.908476	0.1689 [3]	-1.554595	0.7974 [3]	-5.897317	0.0001 [2]
<i>LnGDP</i>	-3.102790	0.1165 [1]	-6.074545	0.0000 [0]	-2.682416	0.2478 [2]	-6.043380	0.0000 [8]
<i>LnCPI</i>	-0.194558	0.9913 [8]	-4.184929	0.0098 [7]	-2.670493	0.2526 [7]	-28.73533	0.0001 [51]
<i>LnLPI</i>	-2.526383	0.3148 [2]	-1.981903	0.5970 [1]	-2.054800	0.5583 [5]	-3.572162	0.0422 [3]
<i>LnPOP</i>	-0.418710	0.9841 [4]	-2.531730	0.3123 [3]	0.643286	0.9994 [5]	-1.861088	0.6602 [5]
<i>LnAL</i>	-5.599904	0.0002 [10]	-4.195096	0.0099 [10]	-4.212997	0.0082 [3]	-11.56574	0.0000 [3]
<i>LnLCC</i>	-3.097552	0.1175 [0]	-5.882637	0.0001 [1]	-3.058810	0.1268 [2]	-7.703130	0.0000 [6]
<i>LnAVA</i>	-1.487037	0.8218 [0]	-4.529780	0.0039 [7]	-1.506937	0.8148 [1]	-7.242419	0.0000 [5]

By 2050, around 20% of the production increases will be due to the expansion of agricultural land (Bruinsma 2009). Nevertheless, studies have shown that even if the two locations' climates are uniform, the agricultural output might still be substantially varied. This is because of the variations in agricultural technology, mechanization, and different inputs like fertilizer and seed. For instance, the average yield in E.U. is 5 tons per hectare, whereas in the developing world, it is 3 tons per hectare and in SSA, it is only 1.2 tons per hectare (FAO 2013). To improve predictions on the consequences of climate change and modern agricultural technology on crop production, it is necessary to identify unanticipated dynamic aspects contributing to crop yield improvement. It will also contribute to enhancing existing agricultural adaptation techniques in the future.

The main contributions of our study are as follows: first, this research work explores the association between carbon dioxide emissions and specific crucial macro-level parameters that have not been studied before in the context of Pakistan. Second, the study tests autoregressive distributed lag model to determine the relationship between CO₂ emissions and all

other chosen parameters. Third, the findings will be helpful to policymakers in establishing an environmental and agricultural-related policy that will strengthen the advanced crop production technologies and reduce carbon emissions to ensure a clean environment. This study recommended the reorganization of production techniques in agriculture in favour of more sustainable practices.

Therefore, this current study employed the ARDL model to identify the relationship between carbon emissions, gross domestic product, crop production index, livestock production index, population, agricultural land, land under cereal crop and agriculture value-added on historical data of Pakistan from 1961 to 2014. The remaining portion of the study is organized in the following way; the second part is a review of previous research on the interconnections among the selected variables. The third part illustrates the materials and methods section, including the model specification and description of the data sources. The fourth part summarizes, the findings and discussions section, which consists of descriptive analysis, unit root measurements,

TABLE 5 Lag selection criteria.

Lag	LR	Final prediction error (FPE)	Akaike information criterion (AIC)	Schwarz information criterion (SIC)	Hannan-Quinn information criterion (HQ)
0	NA	2.04e+64	170.7798	171.0799	170.8948
1	954.6946	5.60e+55	151.0391	153.7408	152.0749
2	171.1558*	5.85e+54*	148.6105*	153.7137*	150.5669*

* indicates lag order selected by the criterion.
 L.R.: sequential modified L.R. test statistic (each test at 5% level).

TABLE 6 ARDL bounds test co-integration (time series model).

Test statistic	Value	Significance (%)	I(0)	I(1)
F-statistic (k)	4.237766 (7)	10	1.92	2.89
		5	2.17	3.21
		2.5	2.43	3.51
		1	2.73	3.9

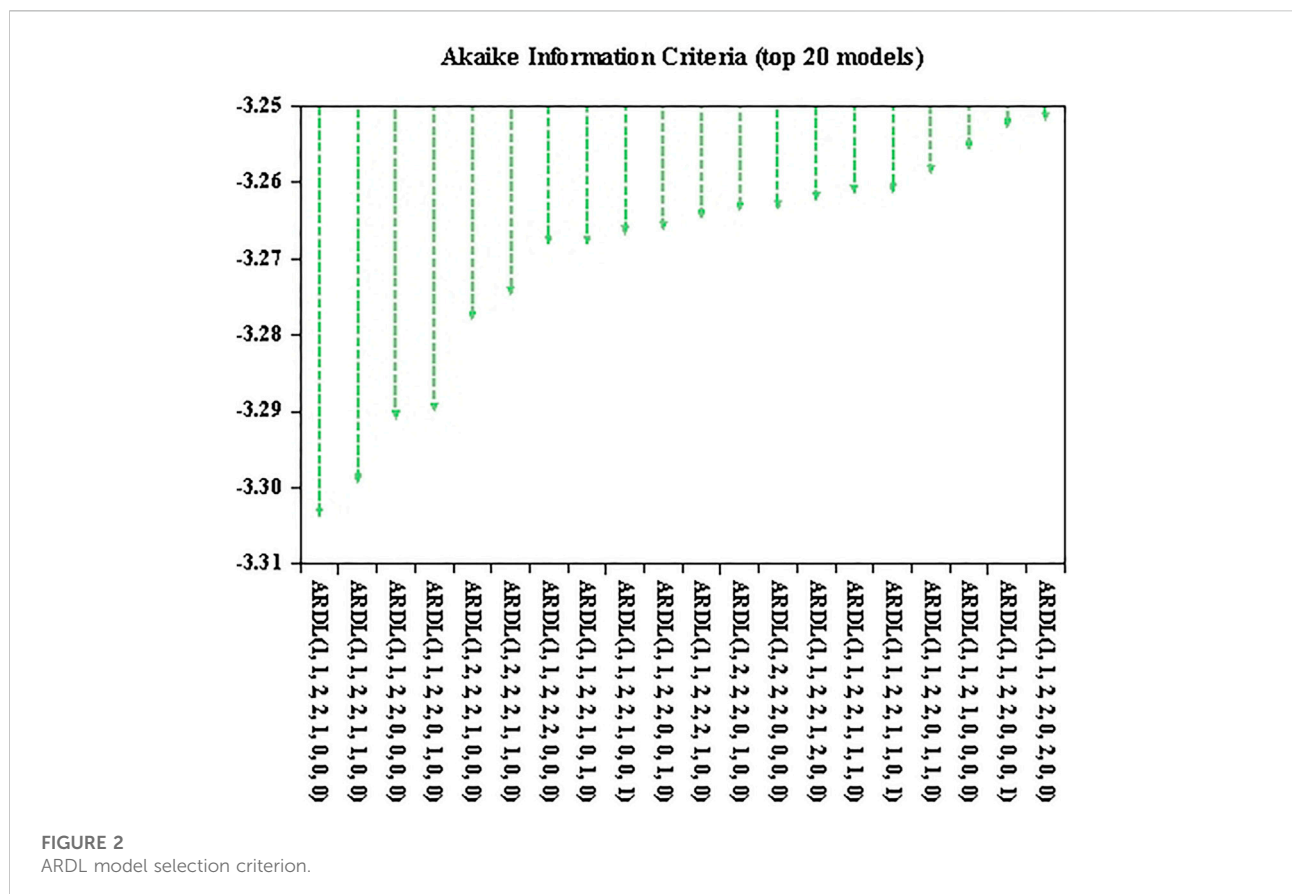


TABLE 7 Johansen co-integration test results.

