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Asymmetric causality among carbon emission from agriculture, energy consumption, fertilizer, and cereal food production – A nonlinear analysis for Pakistan

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ABSTRACT

Pakistan is an agricultural country where cereal crops are used as a staple food, but with time trend cereal production is decreasing. Therefore, this study aims to investigate asymmetric causality between agricultural carbon emissions, energy consumption, fertilizer consumption, and cereal food production in Pakistan. The secondary time series data over the period from1976 to 2018 was used to estimate the nonlinear-autoregressive distributed lag model. The empirical results of the linear Granger causality test confirm that the causality is running from energy consumption and fertilizer to cereal food production. The nonlinear Granger causality test declares cereal food production Granger cause to agricultural carbon emissions and energy consumption. It also confirms the unidirectional causality running from fertilizer consumption to cereal food production. Furthermore, the results of the nonlinear-autoregressive distributed lag model disclose that the positive and negative change in agricultural carbon emission, energy consumption, and fertilizer causes to changes in cereal food production. The dynamic multiplier curve suggests that positive and negative shocks influence cereal food production. The stability of the model was confirmed by the nonlinear-autoregressive distributed lag cumulative sum and cumulative sum of square test. Therefore this study suggests that it is essential for Pakistani farmers to switch from chemical fertilizer, burning non-renewable energy to organic fertilizer, and renewable energy in order to reduce carbon emission and increase cereal food production with a healthy environment.

Introduction

Agriculture is a pathway of life and tradition which has shaped and sustained the economic life, culture, and feelings of the people. Similarly, Pakistan's agriculture is a pathway for rural development and earning for rural areas. Directly or indirectly, 70% of the rural population is involved in the agricultural industry, and agriculture accounts for more than 21% share of Pakistan's GDP [38,43,42,73]. Though the agriculture industry is known as the backbone of the national economy, and it is trending downward with the events of urbanization, overpopulation, increasing applications of fertilizer, traditional agriculture practices, carbon emissions, and climate change [71],. For th improving agricultural production and meet the food demand by using available natural resources, it is essential to switch to modern agriculture from traditional ones [1],. Adoption of modern agriculture brings another challenge for the environment, it increases the carbon emissions from agriculture due to an increase in energy consumption and over applications of fertilizer, which also significantly affects agricultural production [37,63]. Pakistani farmers engage on over-application of fertilizer wıth the thoughts of increasıng food production. Traditional techniques to produce food and increase food production efficiency, owing to over-fertilization causes to reduce soil fertility, contaminate the underground water, and increase the cost of production. Carbon emission rises from agriculture by using machinery to plough on the soil, and apply different fertilizers, such as Nitrogen, Gypsum, Potashto

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Nomenclature

ACO2	Agricultural Carbon emissions
ADF	Augmented Dickey Fuller
AIC	Akaike Information Criteria
ARDL	Autoregressive Distributed Lag
CO2	Carbon emission
CP	Cereal food production
CUSUM	Cumulative Sum
CUSUMQ	Cumulative Sum of Square
EKC	Environmental Kuznets Curve
EU	Energy Use
FER	Fertilizer consumption
GDP	Gross Domestic Product
GHs	Greenhouse gasses
HQC	Hannan-Quinn Criteria
Ln	Sign of Log
NARDL	Nonlinear Autoregressive Distributed Lag
NEG	Negative
POS	Positive
PP	Phillip Parron
SC	Schwarz Criteria

increase soil fertility. It does not only directly affects agriculture but also affects the environment, living habitats, and farmers' health, as well as raises the production cost of the crop [65].

Energy consumption for agricultural production has developed more demand, because of usage of fossil fuel, chemicals, over applications of fertilizer, pesticide, modern agro-based machinery to significance rises in food production [96],. More energy consumption add footprints of carbon emission, climate change, and effects on human health, therefore it is essential to consume sustainable quantity and quality of energy for producing enough food to meet the food demand along with saving the available natural resources [23,29]. Energy consumption in the agriculture sector of Pakistan is increasing with the time trend so that the related glitches rises. Recently, farmers use more energy for higher production. Consequently, there is no incentive to enlarge the agricultural cultivable land, and farmers do not have sufficient knowledge about more efficient and suitable energy resources to use for getting higher production [46],. The rate of energy consumption in the agricultural industry is nearly associated with agricultural production techniques, the number of applications used by the farmer for getting output along with environmental factors (i.e. *climate change and soil fertility*). Thus, the availability energy resources determines the correlation between climate change and food production [96],.

This study estimated the non-linear autoregressive distributed lag (NARDL) model. NARDL model was recently introduced by Shin et al. [80],. It allows the asymmetric nonlinear cointegration between the dependent and independent variables in a framework of a single equation. It also provides several benefits to analyze the nonlinear cointegration approach as compared to analyze the traditional cointegration such as Engle-Granger and Johansen cointegration test. It is the quintessence for estimation of the dynamic error correction hypothesis, which provides vigorous empirical results for even a small sample-sized data. Another main advantage of the NARDL model is it flexible and it is not necessary all the selected variables need to be stationary at the same level, seems no matter the variables are integrated at order 1 or order 2 still it allows for analysis and gives the best empirical results. Furthermore, the NARDL model permit to estimate the hidden cointegration, the concept of hidden cointegration was constructed by Granger and Yoon [31], and declared that hidden cointegration can be found while there is no-cointegration but sometime it is appeared by the shock of positive and negative changes in variables, and it also helps to make the difference between the non-linear cointegration, linear cointegration as well as lake of cointegration.

In the previous literature some scholars conducted research related to this topic for the same study area, they included carbon emission, energy consumption, agricultural economic growth, renewable energy consumption as well as agricultural productivity, constructing linear regression by the ARDL model. This study differs from the previous work in the followıng ways; in this paper, we choose cereal food production as an endogenous variable and carbon emission from agriculture, fertilizer as well as energy consumption selected as regressors. This study analyzes how does the positive and negative changes in agricultural carbon emissions, energy consumption, and fertilizer consumption effects cereal food production both in the long-run as well as short-run nexus. In this study we also analyzed both linear and non-linear Granger causality tests to clearly understand the correlation between variables. In addition, This study will contribute to better understand the relationship between agricultural carbon emission, fertilizer consumption, and energy consumption with cereal food production. The finding of this study wıll be helpful to policymakers in decision making, and designing improved portfolio diversification strategies for sustainable cereal food production. The findings will also be helpful for the Pakistani government to make the policies for the short-term as well as long-term to reduce the agricultural carbon emission and consumption of chemical fertilizer. Further, this study will contribute to the literature by affırmıng that there is non-linear effect of agricultural carbon emission, energy consumption, and fertilizer use on cereal food production. We constructed a non-linear ARDL model using the time series data span from 1976 to 2018, which is different from previous studies. Although from the previous literature authors have declared long- and short-run association between carbon emission with agricultural productivity. Still, there is a need to investigate asymmetric positive and negative changes influence for confirmation of the trend of agricultural carbon emission with agricultural production as well as fertilizer consumption. However, the main objective of this study is to build and buttress the asymmetric causality of carbon emission from agriculture, energy consumption, fertilizer usage, and cereal food production.