Unrestricted co-integration rank test (trace)

Hypothesized No. of C.E. (s)	Eigenvalue	Trace statistic	0.05 critical value	Prob.**
None	0.846012	331.7223	159.5297	0.0000
At most 1	0.735804	236.3074	125.6154	0.0000
At most 2	0.675946	168.4231	95.75366	0.0000
At most 3	0.566828	110.9540	69.81889	0.0000
At most 4	0.496274	68.28642	47.85613	0.0002
At most 5	0.326300	33.31455	29.79707	0.0189
At most 6	0.217087	13.17105	15.49471	0.1087
At most 7	0.013431	0.689603	3.841466	0.4063

Unrestricted co-integration rank test (Maximum Eigenvalue)

Hypothesized No. of CE(s)	Eigenvalue	Max-Eigen Statistic	0.05 Critical value	Prob.**
None	0.846012	95.41488	52.36261	0.0000
At most 1	0.735804	67.88436	46.23142	0.0001
At most 2	0.675946	57.46902	40.07757	0.0002
At most 3	0.566828	42.66761	33.87687	0.0035
At most 4	0.496274	34.97187	27.58434	0.0047
At most 5	0.326300	20.14350	21.13162	0.0683
At most 6	0.217087	12.48145	14.26460	0.0939
At most 7	0.013431	0.689603	3.841466	0.4063

Max-eigenvalue test indicates 5 cointegrating eqn(s) at the 0.05 level.

**MacKinnon-Haug-Michelis (1999) p-values.

ARDL bound tests, long-run and short-run estimations and diagnostic tests. The fifth part is the conclusion of the study.

Literature review

Agriculture seems to be the most sensitive economic sector to such changes, and multiple researchers have sought to investigate the consequences of global warming on agricultural yields and productivity over the last 3 decades (Adams et al., 1990; Mendelsohn et al., 1994; Parry et al., 2004; Schlenker and Robert 2009; Attavanich and McCarl 2013; Miao et al., 2015). By the mid of 20th century, agricultural production has been kept at the same speed of growing population to feed the fast-growing population by increasing the applications of inputs which leads to more carbon emission from the agricultural industry (Burney et al., 2010). Likewise, prior research showed that the future food supply availability may not be sufficient to fulfill demand due to climate change's expected negative effects on the global agricultural chain (Attavanich and McCarl 2013; Brown

et al., 2017). It is forecasted that between 2080–2100, the agricultural output will be reduced by 15–30 percent (FAO 2013). Africa, Latin America and Asia may experience a further decline in crop productivity unless proper adaptation strategies are implemented. According to the estimate of previous research, it would cost about 5–10 percent of GDP to implement climate change adaptation strategies in Africa (Boko et al., 2007). Moreover, they anticipated that by 2020, agricultural production would have decreased by around 50 percent, and crop revenue might have dropped by as much as 90 percent by 2100. Therefore agriculture is known as the main contributor to pollution by the different emissions such as carbon emissions from cattle, from agricultural soil due to using fertilizer, and rice production (Tubiello et al., 2013). The increasing applications of fertilizer result in increasing nitrogen emission by the strong influence of radiations (Reay et al., 2012). Considering the increasing demand for fossil fuel in agriculture for operating agro-based modern machinery, it leads to an increase in carbon emission (Lal 2004).

TABLE 8 ARDL long-run and short-run estimations [selected model: (1, 1, 2, 2, 1, 0, 0, 0)].

Long-run estimations

Variables	Coefficient	Std. Error	t-Statistic	Prob
LnGDP	-0.321685	0.297144	-1.082592	0.2860
LnCPI	-2.725534	1.471299	-1.852468	0.0719
LnLPI	-0.207100	1.555614	-0.133131	0.8948
LnPOP	4.248608	3.440926	1.234728	0.2247
LnAL	3.427185	1.874408	1.828409	0.0756
LnLCC	4.394142	1.930914	2.275680	0.0287
LnAVA	-0.447816	0.655396	-0.683275	0.4987
C	-160.4509	79.97072	-2.006371	0.0522

$$EC = \text{LnCO}_2 - (-0.3217 \times \text{LnGDP} - 2.7255 \times \text{LnCPI} - 0.2071 \times \text{LnLPI} + 4.2486 \times \text{LnPOP} + 3.4272 \times \text{LnAL} + 4.3941 \times \text{LnLCC} - 0.4478 \times \text{LnAVA} - 160.4509)$$

Short-run estimations

Variables	Coefficient	Std. Error	t-Statistic	Prob
D (LnGDP)	0.060055	0.050625	1.186275	0.2431
D (LnCPI)	-0.281260	0.115247	-2.440498	0.0196
D (LnCPI(-1))	0.466920	0.109654	4.258125	0.0001
D (LnLPI)	0.713667	0.438129	1.628898	0.1118
D (LnLPI(-1))	1.333191	0.418145	3.188349	0.0029
D (LnPOP)	-8.990074	1.483107	-6.061649	0.0000
ECM(-1)	-0.225329	0.033084	-6.810753	0.0000

As changes to the environment become more dynamic, the impact of livestock farming on the natural ecosystem is becoming more apparent. Not only is livestock a source of milk, eggs and meat, but it is also the primary source of income for a substantial part of the population and a major contributor to national gross domestic product (GDP). A previous study examined the relationship between livestock and crop production and CO₂ emissions using the Autoregressive Distributed Lags (ARDL) model and variance decomposition (Sarkodie and Owusu 2017). The results of this study, set in Ghana, show that increasing crop and livestock production resulted in increased CO₂ emissions. The outcomes also discovered bi-directional Granger causality between crop production and CO₂ and livestock production and CO₂. Another study in BRICS countries investigated the causal relationship between agricultural production and carbon emissions from 1973 to 2013 (Appiah et al., 2018). Using the dynamic ordinary least square (DOLS) and fully modified ordinary least square (FMOLS) methods, a 1% increase in economic growth, crop production, and livestock production increased carbon emissions by 17, 28, and 28%, respectively.