Furthermore, this study is divided into the following sections: Section "Literature review and theoretical analysis", describes the literature review and shows the missing link of research, and the importance of this study as well as the theoretical background. Section "Methodology" is the methodology and this section provides information about the data collection and model specification. Estimated results and discussion are given in Section "Results and discussion". Section "Conclusion and policy implications" is the conclusion and based on the conclusion it recommends the policy implications for sustainable cereal food production.

Literature review and theoretical analysis

From the literature, we found that there is a congested relationship between selected variables, therefore in this study for an easy and clear understanding of the asymmetry association between variables, we review the existing literature to find out the missing link between this research and previous research.

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 [19],. 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 [15,89]. Several mitigation policies were developed in diverse costs, but make it essential to change in agricultural practices for consumption trends. Considering the policies for food supply owing to saving natural resources by a healthy environment [69,84]. 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. The increasing applications of fertilizer result in increasing nitrogen emission by the strong influence of radiations [64],. Considering the increasing demand for fossil fuel in agriculture for operating agro-based modern machinery, it leads to an increase in carbon emission [45],.

The literature considering carbon emission, energy consumption, and agricultural productivity covers several researchers who investigated the association. Early research has taken account of energy consumption, CO2 emission, and technical efficiency of potato for Iranian agriculture. Results reveal that seed, irrigation water, and energy consumption shows a positive and significant impact on potato production [60],. A study from Thailand conducted by Soni et al. [85], sorting that the nexus of CO2 emission, energy consumption for rain-fed agricultural production, and the finding connotes that the over use of energy consumption and modern technologies are directly correlated with farm economic and climate change. Major energy consumption so-called fossil fuel as fresh pond culture depends on fish feed. Feedstock productivity possible to increase by reducing fertilizer and energy consumption to achieve targeted food production by reducing in greenhouse gasses emissions [57],. [Khoshnevisan et al. 41] estimated the nexus of energy consumption, Greenhouse gasses (GHs) emission for the open farm of strawberry production in Iran. Their results reveal that the optimization utility of energy consumption in the GHs production resulting in reducing total GHs significantly. Ozturk [58] a dynamic nexus between agricultural sustainability, food-water-energy, and poverty using panel data for sub-Saharan African countries from 1980 to 2013. The overall results concluded that forest area, cereal yield, and agricultural value-added have a negative and significant influence on the food-water-energy poverty nexus, which brings to economic growth and price level with the costs of degradation in the environment. Several researchers found the positive and significant impact of carbon emission, fertilizer consumption, and fertilizer intake as well have a significant effect on different crop production and technical efficiency [48,40,53,52,13,65,39].

Considering the model estimations, different scholars used different models to analyze the linear or non-linear nexus between desired variables. Chandio et al [21] from Pakistan estimated the relationship of energy consumption and agricultural economic growth by using ARDL model analyses for the time series data from 1984 to 2016. Their findings reveal that agricultural economic growth is positively and significantly affected by energy consumption both in the long- and short-run. Another study from Pakistan argued that changes in prices of energy (i.e. *fuel, gas e.t.c*) significantly affect farm income as well as farm productivity [21]. Recently Sharif et al. [79] reinvestigate the non-renewable and renewable energy consumption on Turkey's ecological footprints by using Quantile ARDL. The results concluded that there is bidirectional nexus running from non-renewable energy consumption, renewable energy consumption, and economic growth towards the ecological footprint. An earlier study conducted by Siddique [81] used the ARDL bound testing model and estimated the impact of energy consumption and financial development on CO2. He found that the long-run association running from energy consumption and financial development towards the CO2 emission. For 7-G countries using the historical decomposition approach estimated the environmental Kuznets curve (EKC) hypothesis and results show that for the UK, the USA, Japan, Canada, and Germany have the contrary EKC results. Besides, results also reveal that there is a N-shaped EKC curve in France and Italy [14]. A study used panel data from 1980 to 2014 for South Asian countries to estimate the short-run and long-run nexus between economic growth, trade openness, urbanization, and technology in the environment, and results shows an inverted U-shaped curve of EKC between carbon emission and economic growth [50]. Some other authors also found U-shaped EKC curve [25,76,75,5,12,17,86,43,42,87,91]. For China from the dearth of literature, it can be seen that numerous researchers have used the ARDL model to investigate the nexus of CO2 emission with a different time lag as well as using ARDL bound testing model [9,35,77,34,78,94,95,26,44]. AhAtil et al [2] investigated the factor influencing CO2 emission using panel data of 1970Q1 to 2014Q4 by analyzing the NARDL model. Their findings divulge that in the short-run economic, social globalization and financial globalization have a positive and significant influence on CO2 emissions. Hammoudeh et al [33] applied NARDL model to empirically investigate energy cost passing through CO2 emission, they found that energy cost price including crude oil, electricity, and fossil fuel shows non-linear and asymmetric association with CO2 emissions. Estimating the NARDL model concluded the asymmetric significantly negative effect of non-renewable energy consumption on economic growth [10]. No asymmetry association running from carbon emission, financial development importing provision to symmetric impact by the shock of positive and negative change in financial development [3]. From Pakistan by estimating the NARDL model confirmed the increasing industrial causes to increase the CO2 emission while deindustrialization resulting to a decrease in CO2 emissions [92]. For South Africa asymmetries relationship between pollution, energy consumption, and real output using the NARDL model estimated by [54] their findings show that short-run asymmetries are running from energy consumption and CO2 emission to real output. Further confirmed the positive and significant correlation of real output affected by energy usage and CO2 emission. In previous literature, many scholars estimated the one way as well as two-way asymmetries of CO2 emission by the change of positive or negative in exogenous variables for different countries using different time span panel as well as time-series data [56,3,6,68,93,97,24,88].