The nexus between agricultural production and carbon emission from agriculture is not certain clear. First, the farmers pay attention to invest in increasing productivity by increasing inputs which exerts pressure on the environment as well as the agriculture industry in the long- and short-run, those applications can increase productivity but instigate damage to the environment and soil fertility in the long run (Koonthar et al., 2021). The consensus among scholars on economic growth and its effect on the environment is that development damages the natural environment, especially during the early stages. Many studies have proved that rapid economic growth leads to a rapid increase in carbon emissions (Kasman and Selman 2015; Azam et al., 2016; Elliott et al., 2017). A comparative study between India and China was conducted on the causal relationship between energy consumption, economic growth and carbon dioxide emissions. In China, economic growth and energy consumption were found to directly cause an increase in carbon emissions, but in India, this relationship could not be established (Jayanthakumaran et al., 2012).

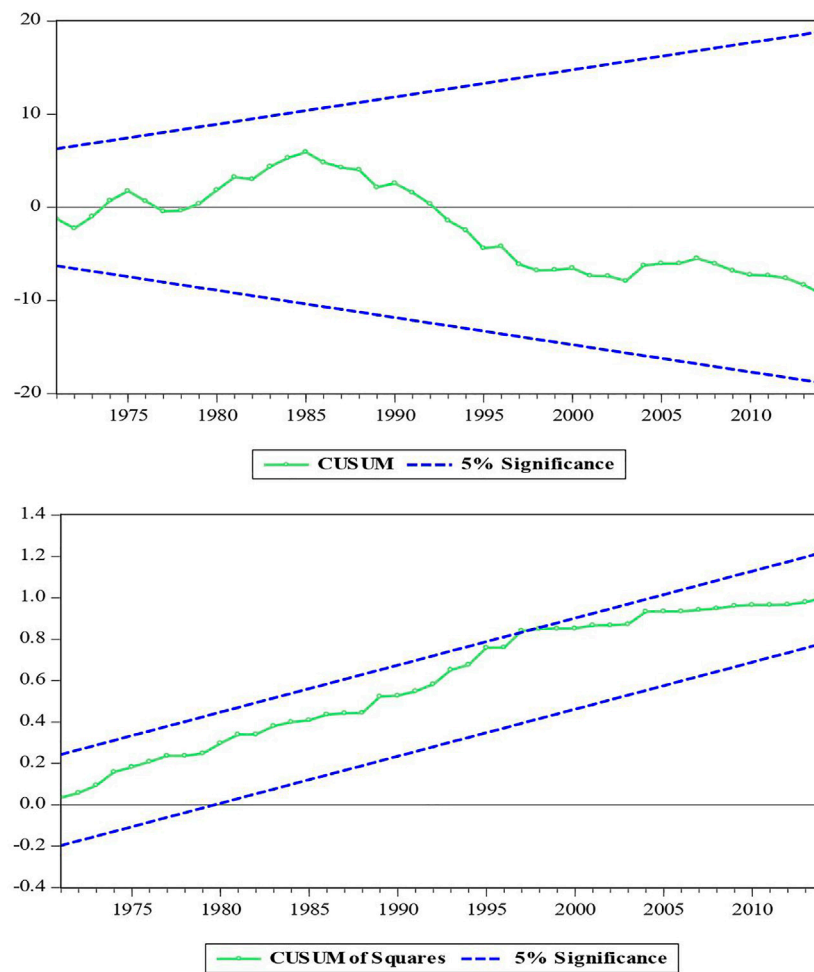


FIGURE 3
CUSUM and CUSUMsquare tests.

The empirical evidence and recent research reflect that population growth is one of the main reasons for CO₂ emissions globally. The previous study conducted in OECD countries proved that; there exists a negative relationship between population growth and emissions (Özokcu and Özdemir 2017). On the other hand, few researchers proved a significantly positive relationship between growth and emissions (Bargaoui et al., 2014; Feng et al., 2015; Yeh and Liao 2017; Yu et al., 2018). The profound study has established a linkage between GDP, agricultural value-added, CO₂ emissions and the occupied land under cereal crops from 1961 to 2014 in Pakistan; it showed an insignificant positive relationship among the mentioned variables in the long run. While, in the short run, it was insignificant and negative. Based on these unique findings, researchers urged policymakers to make policies to minimize CO₂ emissions (Ali et al., 2019b).

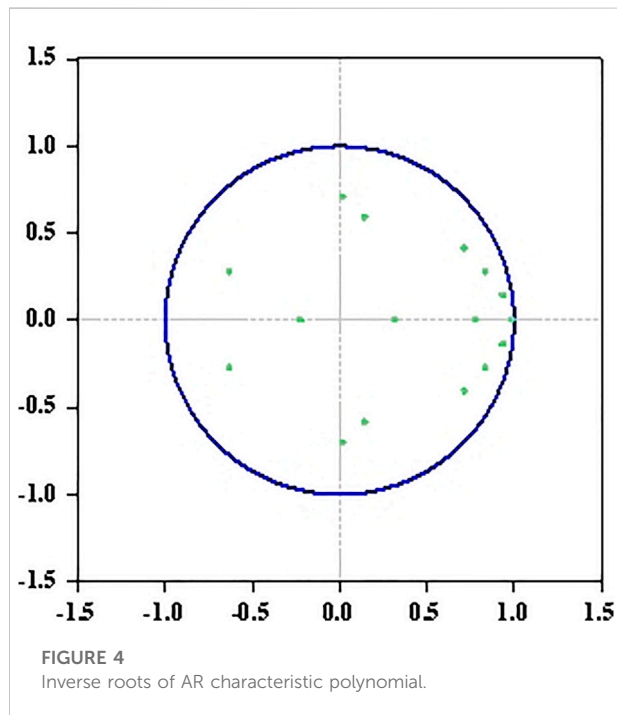
Study materials and methodology

Data sources and description

A recent study considered annual data for Pakistan covering 1961 to 2014. The primary difficulty was data availability; thus, we have chosen a time range due to the limited availability of variables in the study. The different variables data for this study were obtained from the World Development Indicator and the Pakistan statistical yearbook. The present study planned to use carbon dioxide emissions (CO₂) data in kilotons. The gross domestic product (GDP) is measured in current U.S. dollars. The crop production index (CPI) and livestock production index (LPI) data were taken from 2004 to 2006 = 100. Population (POP) data is the country's total population during the study period from 1961 to 2014. The agricultural land (AL) data is taken in square kilometers, while land under cereal crop (LCC) is

TABLE 9 Model diagnostic tests results.