From the above dearth of literature, it is clear that many authors using linear and non-linear approaches investigate the long-run and short-run relationship between, energies consumption, greenhouses gases emissions, carbon emissions, economic growth, and agricultural economic growth by using different time span time series and panel data for different countries. Still, there is no author who has done the nonlinear asymmetric analysis for Pakistan by selecting agricultural carbon emission, energy consumption, fertilizer, and cereal food production. Therefore, for the analysis of asymmetry causality between agricultural carbon emission, energy consumption, fertilizer and cereal food production, this study first of all analyzed the Augmented Dicky Fuller, Phillip Perron, and structural breaking unit root test to check the stationarity of the variables and checking the breaking structural stationary series. Secondly, this study investigated the linear and nonlinear Granger causality test to investigate the causality between selected variables. Thirdly, this study analyzes the positive and negative asymmetry for both long-run and short-run nexus to check how does the positive or negative shock of regressors resulting to change in cereal food production in the short-run as well as long-run. In the fourth, this study analyzes the dynamic multiplier to confirm the linear trend of the variables, and for confirming the stability of the model cumulative sum and cumulative sum of square were analyzed.

Theoretical analysis

Before going for further analysis. First, we want to demonstrate how carbon is emitted by agriculture, how does energy is used in agriculture, the effects of fertilizer is causes to increasing carbon emission, and how does the whole system positively or negatively affect cereal food production. In the Fig. 1, can be seen that it is just like a recycling system that carbon emission from agriculture and its return to the effect on agricultural products and the environment. In order to meet the food demand, farmers do over application of fertilizer and modern agricultural machinery which causes them to consume fossil fuel. Fertilizer has a two-way cause of carbon emission; First, the process of producing fertilizer, industry consumes plentiful energy, and discharge smokes in the form of carbon emissions. Secondly, the over-application of fertilizer

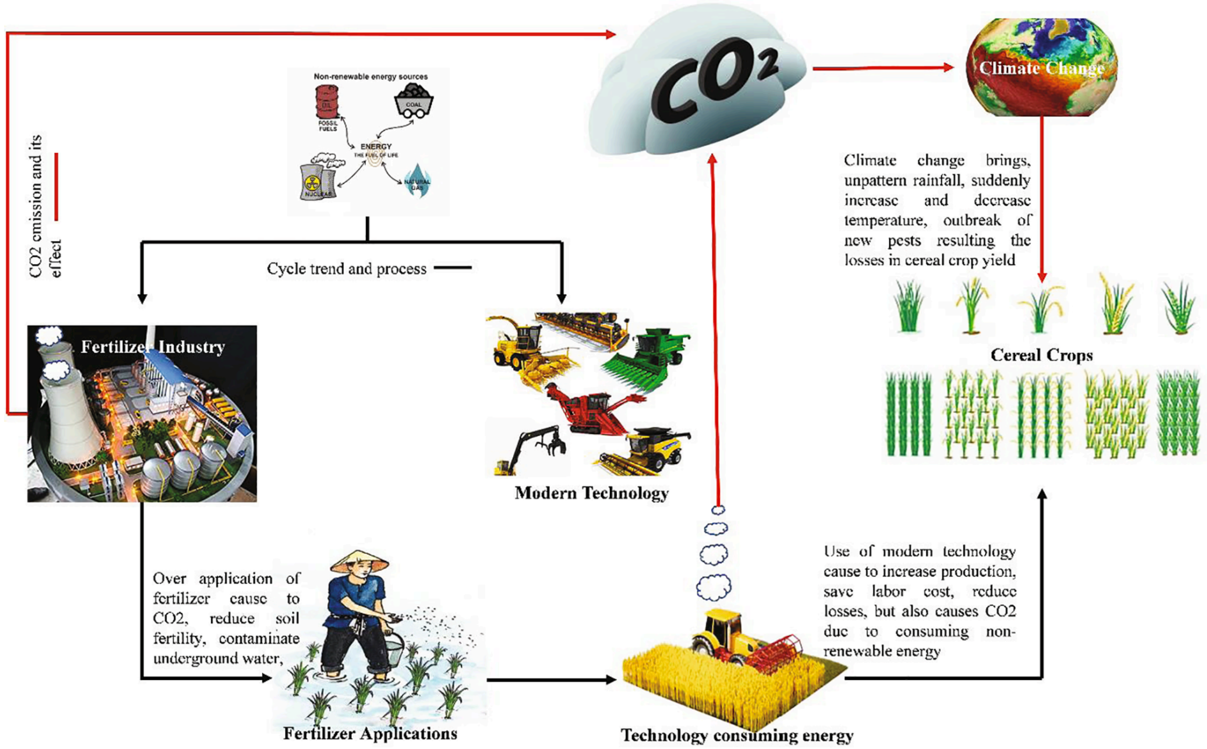

Fig. 1. Theoretical analysis.

combines with water and evaporates in the air. No doubt over-application of fertilizer increases agricultural production in the short-run axis, over usage of fertilizer not only causes carbon emission, but also decreases the soil fertility in the long-run axis, and increase the cost of production as well. Carbon emissions cause change in climate, climate change leads to increased risk of disease, change in raining schedule, and suddenly increase and decrease in temperature, which ultimately leads to reducing grain production.

Methodology

Data collection

For this study, secondary time series data from 1976 to 2018 were collected to investigate the asymmetric causality connection of energy use in agriculture measuring in kg/capita, carbon emission from agriculture 1000 million tons equivalent to CO2, fertilizer usage in kg/hec, and crop production in matric tones was collected from the indicators of World Bank as well as Government of Pakistan. Further details for variables are seen in Table 1.

Table 1
Detail of the variables and data source.

Variable	Abbri	Short-form	Unit	Data Source
Cereal food production	lnFood	Y	Mt	World Bank
Agricultural carbon emissions	lnACO2	X1	1000 m CO2 equi	World Bank
Energy use	lnEU	X2	Kg/capita	World Bank
Fertilizer consumption	lnFer	X3	Kg/hec	Government of Pakistan

Authors collected.