Heteroskedasticity test: Breusch-Pagan-Godfrey		Breusch-Godfrey serial correlation LM test	
F-statistic	2.328662	F-statistic	0.399049
Observed R-squared	15.76503	Observed R-squared	0.988342
Scaled explained SS	26.67757	Prob. F (2,42)	0.6735
Prob. F (8,44)	0.0352	Prob. Chi-Square (2)	0.6101
Prob. Chi-Square (8)	0.0459		
Prob. Chi-Square (8)	0.0008		



taken in hectares. The last variable, agriculture value-added (AVA), is taken as a percentage of GDP. Table 1 summarizes the time-series data used by the model. The objective of this study is to establish the relationship between CO₂ emissions, GDP, CPI, LPI, POP, AL, LCC and AVA, respectively.

Model specification

This research employed Autoregressive Distributed Lag (ARDL) bound methodology introduced by (M. H. Pesaran et al., 2001) to assess the equations when the variables are stable at a level *I(0)* as well as at a first difference *I(1)* (Shahbaz et al., 2013; Asumadu-Sarkodie and Owusu 2016; Rahman et al., 2017; Danish et al., 2018). There might be a possibility of a spurious regression while using time-series data. To avoid spurious regression, a co-integration method was designed and used to identify a long-run connection among time series variables (Nkoro and Uko, 2016). According to the previous

study, the concept of co-integration may be understood when two or more integrated individual series are exhibited, although some of these linear combinations simply show integration at a lower order (Engle and granger, 1987). These sorts of series are considered co-integrated. In this study, we incorporated the ARDL approach to evaluate the long-run association among the modelled variables.

There are several advantages of the model that is used in this study. 1) The ARDL model is appropriate if the sample size is small. 2) Another aspect of the ARDL model is that it is used whether the variables were stationary in their level form [*I(0)*] or integrated at the first order and stationary in their difference [*I(1)*] or a mixture of both *I(0)* and *I(1)*. (c) It is feasible to simultaneously estimate long-run and short-run coefficients using the ARDL model. The short-run coefficients designate the relationship between the deviation of the dependent variable and its long-run tendency. It is essential to mention that in the ARDL approach, both the bias-corrected bootstrap technique and nonlinear functions of the conditional error correction model coefficients can be used to estimate the statistical effects of the long-run relations between study variables.

Relying on the econometric model, this study estimated the linkage between the dependent variable (carbon dioxide emissions) and the independent variables (gross domestic product, crop production index, livestock production index, population, agricultural land, land under cereal crop, agriculture value-added (Zakarya et al., 2015; Rahman et al., 2017; Saidi et al., 2017; Mbarek et al., 2018)). The variables can be expressed using the following econometric notation;

$$CO_2 = f (GDP, CPI, LPI, POP, AL, LCC, AVA) \quad (1)$$

$$\begin{aligned} \ln CO_{2t} = & \gamma_0 + \gamma_1 \ln GDP_{t-i} + \gamma_2 \ln CPI_{t-i} + \gamma_3 \ln LPI_{t-i} \\ & + \gamma_4 \ln POP_{t-i} + \gamma_5 \ln AL_{t-i} + \gamma_6 \ln LCC_{t-i} \\ & + \gamma_7 \ln AVA_{t-i} + \varepsilon_t \end{aligned} \quad (2)$$

All the model variables are converted to their logged form (ln). The parameters in Eq. 2; $\gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma_5, \gamma_6, \gamma_7$ are the long-run elasticity coefficient of gross domestic product, crop production index, livestock production index, population, agricultural land, land under cereal crop and agriculture value-added for carbon dioxide emissions correspondingly and ε_t is the error term.

TABLE 10 Pairwise Granger causality test.

Null hypothesis	Observation	F-statistic	Prob
LnGDP \neq LnCO ₂	52	0.34510	0.7099
LnCO ₂ \neq LnGDP		8.51829***	0.0007
LnCPI \neq LnCO ₂	52	1.54462	0.2240
LnCO ₂ \neq LnCPI		2.02433	0.1434
LnLPI \neq LnCO ₂	52	3.96140**	0.0257
LnCO ₂ \neq LnLPI		2.59882*	0.0850
LnPOP \neq LnCO ₂	52	2.74684*	0.0744
LnCO ₂ \neq LnPOP		12.6480***	0.0000
LnAL \neq LnCO ₂	52	1.08694	0.3456
LnCO ₂ \neq LnAL		1.43496	0.2484
LnLCC \neq LnCO ₂	52	1.91090	0.1593
LnCO ₂ \neq LnLCC		1.81672	0.1738
LnAVA \neq LnCO ₂	52	2.63228*	0.0825
LnCO ₂ \neq LnAVA		0.42783	0.6544
LnCPI \neq LnGDP	52	0.52205	0.5967
LnGDP \neq LnCPI		2.28753	0.1127
LnLPI \neq LnGDP	52	1.40367	0.2558
LnGDP \neq LnLPI		3.54278**	0.0369
LnPOP \neq LnGDP	52	2.79755*	0.0711
LnGDP \neq LnPOP		4.73653**	0.0134
LnAL \neq LnGDP	52	0.06327	0.9388
LnGDP \neq LnAL		0.31887	0.7285
LnLCC \neq LnGDP	52	1.78823	0.1784
LnGDP \neq LnLCC		6.22181***	0.0040
LnAVA \neq LnGDP	52	1.03562	0.3630
LnGDP \neq LnAVA		0.13864	0.8709
LnLPI \neq LnCPI	52	1.67590	0.1981
LnCPI \neq LnLPI		5.08638**	0.0100
LnPOP \neq LnCPI	52	6.07731***	0.0045
LnCPI \neq LnPOP		1.31893	0.2771
LnAL \neq LnCPI	52	3.68734**	0.0325
LnCPI \neq LnAL		0.70677	0.4984
LnLCC \neq LnCPI	52	1.17121	0.3189
LnCPI \neq LnLCC		4.28601**	0.0195
LnAVA \neq LnCPI	52	1.53547	0.2260
LnCPI \neq LnAVA		0.48206	0.6205
LnPOP \neq LnLPI	52	6.12934***	0.0043
LnLPI \neq LnPOP		3.97472**	0.0254
LnAL \neq LnLPI	52	0.65655	0.5233
LnLPI \neq LnAL		0.74754	0.4791
LnLCC \neq LnLPI	52	3.50782**	0.0380
LnLPI \neq LnLCC		2.60024*	0.0849
LnAVA \neq LnLPI	52	6.68756***	0.0028
LnLPI \neq LnAVA		0.36426	0.6967
LnAL \neq LnPOP	52	0.30446	0.7390
LnPOP \neq LnAL		0.30869	0.7359
LnLCC \neq LnPOP	52	0.53077	0.5916
LnPOP \neq LnLCC		8.48616***	0.0007

(Continued on following page)

TABLE 10 (Continued) Pairwise Granger causality test.