Model specification

In order to confirm the long-run and short-run asymmetry between the cereal food production energy use, fertilizer consumption, and agricultural carbon emission. This study chooses to analyze the nonlinear autoregressive distributed lag (NARDL) model, it was introduced by Shin et al. [80]. NARDL model is the modified extension of the autoregressive distributed lag (ARDL) cointegration model which was introduced by Pesaran et al. [59]. The simplified linear ARDL model does not contemplate the possibility of positive change or negative change in the independent variable does cause to influence on the dependent variable. While the NARDL model doesn't only show the positive or negative change in explanatory variables, which brings to change in the dependent variable but also allows to estimate the cointegration in a single equation. In addition, there are many more benefits of estimating NARDL which are already previously explained in the introduction section, such as more other cointegration techniques that are commonly used, and it is also more flexible, i.e no need to all variables have stationarity at the same order. It also helps to discover the hidden cointegration nexus between the variables, it avoids omitting the nexus which does not appear in linear ARDL and is convenient to use for a small sample size. Thus study used the NARDL model by estimating a commonly used equation of NARDL including long- and short-run asymmetry regression equation is given below:

$$\nabla Food_t = \omega + \sigma_{Food2} Food_{t-1} + \sigma^+_{EU} EU^+_{t-1} + \sigma^-_{EU} EU^-_{t-1} + \sigma^+_{FER} FER^+_{t-1} + \sigma^-_{FER} FER^-_{t-1} + \sigma^+_{ACO2} ACO2^+_{t-1} + \sigma^-_{ACO2} ACO2^-_{t-1} + \sum_{i=1}^{\sigma-1} \nabla Food_{t-1} + \sum_{i-1}^{\tau-1} (\alpha^+_i EU^+_{t-1} + \alpha^-_i EU^-_{t=1}) + \sum_{i-1}^{\tau-1} (\gamma^+_i FER^+_{t-1} + \gamma^-_i FER^-_{t=1}) + \sum_{i-1}^{\tau-1} (\beta^+_i ACO2^+_{t-1} + \beta^-_i ACO2^-_{t=1}) + \varepsilon_t \quad (1)$$

Where Food reflects cereal food production, ACO2 indicates carbon emission from agriculture, EU stands for energy use in agriculture, FER stands for fertilizer consumption. t refers to the time period, ω_0 specifies the intercept of a constant, ∇ different mechanism, and α,γ,β for the long-run coefficient. The sign of $+$ and $-$ indicate the positive and negative partial sum changing process of the selected variable. In the previous Eq. (1) we run the model independently for each dimension of cereal food production. Therefore for the $Food_t^+$ and $Food_t^-$ see Eqs. (2) and (3).

$$Food_t^+ = \sum_{i=1}^{t} \Delta Food_Z^+ = \sum_{i=1}^{t} max(\Delta Food_z, 0) \quad (2)$$

$$Food_t^- = \sum_{i=1}^{t} \Delta Food_Z^- = \sum_{i=1}^{t} max(\Delta Food_z, 0) \quad (3)$$

The coefficients of short-run (−) and long-run (+) could be estimated like

$$\vartheta_{EU}^+ = -\sigma_{EU}^+/\sigma ACO2\, and\, \vartheta_{EU}^- = -\sigma_{EU}^-/\sigma ACO2\, for\, Energy\, use''EU'' \quad (4)$$

$$\vartheta_{FER}^+ = -\sigma_{FER}^+/\sigma ACO2\, and\, \vartheta_{FER}^- = -\sigma_{FER}^-/\sigma ACO2\, for\, fertilizer\, consumption''FER'' \quad (5)$$

$$\vartheta_{Food}^+ = -\sigma_{Food}^+/\sigma ACO2\, and\, \vartheta_{Food}^- = -\sigma_{Food}^-/\sigma ACO2\, for\, Food\, production''Food'' \quad (6)$$

The long-run symmetry effect of energy use in agriculture, fertilizer consumption, and cereal food production is verified by analyzing the Wald test, considering the null hypothesis $\vartheta_{EU}^+ = \vartheta_{EU}^+, \vartheta_{FER}^+ = \vartheta_{FER}^-, \vartheta_{Food}^+ = \vartheta_{Food}^-$. Similarly, the short-run symmetry of selected variables tested with the Wald test by a hypothesis of $\alpha_i^+ = \alpha_i^-, \gamma_i^+ = \gamma_i^-, \beta_i^+ = \beta_i^-$ for $i = 1,2....,\tau^{-1}$.

Formerly asymmetric identified separately in long-run and short-run or found at the same time in both axis then it is essential to calculate dynamic multipliers that stretch proposed trajectory of CO2 emitted by agriculture with the positive and negative values vicissitudes of EU^+, EU^-, FER^+, FER^-, $Food^+ and Food^-$ respectively. Correspondingly the dynamic multiplier subsequent a value change in $Food_t^+ and Food_t^-$ are estimated as follows.

$$m_{Food,\forall}^+ = \sum_{j=0}^{\forall} \frac{\varphi IP_{t+J}}{\varphi Food_t^+} and m_{Food,\forall}^- = \sum_{j=0}^{\forall} \frac{\varphi IP_{t+J}}{\varphi Food_t^-}, respectively \quad (7)$$

Shin et al [80] reveals that $m_{Food,\forall}^+ \rightarrow \delta_{Food}^+$ and $m_{Food,\forall}^- \rightarrow \delta_{Food}^-$ while $\forall = \varnothing$. Estimated the dynamic multiplier are given below in Fig. 3, for considering the individual shock of regressors selected for this study.

Results and discussion

Table 2 presents the results of the unit root test. Initially, we estimated the unit root test to confirm the stationarity of the variables. Although it doesn't require for the NARDL that all the variables should be stationary at the same order, still we use it to check the stationarity series of the variables. The results of the ADF (*Augmented Dickey-Fuller*) test reveal that lnFood and lnFER rejected the null hypothesis at 1st difference with a significance level of 1%, and lnACO2 and lnEU have the significant sign of 5% acquire the null hypothesis rejected at 5% significant level in 1st difference. While in case of PP (*Phillip-Perron*) test all the variables are integrated at 1st difference with 1% significant level, which means a null hypothesis is rejected and the alternative hypothesis is accepted, and all the variables are integrated at a level I(0) as well as 1st difference I(1) meaning that unit root test allows to smoothly run NARDL model.

Further, the structural break of the unit-root test was applied because in old traditional unit-root tests such as Augmented Dicky Fuller and Phillip Perron ignore to show the breaking stationary series. Therefore, to find the single break in unit-root stationarity series modified tests were introduced by Quandt's statistics, Quandit and Andrew, Zivoit-Andrew, and so on. Thus this study also chooses to estimate the structural break unit-root test. Results present in Table 3 shows that cereal food production is significant at the level of 1% with t-state value of −12.045, and also shows the breaking stationarity series in 1984. Maybe it has a break in 1984 because this year was a better year for agriculture around the world especially for cereal food production [30]. In the case of carbon emission t-state value is matched to the value reported by perron and it is also significant at 1% significant level and reported 2010 is the breaking stationarity year. Energy consumption rejects the null hypothesis and accepts the alternative hypothesis with the value of t-state −6.850 and a 1% significant level. It shows 2008 was the breaking stationarity year for energy consumption because in 2008 the president of Pakistan took the initiative to tackle the shortage of energy supply and it reached crises of energy supply [51]. In addition, the fertilizer consumption accepts the alternative hypothesis and reject the null hypothesis at a 1% significant level, and it reported that 2011 was the stationarity breaking year for fertilizer. It is because the government of Pakistan takes the initiatives to improve the cotton production and boost up the textile industry therefore it urge to farmers produce more cotton and farmers due to lake of modern technologies and proper information just applied more applications of fertilizer which resulting 9.8% more production of cotton in 2011 [66].

Considering the clear causality between variables, we analyzed both linear and nonlinear Granger causality tests to confirm the causality between selected variables. The results of the linear Granger causality test are presented in Table 3 and show that the energy consumption confirms to have unidirectional correlation at 1% significant level, which indicates that energy consumption does Granger cause to cereal food production. Furthermore, fertilizer use in agriculture is also declared to have unidirectional causality with a 1% significant level, which reveals fertilizer use in agriculture does Granger cause to cereal food production. Overall conclude that there is a strong causality correlation between energy consumption fertilizer consumption and cereal food production in Pakistan. Results also confirm the availably of EKC (Environmental Kuznets Curve) between variables selected for this study. Some other authors also used the Granger causality test to confirm the correlation of variables as well as confirmation of EKC [18,74,17,28]. For the results of the nonlinear Granger causality test

Table 2
Results of Augmented Dickey-Fuller and Phillip and Perron based on Unit root test.

Variables	Level		1st diff		Outcome
	Intercept	Trend and intercept	Intercept	Trend and intercept	
Augmented Dickey fuller					
lnFood	−1.862	−4.326[b]	−7.708[a]	−7.637[a]	**Mixed**
lnACO2	−1.509	−2.405	−6.363[a]	−5.075[b]	**I(I)**
lnEU	−2.980	−0.505	−5.041[a]	−6.069[b]	**I(1)**
lnFer	−3.107	−3.105	−6.204[a]	−6.849[a]	**I(I)**
Phillip-Perron					
lnFood	−2.075	−4.292[b]	−10.631[a]	−10.936[a]	**Mixed**
lnACO2	−1.535	−2.551	−6.363[a]	−6.283[a]	**I(1)**
lnEU	−2.903	−0.528	−5.125[b]	−6.064[a]	**I(1)**
lnFer	−7.519	−3.262	−6.256[a]	−12.493[a]	**I(1)**

[a] Acquired null hypothesis rejected at 1% level
[b] Reject the null hypothesis as 5% significant level, Results in author calculation by using Eviews 10.

Table 3
Structural break Unit-root test.

Variables	t-State	Break Year
lnFood	−12.045[a]	1984
lnACO2	−5.228[a]	2010
lnEU	−6.850[a]	2008
lnFer	−7.242[a]	2011

[a] Acquired null hypothesis rejected at 1% level.

please see Table 7, and for the pairwise granger causality test see Appendix 1.

It is necessary to know the appropriate lag order for the estimation of the NARDL model. Pesaran et al indorsed to use AIC (*Akaike Information criteria*), SC (*Schwarz Criteria*), and HQC (*Hannan-Quinn Criteria*). Therefore we also estimated the same criteria equations to confirm the lag order, and our results confirm that lag 4, and 3 are suitable for this study (Fig. 2). In the previous studies, most of the researchers used the same equation to estimate the suitable lag order [98,8,62,70,47].

Table 4 shows the results of NARDL long- and short-run estimations to know the asymmetric nexus between selected variables. NARDL model was estimated using cereal food production as a dependent variable and agricultural CO2 emission, energy use, and fertilizer consumption with the positive and negative change, ACO2_POS ACO2_NEG, EU_POS EU_NEG, FER_POS FER_NEG were selected as independent variables. The suitable lag order (4, 4, 4, 4, 3, 3, 4) was selected to estimate the nonlinear ARDL model. Results show that ACO2_P is significant at a 1% level, and ACO2-N is significant at a 5% level. The cereal food production of Pakistan reacts with higher magnitude while the carbon emission from agriculture increases as well as agricultural carbon emission decreases. We use formula for the calculation of long-run equation in exogenous variables P or N = coefficient of 1st difference divided by coefficient of constant variable 1st difference i.e. ACO2_P+ = ACO2_P (−1)/Food(−1) = −0.8439/−1.1063 = 0.762, ACO2_N = ACO2_N(−1)/Food(−1) = 0.0156/−1.1063 = −0.014. The calculation reveals that the difference of both coefficients are against the value of Wald statistics, and rejected the null hypothesis at 5% and 1% significant levels. This means that the cereal food production of Pakistan can be increased and decreased owing to agricultural carbon emission. In the case of energy use in the agriculture industry the coefficient of 1st difference is positive as well as negative and are significant at 1% level, the calculated significance difference of both coefficients are EU_P = 2.879 and EU_N = −1.138 which reveals that the energy use in agriculture have positive and negative change asymmetric impact on cereal food production Furthermore, the fertilizer application used to produce food show that both positive and negative change with 1st difference are significant at 1% level. Also, the estimated coefficient FER_P = −0.288, FER_N = 3.010 of positive change and negative change in long-run asymmetric reveal that the coefficient of positive shows that 1 unit of fertilizer increasing causes to reduce cereal food production at 0.288% and negative change shows 1% decrease in fertilizer causes to increase cereal food production at 3.010%, while both coefficients reject the null hypothesis at 1% significant level, these results are contrary with the results of [20].

Table 4
Linear Granger causality test.