Null hypothesis	Observation	F-statistic	Prob
LnAVA ≠ LnPOP	52	1.47963	0.2381
LnPOP ≠ LnAVA		2.09945	0.1339
LnLCC ≠ LnAL	52	0.43003	0.6530
LnAL ≠ LnLCC		0.39629	0.6750
LnAVA ≠ LnAL	52	0.67169	0.5157
LnAL ≠ LnAVA		1.19693	0.3112
LnAVA ≠ LnLCC	52	3.95660**	0.0258
LnLCC ≠ LnAVA		1.43426	0.2485

Note: ≠ means “does not Granger Cause”.

***, **, and * stands for 0.01, 0.05, and 0.10 significance level.

Sources: Author's computation.

Where the Δ is the first difference operator, the parameters $\gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma_5, \gamma_6, \gamma_7$ while the coefficient of the long-run relationship is denoted by $\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6, \varphi_7$ are the elasticities and the ε_t donates the residual term. After validating the long-run relationship between variables in the study, we will evaluate the short-run relationship between variables by developing an error correction model (ECM) based on ARDL techniques. The following is an expression for the error correction model:

$$\begin{aligned} \Delta \ln CO_{2t} = & \gamma_0 + \sum_{i=1}^k \gamma_1 \Delta \ln GDP_{t-i} + \sum_{i=1}^k \gamma_2 \Delta \ln CPI_{t-i} \\ & + \sum_{i=1}^k \gamma_3 \Delta \ln LPI_{t-i} + \sum_{i=1}^k \gamma_4 \Delta \ln POP_{t-i} \\ & + \sum_{i=1}^k \gamma_5 \Delta \ln AL_{t-i} + \sum_{i=1}^k \gamma_6 \Delta \ln LCC_{t-i} \\ & + \sum_{i=1}^k \gamma_7 \Delta \ln AVA_{t-i} + \varphi ECM_{t-i} + \varepsilon_t \end{aligned} \quad (11)$$

Results and discussion

Descriptive statistics and correlations

Descriptive statistical analysis is aimed to understand the fundamental features of all the research variables. Skewness measures the degree of unevenness of the collected data, whereas kurtosis determines the uniformity of the dispersion order. According to Table 2, LnGDP, LnCPI, LnPOP and LnLCC, all have negative leftward tails, while the remaining variables have positive rightward tails, respectively. The Jarque-Bera (J-B) test is used to determine the normality of all variables. The J-B test displays highly insignificant values at a 5 percent significance level, indicating that all the variables' residuals are normal. Consequently, kurtosis can be classified

into three states, 1) Mesokurtic represents the natural dispersion where the kurtosis value is equal to 3, 2) Leptokurtic determines a peaked arc where the positive kurtosis is more than three and 3) lastly the Platykurtic postulates flatted arc where negative kurtosis value is less than 3. The outcomes illustrated in Table 2 demonstrate that only LnAL is Leptokurtic, with the kurtosis value greater than 3. The remaining research variables are Platykurtic, with the kurtosis value smaller than 3.

In order to establish the interrelationship between variables, Table 3 summarizes the correlation analysis conducted for all variables. The findings reveal that LnGDP, LnCPI, LnLPI, LnPOP and LnLCC impact carbon dioxide emissions, with 97.8197 percent, 97.7695 percent, 99.3391 percent, 98.8421 percent, and 95.6098 percent, respectively. It has been illustrated from the trend analysis (Figure 1) that all the research variables except agricultural land and agriculture value-added have an increasing upward trend from 1961 to 2014 in Pakistan.

Unit root test results

Knowing the stationarity characteristics of study variables is crucial before estimating ARDL bounds testing. We initially performed the unit root tests to prevent spurious regression. We use the Augmented Dickey and Fuller (ADF) test that was introduced by (Dickey and Fuller 1979) and Phillips-Perron (P.P.) unit root tests (Phillips and Pierre Perron 1988). According to the ADF results, the variables LnAL and LnAVA were stationary in their level and first difference form (Table 4). At the same time, the outcome from P.P. shows that the variables LnCO₂, LnGDP, LnLPI, and LnLCC were not stationary in level form but became stationary at their first differences at the 1 percent level of significance. Variables LnCPI, LnAL and LnAVA were stationary in both levels and at the first difference at a 1 percent significance level. Table 4. Results of unit root testing.

TABLE 11 Variance decomposition cholesky ordering: LnCO₂ LnGDP LnCPI LnLPI LnPOP LnAL LnLCC LnAVA.Variance decomposition of LnCO₂

Period	S.E.	LnCO ₂	LnGDP	LnCPI	LnLPI	LnPOP	LnAL	LnLCC	LnAVA
01	0.051453	100.0000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
02	0.081393	94.11254	0.011774	0.285123	0.412697	0.020300	2.231137	2.594298	0.332128
03	0.106243	90.60768	1.121883	1.848808	0.697676	0.079684	2.885046	1.867666	0.891557
04	0.126789	87.15499	0.875108	2.640828	0.732681	0.193592	4.589037	1.430672	2.383094
05	0.143857	85.40095	0.702817	3.656783	0.571966	0.165838	4.387040	1.548522	3.566083
06	0.160802	83.27052	0.613208	4.315181	0.520394	0.172954	5.059023	1.756489	4.292231
07	0.174466	82.22265	0.535338	4.421230	0.523415	0.159333	5.363198	1.876163	4.898674
08	0.188156	81.38590	0.484435	4.616554	0.548337	0.161806	5.884705	1.823631	5.094636
09	0.200498	80.50846	0.436803	4.884232	0.566356	0.147344	6.269350	1.885392	5.302063
10	0.212046	79.50379	0.415902	5.447169	0.591452	0.131766	6.508946	1.956828	5.444142

Variance Decomposition of LnGDP

Period	S.E.	LnCO ₂	LnGDP	LnCPI	LnLPI	LnPOP	LnAL	LnLCC	LnAVA
01	0.089550	6.891548	93.10845	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
02	0.147551	31.70923	62.78902	0.576398	0.085136	1.338595	0.927531	0.420960	2.153129
03	0.189403	39.39417	47.44804	1.723039	0.051878	2.345684	0.571162	2.724216	5.741814
04	0.215759	40.59109	42.33837	2.875443	0.049823	2.578815	0.461299	2.815760	8.289400
05	0.243319	39.01985	40.58751	3.771832	0.051551	2.551681	0.424298	2.427650	11.16563
06	0.274108	36.32470	38.61859	4.979566	0.324782	2.842726	0.353785	2.925988	13.62986
07	0.302365	34.37339	36.55937	5.878580	0.880966	3.012581	0.298773	3.712684	15.28366
08	0.326684	32.88687	35.80829	5.956421	1.345093	3.121266	0.273587	3.947706	16.66076
09	0.349730	32.11035	35.26605	6.009610	1.743168	3.137994	0.272763	3.972464	17.48759
10	0.371713	31.45978	34.66379	6.168086	2.094243	3.143804	0.293037	4.165479	18.01178

Variance Decomposition of LnCPI

Period	S.E.	LnCO ₂	LnGDP	LnCPI	LnLPI	LnPOP	LnAL	LnLCC	LnAVA
01	0.051505	0.006386	0.436652	99.55696	0.000000	0.000000	0.000000	0.000000	0.000000
02	0.063421	0.006770	1.268621	96.36854	0.360893	0.227470	1.124615	0.212399	0.430697
03	0.070646	0.650263	1.045712	89.55437	0.334728	0.196550	2.715276	1.819483	3.683613
04	0.079370	0.531105	1.245605	82.58283	0.420237	0.815019	2.196602	3.532688	8.675915
05	0.087010	1.409252	1.115806	76.83165	1.038800	0.889085	2.332731	3.851150	12.53153
06	0.095857	1.384474	1.187285	71.67378	1.555750	1.169898	2.131112	4.805369	16.09233
07	0.102371	1.500847	1.053910	67.85100	2.372145	1.278916	2.282889	5.439023	18.22127
08	0.109322	1.382554	1.074693	64.43943	3.048434	1.365620	2.632503	5.889998	20.16676
09	0.115358	1.283187	1.079195	61.50441	3.800294	1.582194	2.591920	6.374946	21.78385
10	0.121377	1.191585	1.096831	58.50874	4.556436	1.763144	2.773267	6.910119	23.19988

Variance Decomposition of LnLPI

Period	S.E.	LnCO ₂	LnGDP	LnCPI	LnLPI	LnPOP	LnAL	LnLCC	LnAVA
01	0.011634	2.542151	0.464573	1.849006	95.14427	0.000000	0.000000	0.000000	0.000000
02	0.019103	4.502385	0.445772	2.159279	91.07978	0.001151	1.429833	0.333733	0.048063
03	0.027695	4.774824	0.212817	1.088843	89.68823	0.004777	2.091825	2.009444	0.129236
04	0.035596	5.932409	0.163312	0.751226	86.81802	0.002930	3.710740	2.449013	0.172347
05	0.042562	7.051660	0.201378	0.660646	85.66338	0.023786	3.781615	2.413010	0.204528
06	0.049069	7.607380	0.236579	0.801365	84.56050	0.045271	3.997399	2.542453	0.209051

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TABLE 11 (Continued) Variance decomposition cholesky ordering: LnCO₂ LnGDP LnCPI LnLPI LnPOP LnAL LnLCC LnAVA.

Variance decomposition of LnCO₂

Period	S.E.	LnCO ₂	LnGDP	LnCPI	LnLPI	LnPOP	LnAL	LnLCC	LnAVA
07	0.055269	8.472573	0.253869	0.994328	83.29772	0.101744	3.807771	2.886015	0.185985
08	0.061122	9.169633	0.265598	1.175720	82.34329	0.133386	3.688649	3.063463	0.160263
09	0.066636	9.738545	0.323724	1.225184	81.67984	0.161181	3.516732	3.219908	0.134885
10	0.071846	9.989653	0.354834	1.239945	81.37048	0.168968	3.380722	3.379355	0.116042

Variance Decomposition of LnPOP

Period	S.E.	LnCO ₂	LnGDP	LnCPI	LnLPI	LnPOP	LnAL	LnLCC	LnAVA
01	8.56E-05	1.236602	1.540966	28.83939	0.163589	68.21946	0.000000	0.000000	0.000000
02	0.000307	3.397703	1.801112	38.52464	0.019178	54.19114	0.644782	0.276725	1.144726
03	0.000737	6.463457	1.473118	42.56634	0.004093	43.87832	1.735737	0.959625	2.919306
04	0.001454	9.286997	1.384164	42.68470	0.040261	36.69813	2.865398	1.921508	5.118847
05	0.002507	11.18971	1.562250	40.77367	0.257358	32.13746	3.815299	2.896682	7.367571
06	0.003916	12.23031	1.847558	38.26885	0.686052	29.26518	4.487099	3.781368	9.433586
07	0.005680	12.73143	2.127006	35.86867	1.264463	27.35486	4.875576	4.551289	11.22671
08	0.007789	12.95769	2.361195	33.82751	1.920159	25.97473	5.033540	5.198619	12.72656
09	0.010229	13.05841	2.552285	32.16368	2.600800	24.89893	5.036622	5.731995	13.95728
10	0.012984	13.10126	2.708759	30.81876	3.276508	24.01418	4.950967	6.173033	14.95654

Variance Decomposition of LnAL

Period	S.E.	LnCO ₂	LnGDP	LnCPI	LnLPI	LnPOP	LnAL	LnLCC	LnAVA
01	0.017731	1.513547	0.043109	4.961794	0.015709	7.840537	85.62530	0.000000	0.000000
02	0.021344	2.767346	0.155601	9.996214	0.067841	6.090640	79.51636	0.330485	1.075508
03	0.027657	1.652143	0.094790	15.54218	0.105683	5.644718	75.90181	0.314662	0.744007
04	0.030897	2.280077	0.640667	15.71281	0.089307	5.005662	74.95117	0.285496	1.034816
05	0.034243	2.100645	0.527012	18.40067	0.134367	4.654433	73.07903	0.232987	0.870858
06	0.037455	2.493667	0.559064	18.67930	0.134248	4.309556	72.71987	0.214269	0.890023
07	0.039945	2.889459	0.533217	20.14133	0.150294	4.010000	71.20992	0.194535	0.871245
08	0.042739	3.000181	0.548214	20.86079	0.181358	3.761879	70.55356	0.184835	0.909187
09	0.044970	3.375418	0.582954	21.67824	0.210918	3.509298	69.41947	0.217650	1.006046
10	0.047388	3.464223	0.571346	22.33784	0.259193	3.330648	68.76006	0.217615	1.059076

Variance Decomposition of LnLCC

Period	S.E.	LnCO ₂	LnGDP	LnCPI	LnLPI	LnPOP	LnAL	LnLCC	LnAVA
01	0.023886	10.93995	0.119725	10.05463	7.477490	4.518644	2.320741	64.56882	0.000000
02	0.032339	11.21300	1.969477	6.959014	5.296578	4.156007	1.351607	69.05224	0.002080
03	0.037433	18.08795	1.470101	7.409074	4.175880	4.000545	2.513260	60.17368	2.169505
04	0.044287	22.93713	1.355906	5.494167	3.210299	4.932666	1.818014	54.14250	6.109313
05	0.052165	23.89923	1.041967	4.291337	3.184118	5.063046	1.750680	52.45694	8.312683
06	0.058251	22.09156	0.836327	3.490331	3.474126	5.397965	1.764497	51.87488	11.07031
07	0.063684	21.23790	0.756954	2.967119	4.148839	5.649550	1.701780	50.18277	13.35509
08	0.069833	20.20076	0.740871	2.541344	4.991914	5.835392	1.657206	49.09606	14.93646
09	0.075736	19.09465	0.648268	2.287887	5.836008	6.011091	1.621051	48.69767	15.80337
10	0.080883	18.23917	0.595718	2.083895	6.534016	6.096303	1.762521	48.10524	16.58314