Null Hypothesis	Linear Granger causality test	Decision	Direction Remarks
LnACO2⇒LnFood	1.885	H_0: Accept	Uni-direction
LnFood⇒LnACO2	1.334	H_0: Accept	
LnEU⇒LnFood	9.112[a]	H_0: Reject	Uni-direction
LnFood⇒LnEU	0.409	H_0: Accept	
LnFER⇒LnFood	7.209[a]	H_0: Reject	Uni-direction
LnFood⇒LnFER	1.736	H_0: Accept	

[a] Null hypothesis rejected at 1% significant level.

It is possible to have a significant asymmetric association with cereal food production due to over applications of fertilizer causes to reduce soil fertility owing to the increasing cost of production. Considering the reduced soil fertility and availability of resources, farmers for achieving higher production, use more applications of fertilizer, and consume more energy to operate modern agro-based technologies to meet the food demand [90]. These factors, energy consumption, and fertilizer consumption increase carbon emission from agriculture, which directly and indirectly reduces agriculture production [58,67]. In the case of the direct effect, it reduces grain size, total grain production, weight loss e.t.c. The indirect effect on food production causes pest attack, changes in the pattern of rainfall, soil erosion, increase salinity, and unhealthy environment causes to reduce farmer's potential which ultimately reduces crop production.

In the case of short-run effect, results reveal that DACO2_P rejected the null hypothesis with a 1% significance level, which means 1% increasing in agricultural carbon emission will significantly increase 0.8742%, and 0.4695% in cereal food production, the accumulated calculation for 1st and 4th difference is 1.343%. .What's more, ACO2_N also rejected the null hypothesis at a 1% significant level, which acquires that a 1% decrease in agricultural carbon emission will cause to change 0.0876%, and 0.0120% in cereal food production with 1st and 4th difference of order lag overall change will be 0.099%. Considering to results of energy consumption shows that 1% more energy consumption leads to change −1.299 in cereal food production, and 1% reducing energy consumption will cause to change 0.1187%. The results of fertilizer consumption show 1% positive shock in the application of fertilizer possible to change 0.2144%, and 0.0839 respectively in cereal food production. 1st difference and 2nd difference overall change can be 0.2983 in cereal food production due to increasing one application of fertilizer. While 1% negative shock to fertilizer will ultimately lead to

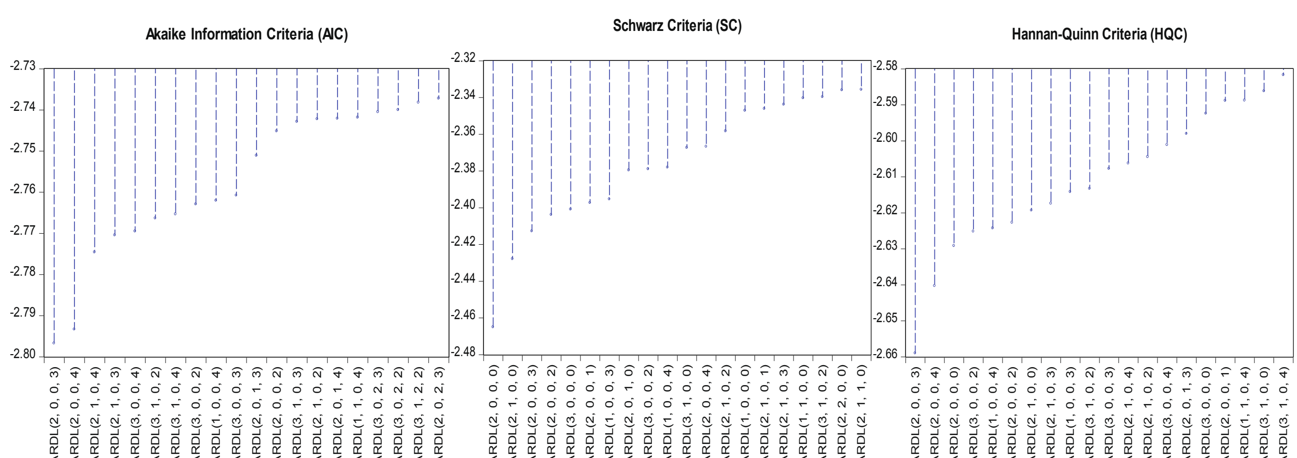

Fig. 2. Lag length order selection by AIC, SC, and HQC.

change in cereal food production −0.3087%, 0.0072%, and −0.0703% respectively. Overall change with 1st, 2nd' and 4th difference is −0.33718%. The result of the error correction term rejects the null hypothesis at 1% significant level with a negative sign of the coefficient. The speed of coefficient adjustment in the estimated NARDL model that is supposed to be in (-1; 0) is below −1, which implies that over time the system does not converge to long-run equilibrium. Considering the results of NARDL cointegration the value of the F-state is bigger than the upper bound and lower bound critical value seems that the cointegration exists between the variables. Therefore, it will not be wrong if we rewrite for cointegration correlation like EC = Food − (−0.197*ACO2_POS + 5.348*ACO2_NEG + 2.996*EU_POS + 1.752*EU_NEG −0.830*FER_POS −5.746*FER_NEG + 16.763). Generally, the overall results reveal that fluctuation with time trends of carbon emission, energy consumption, and fertilizer influence cereal food production.

In addition for the short-run and long-run asymmetry, the correlation was analyzed by wald statistics, the long-run imposed with $\alpha_i^+ = \alpha_i^-$, $\gamma_i^+ = \gamma_i^-, \beta_i^+ = \beta_i^-$ and the short-run indicated with $\partial i = \partial_i^+, \hbar^+, \hbar^-, \pi^+, \pi^- = 0$. The results confirm both long-and short-run asymmetry between carbon emission from agriculture, fertilizer, energy consumption, and cereal food production. The asymmetry results are contrary to a study that investigated the long-run asymmetry correlation between CO2 emission, energy consumption, and economic growth for Cameroon and Canada [22]. Ndoricimpa [54] confirm the long-run asymmetry between pollution emissions, energy consumption, and economic output for South Africa.

Table 5
Short-run and Long-run asymmetric nexus.