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TABLE 11 (Continued) Variance decomposition cholesky ordering: LnCO₂ LnGDP LnCPI LnLPI LnPOP LnAL LnLCC LnAVA.Variance decomposition of LnCO₂

Period	S.E.	LnCO ₂	LnGDP	LnCPI	LnLPI	LnPOP	LnAL	LnLCC	LnAVA
Variance Decomposition of LnAVA									
Period	S.E.	LnCO ₂	LnGDP	LnCPI	LnLPI	LnPOP	LnAL	LnLCC	LnAVA
01	0.041499	0.079441	0.494401	1.846054	2.233642	7.991536	2.525737	8.631109	76.19808
02	0.060791	0.766754	1.216052	0.862849	5.138049	8.522230	2.534145	5.050892	75.90903
03	0.070852	0.737889	0.915486	0.807608	9.692896	7.975831	1.865562	4.147113	73.85761
04	0.079496	0.618240	0.888554	0.856325	12.15552	7.234330	1.759048	4.543905	71.94407
05	0.086869	0.596098	0.747094	0.723295	14.27584	6.855939	1.632949	4.932245	70.23654
06	0.093456	0.593030	0.645484	0.647922	16.27895	6.767788	1.553468	4.849467	68.66389
07	0.099745	0.717681	0.572393	0.612312	17.69585	6.949384	1.406780	4.696362	67.34924
08	0.105944	0.910765	0.508684	0.622350	18.61719	7.200502	1.272238	4.634012	66.23425
09	0.112369	1.171401	0.455747	0.704147	19.22806	7.597147	1.131420	4.437750	65.27433
10	0.119174	1.458415	0.410366	0.919447	19.71454	8.077135	1.009291	4.110995	64.29981

Selection criteria for lag order

It is critical to discover the number of lags that should be utilized in the ARDL estimation. Consequently, we used unrestricted Vector Autoregression (VAR) lag selection criteria to identify the optimal number of lags for the model. Both Akaike Information Criterion (AIC) (Akaike 1974) and Schwarz Information Criterion (SIC) (Schwarz 1978) are some of the most frequently used criteria. This current study used the AIC lag selection analysis, demonstrating that lag two is our model's best-chosen lag value (Table 5). Earlier researchers employed the AIC criteria to determine the lag length in the ADF test (Farhani and Ozturk 2015; Jebli and Ben Youssef 2017; Xu and Lin 2017; Rauf et al., 2018; Ali et al., 2019b; Naseem et al., 2020; Ali et al., 2021a; Ali et al., 2021b).

ARDL testing method

Having performed the unit root test, the next step is to run the ARDL bounds testing technique. Generally, the ARDL bounds testing method is mainly based on the AIC and SIC because they provide relatively parsimonious specifications. The calculated findings in Table 6 demonstrate that the F-statistics calculated value is 4.237766, higher than the lower and upper bound values at a 5 percent significance level, indicating that the ARDL model should be used in this circumstance. The results indicate that the null hypothesis is denied, indicating no co-integration, while the alternative hypothesis of co-integration is acknowledged. Figure 2 illustrates the top 20 probable feasible lags for the ARDL model.

Johansen test of co-integration

Consequently, this research then sums up Johansen's co-integration approach suggested by (Johansen and Juselius 1990) to find out the long-run connection between carbon dioxide emissions, gross domestic product, crop production index, livestock production index, population, agricultural land, land under cereal crop, and agriculture value-added. The outcomes of the trace statistic test showed that six co-integration equations are statistically significant at a 5 percent level (Table 7). Whereas the outcomes of the maximum eigenvalue test showed that five co-integration equations are statistically significant at a 5 percent level. The findings of the trace statistics and maximum eigenvalue tests discover that there has been a long-run relationship between the selected research variables.

Estimations of long-run and short-run

The results of the long-run coefficient were presented in Table 8, which shows that the coefficients of agricultural land and land under cereal crops were both positive and statistically significant. A 1 percent increase in agricultural land and land under cereal crops will lead to a 3.427185 percent and 4.394142 percent increase in CO₂ emissions. The findings also estimated that the population coefficient was positive but not statistically significant. Moreover, the crop production index coefficient was negative and significant, which means that a 1 percent increase in crop production index will lead to a 2.725534 percent decrease in CO₂ emissions. The coefficients of the remaining study variables (gross domestic product, livestock production index and agriculture value-added) were all negative and non-significant.

The empirical data suggest a short-run relationship between the variables based on the ARDL bounds test technique. The coefficient of crop production index and livestock production index are positive and statistically significant at a 1 percent level. This implies that the crop production index and livestock production index will play a critical role in boosting CO₂ emissions in Pakistan in the short run. The results estimate that a 1 percent increase in the crop and livestock production index leads to an increase in CO₂ emissions by 0.466920 percent and 1.333191 percent, respectively (Table 8). The gross domestic product has a positive and non-significant impact on CO₂ emissions in short-run estimates. The findings also reveal that the coefficient of population is negatively significant, meaning that a 1 percent increase in population will lead to an 8.990074 percent decrease the carbon dioxide emissions. The outcomes of the short-run estimates provide an error correction model (ECM) that reflects the co-integration connection between the variables. The outcomes indicate that the coefficient of ECM(-1) is negatively significant at a 1 percent level, indicating that the disequilibria from the shock of previous year converge to the long-run equilibrium in the current year by around 0.225329 percent.

ARDL diagnostic tests

Depending on the recursive regression residuals, the cumulative sum (CUSUM) and cumulative sum of the square (CUSUMsq) analyses were used, as proposed by (Brown et al., 1975), in a befitting manner to implement the model reliability. According to this test, it would be suggested that the estimated coefficient of ARDL model is stable if the statistical line falls within the critical boundaries at a significance level of 5 percent. Figure 3 demonstrates that the carbon dioxide emissions statistics are inside the 5% critical lines, indicating that the model coefficients are stable and that we can confidently perform the ARDL model. Several scholars have also performed CUSUM and CUSUMsq tests to ensure the model's reliability (Ploberger and Kramer 1992; Xiao and Phillips 2002; Lee et al., 2003; Westerlund 2005; Afzal et al., 2010; Huang et al., 2011; Seker et al., 2015; Ali et al., 2019a; Ali et al. 2019b; Ali et al. 2019c; Rehman et al., 2019; Ali et al., 2020). Furthermore, we conduct additional diagnostic tests to confirm the reliability of the ARDL model employed in this research, with favorable outcomes for the selected variables. These diagnostics tests include the Breusch-Godfrey serial correlation L.M. test and the Heteroskasticity test, displayed in Table 9. By demonstrating the inverse root of A.R. polynomial estimate, Pesaran (Pesaran and Pesaran 1997) introduced the stability vector autoregression (VAR) test. Figure 4 demonstrates that all of the green dotted-shaped patterns are contained within the blue circle, indicating that our model is stable and valid.

Pairwise Granger causality and variance decomposition analysis

By hand investigation, to determine the robustness of the selected model, we performed a Pairwise Granger causality test (Granger and Jji 1988). Table 10 estimates the Pairwise Granger causality test, which illustrates the directional relationships between the selected variables at a given time. The findings suggest a unidirectional causality between LnCO₂ to LnGDP, LnPOP to LnCO₂, LnAVA to LnCO₂, LnGDP to LnLPI, LnGDP to LnLCC, LnCPI to LnLPI, LnPOP to LnCPI, LnAL to LnCPI, LnCPI to LnLCC, LnAVA to LnLPI, LnPOP to LnLCC and LnAVA to LnLCC. The results show a bidirectional causality between LnLPI to LnCO₂, LnPOP to LnGDP and LnPOP to LnLPI, respectively.

In addition, we calculated Cholesky's technique of random innovation to determine the variance decomposition for all variables (Payne 2002). The outcomes estimated in Table 11 show that around 0.41 percent of the future variation in LnCO₂ is due to disturbances in LnGDP, 5.44 percent of the future variation in LnCO₂ is due to disturbances in LnCPI, 0.59 percent of the future variation in LnCO₂ is due to disturbances in LnLPI, 0.13 percent of the future variation in LnCO₂ is due to disturbances in LnPOP, 6.5 percent of the future variation in LnCO₂ is due to disturbances in LnAL, 1.95 percent of the future variation in LnCO₂ is due to disturbances in LnLCC, and 5.44 percent of the future variation in LnCO₂ is due to disturbances in LnAVA, respectively. Descriptions from the outcomes indicate that almost 6.16 percent of the future variation in LnGDP is due to disturbances in LnCPI, 2.09 percent of future variation in LnGDP is due to disturbances in LnLPI, 3.14 percent of the future variation in LnGDP is due to disturbances in LnPOP, 0.29 percent of the future variation in LnGDP is due to disturbances in LnAL, 4.16 percent of the future variation in LnGDP is due to disturbances in LnLCC, and 18 percent of the future variation in LnGDP is due to disturbances in LnAVA. Furthermore, suggestions from the outcomes show that nearly 4.55 percent of the future variation in LnCPI is due to disturbances in LnLPI, 1.76 percent of the future variation in LnCPI is due to disturbances in LnPOP, 2.77 percent of the future variation in LnCPI is due to disturbances in LnAL, 6.91 percent of the future variation in LnCPI is due to disturbances in LnLCC and 23.1 percent of the future variation in LnCPI is due to disturbances in LnAVA, respectively. Finally, the evidence from variance decomposition results show that around 1.45 percent of the future variation in LnAVA is due to disturbances in LnCO₂, 0.41 percent of the future variation in LnAVA is due to disturbances in LnGDP, 0.91 percent of the future variation in LnAVA is due to disturbances in LnCPI, 19.7 percent of future variation in LnAVA is due to disturbances in LnLPI, 8.07 percent of the future variation in the LnAVA is due to disturbances in LnPOP, 1 percent of the future variation in

the LnAVA is due to disturbances in LnAL, and 4.11 percent of the future variation in LnAVA is due to disturbances in LnLCC, respectively.

Conclusion and policy implications

The persistent threat posed by climate change resulting from carbon dioxide emissions has compelled world leaders to strive diligently to tackle it with full seriousness. In this study, we analyze the relationships among the carbon dioxide emissions, gross domestic product, crop production index, livestock production index, population, agricultural land, land under cereal crops and agriculture value-added in Pakistan between 1961 and 2014. We perform ADF and PP unit root tests on all research variables before employing an Autoregressive Distributed lag (ARDL) bound technique to determine the short-run and long-run correlations between all study variables.

The outcomes of the short and long-term approximations display that most of the study variables have a statistically positive relationship with the dependent variable (carbon dioxide emissions). The F-statistics value was 4.237766, higher than the upper bound value at a 1 percent significant level. The results of the long-run coefficient show that the coefficients of agriculture land and land under cereal crops were both positive and statistically significant. The findings also estimated that the coefficient of population was positive but not statistically significant. In addition, the coefficient of crop production index was negative and statistically significant, revealing that an increase in crop production index will lead to a decrease in carbon dioxide emissions. The outcomes from short-run estimates show that the coefficients of CPI and LPI are both positive and statistically significant, which implies that these variables are crucial in boosting carbon emissions. According to the short-run relationship estimates, the error correction model (ECM) was negative and statistically significant at a 1 percent level, indicating that around 0.225329 percent of disequilibria from the previous year's shock converge to the long-run equilibrium in the current year. Moving to the Pairwise Granger causality analysis, the outcome reveals unidirectional and bidirectional causality between chosen variables for this research work.

We focused on Pakistan for this research because the country's economic growth and carbon dioxide emissions are

hampered by increasing population and energy shortages. According to the findings of this study, Pakistan should address the major problems facing its agricultural sector, notably those related to crop and livestock output. The outcome of this research might lead to a number of different policy changes that would guarantee long-lasting progress.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization by SA; Data curation by AG and SA; Formal analysis by SA; Methodology by SA and AS; Supervision by MT; Writing-original draft by SA; Writing-review and editing by SA.

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Conflict of interest

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

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Glossary

CO₂ Carbon dioxide	FAO Food and Agriculture Organization
GHG Greenhouse gas emissions	VECM Vector error correction model
DOLS Dynamic ordinary least squares	ARDL Autoregressive distributed lag
ADF Augmented Dickey-Fuller	MENA Middle East and North African
P.P. Phillips-Perron	EKC Environmental Kuznets Curve
BRICS Brazil, Russia, India, China, South Africa	CUSUM Cumulative Sum
ASEAN Association of Southeast Asian Nations	CUSUMsq Cumulative Sum of the Square
INDC Intended Nationally determined Contribution	CIS Commonwealth of Independent States
U.S. United State	WDI World Development Indicator
FMOLS Fully Modified Ordinary Least Square	J-B Jarque-Bera
OECD Organization for Economic Co-operation and Development	CSD Cross-section dependency
GDP Gross domestic product	LM Lagrange multiplier
POP Population	AIC Akaike Information Criterion
AL Agricultural Land	SIC Schwarz Information Criterion
LCC Land Under Cereal Crop	VAR Vector Autoregression
AVA Agriculture value-added	CADF Cross-sectional Augmented Dickey-Fuller
	ECM Error Correction Model