Regressors	Coefficient	Std-error	T-stat	P-value	
Long-run Asymmetric analysis					
C	17.7392	0.0358	495.2881	0.0013[a]	
Food(-1)	−1.1063	0.0021	−518.5914	0.0012[a]	
ACO2_P(-1)	−0.8439	0.0030	−280.0388	0.0023[a]	
ACO2_N(-1)	0.0156	0.0003	53.2081	0.0120[b]	
EU_P(-1)	−3.1855	0.0231	−137.8372	0.0046[a]	
EU_N(-1)	1.2594	0.0051	245.3868	0.0026[a]	
FER_P(-1)	0.3195	0.0012	259.2346	0.0025[a]	
FER_N(-1)	−0.3302	0.0027	−122.6826	0.0052[a]	
Short-run Asymmetric analysis					
Dfood_N(-1)	−4.1434	0.0310	−133.5019	0.0048[a]	
DACO2_P(-1)	0.8742	0.0068	129.0329	0.0049[a]	
DFER_P	0.2144	0.0008	265.3601	0.0024[a]	
DACO2_P(-4)	0.4695	0.0019	245.5359	0.0026[a]	
DEU_N	0.1187	0.0096	12.3784	0.0513[c]	
DFER_N(-4)	−0.3087	0.0015	−207.0139	0.0031[a]	
DACO2_N(-4)	0.0876	0.0036	24.6338	0.0258[b]	
DEU_P(-4)	−1.2991	0.0043	−300.8657	0.0021[a]	
DFER_P(-2)	0.0839	0.0008	102.0243	0.0062[a]	
DACO2_N(-1)	0.0120	0.0002	69.4785	0.0092[a]	
DFER_N(-1)	0.0072	0.0011	6.2775	0.1006	
DFER_N(-2)	−0.0703	0.0164	−4.2758	0.1463	
ECT (-1)	−2.122	0.135	−15.671	0.000[a]	
Cointigration test $\vartheta_{EU}^+ = \vartheta_{EU}^+$, $\vartheta_{FER}^+ = \vartheta_{FER}^-$, $\vartheta_{Food}^+ = \vartheta_{Food}^-$.	12.791				
Asymmetry test long-run$\alpha_i^+ = \alpha_i^-$, $\gamma_i^+ = \gamma_i^-$, $\beta_i^+ = \beta_i^-$	10.038[a]				
Asymmetry test short-run$\partial i = \partial_i^+$, $\hbar^+, \hbar^-, \pi^+, \pi^- = 0$	6.214[b]				
R^2	98.716%	Adj-R^2	96.180%		
AIC	−5.563	HC	−4.443	HQC	−5.165

Note: Only significant values are mentioned for short-run asymmetry in the above table.
[a] Null hypothesis rejected at 1% significant level.
[b] Null hypothesis rejected at 5% significant level.
[c] Null hypothesis rejected at 10% significant level.

Table 6
Wald statistics for long-run and short-run asymmetry.

$Wald_{-stat}$	Long-run asymmetry	
	Positive	Negative
	10.896[a]	5.437[b]
$Wald_{-stat}$	**Short-run asymmetry**	
	Positive	Negative
	7.959[a]	4.068*

[a] Null hypothesis rejected at 1% significant level.
[b] Null hypothesis rejected at 5% significant level.

Next, we estimated the long-run and short-run asymmetry for both positive (θ^+)and negative (θ^-)change because in the above Table 5, short-run and long-run asymmetry are significant at 5% and 1% level respectively. Therefore we choose to estimate separately for understanding the clear asymmetry nexus with the positive and negative shock. Table 6 represents the results of long- and short-run asymmetry for both positive and negative shock. The interesting results are in both short- and long-run positive shock is highly significant as compared to a negative shock. These results reveal that cereal food production in Pakistan collapse when there is a positive or negative change in agricultural CO2 emission, energy consumption, and applications of fertilizer for both long-term as well as short-term.

Fig. 3 shows the results of the dynamic multiplier of the regressors and it implies the asymmetry curve shows a linear correlation of dynamic multiplier by positive and negative shocks. The positive and negative change curve reveals the speed of adjustment after one unit change in positive or negative of the proposed horizon. The curve of the upper and lower bound reflects a 95% confidential interval for asymmetry. The curve of the dynamic multiplier effect of carbon emission released by agriculture show changes in both positive and negative does cause to change in cereal food production. Nevertheless, if the asymmetry give shocks towards the positive does not cause to change in cereal food production. But asymmetry shock towards the decreasing agricultural carbon emission is possible to bring change in cereal food production because the negative change and asymmetry curve are running in parallel after 5 years trend and then start fluctuation towards the lower bound. After the passing of 10 years found little change by the given shock of the upper bound, then again the curve drops to the lower bound and continues fluctuation. In the case of the multiplier dynamic curve effect of energy consumption to cereal food production, indicate that asymmetry shock change in positive or negative causes to change in cereal food production. The fluctuation of the graph towards the upper bound and lower bound implies one shock of asymmetry causes to change in positive as well as negative in energy consumption will oscillate the cereal crop production. Furthermore, the multiplier dynamic impact of fertilizer on cereal crop production can be seen very clearly from the graph. It reflects the one asymmetry shock in fertilizer towards the positive change does not cause to change in cereal food production because of the straight line of positive change into the graph. It is also clear and understandable that one asymmetry shock to a negative change of fertilizer causes to change in food production. After 1 year gives one asymmetry shock to reduce the application of fertilizer causes to positive change in cereal food production till 10 years, then it drops down to the lower band after 13 years again the one symmetry shock changes bring towards the upper band. However, the asymmetry trend is null in Fig. 3, and it's contrary with other researchers who

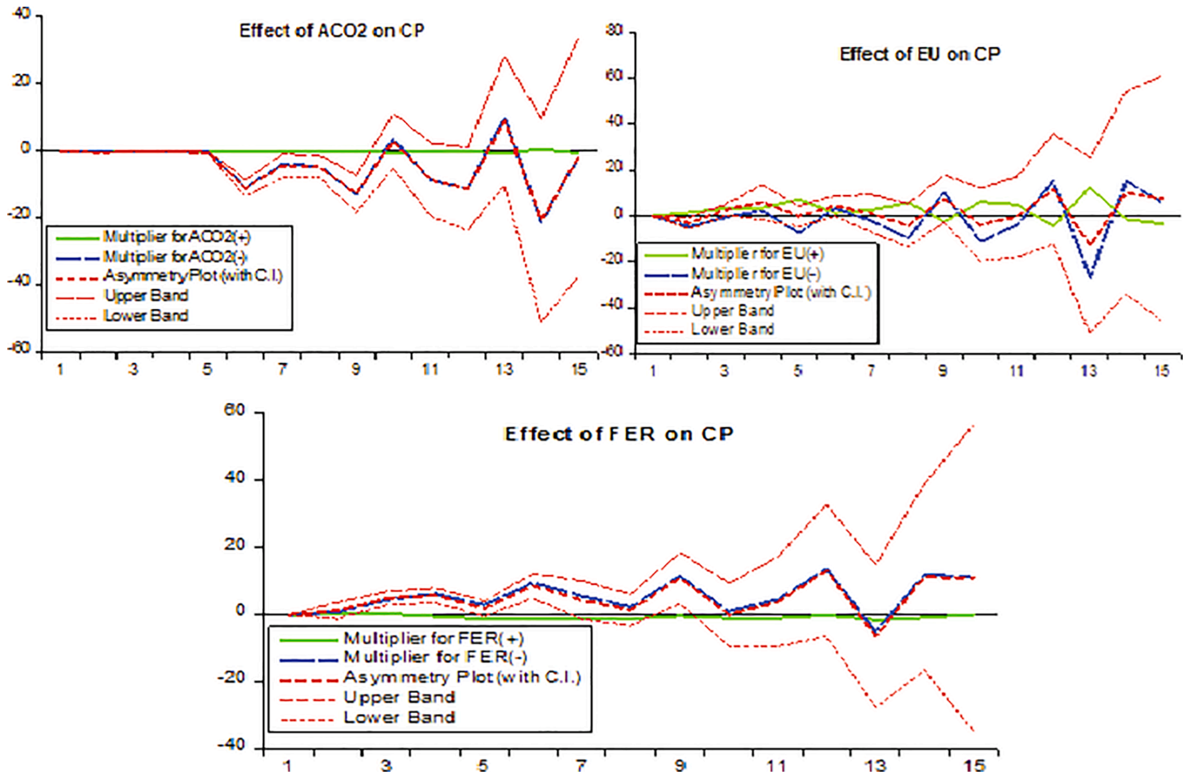

Fig. 3. Dynamic multiplier asymmetry.

concluded the null asymmetry for different studies [32,49,61,82,55].

Further for the coefficient of long- and short-run NARDL CUSUM (*cumulative sum*) and NARDL CUSUMQ (*cumulative sum square*) were estimated to know the stability of the model. Inauspiciously, in the Fig. 4, what commonly found in both plot, the CUSUM and CUSUMQ line is between the upper and lower bound critical value and it is significant at less than 5% level, It seems that the null hypothesis rejected and the alternative hypothesis accepted at 5% significant level and represents that model is enough stable. In the previous literature, few researchers analyzed the CUSUM and CUSUMQ for checking the stability of the model [56,7,16,28,72].

Above in Table 4, we mentioned the results of the linear Granger causality test in order to confirm the causality relationship between cereal food production, agricultural CO2 emission, energy, and fertilizer consumption. Furthermore, this study implies the non-linear Granger causality test investigated to find the moving directions between variables followed by the literature many studies have already used the nonlinear granger causality test for guarantees the relationship between variables. There are many nonlinear Granger causality test which different researchers have estimated in different studies Heimstra and

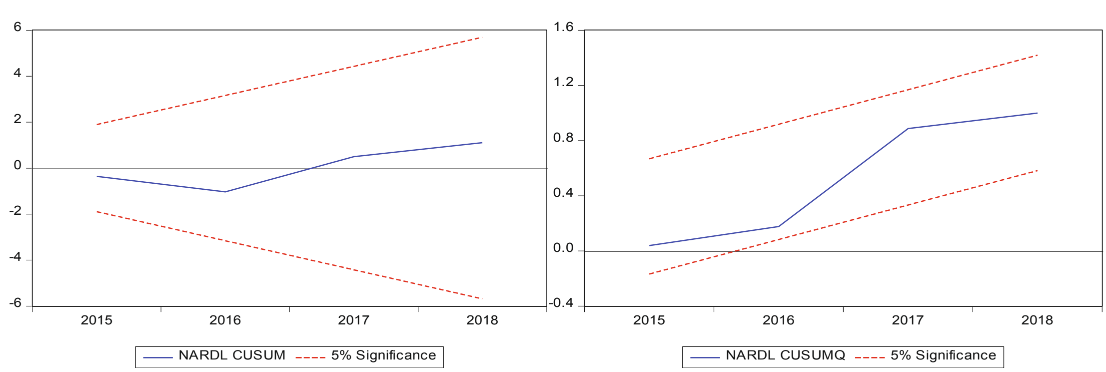

Fig. 4. NARDL CUSUM and CUSUMQ.

Table 7
The results of the Non-linear Granger causality test.

ConsA ↔ B	F-state	Sign level	Causality
ConsACO2→Food	0.324	0.859	No-causality
ConsFood→ACO2	2.198	0.093*	Causality
ConsEU→Food	0.742	0.570	No-causality
ConsFood→EU	2.397	0.072*	Causality
ConsFER→Food	2.807	0.043**	Causality
ConsFood→FER	0.592	0.670	No-causality
ConsEU→ACO2	3.482	0.018**	Causality
ConsACO2→EU	0.231	0.918	No-causality
ConsFER→ACO2	0.994	0.425	No-causality
ConsACO2→FER	1.205	0.329	No-causality
ConsFER→EU	0.769	0.553	No-causality
ConsEU→FER	0.906	0.472	No-causality

**,*, Null hypothesis rejected at 5% and 10% significant level.

Jones [36]. Heimstra and Jones [36] are widely used for economic and financial related research [27]. However, this study estimated the Diks and Panchenko [27] nonlinear Granger causality test because it improved the test as compared to previous tests. Diks and Panchenko [27] Granger causality test was selected for analysis because it has the more flexibility to select the i.i.d series which is already introduced by Heimstra and Jones [36] but also can be used for a large sample, which resulting the more possibilities to reject the null hypothesis. Besides, there will be nothing wrong, if we say the Diks and Pachenko [27] test is the modified extension of Heimstra and Jones [36] test, which uses correlation integrals to measure the discrepancy between equality of conditional independence whose Beak and Brock [11] test make use of the first develop the nonlinear granger causality. Pachenko stated that equality does not always exist, that why Heimstra and Jones test to accept the alternative hypotehsis and reject the null hypothesis while the sample increases. The results of Table7 implies that the unidirectional causality correlation running from cereal food production towards the agricultural carbon emissions and energy consumption at 10% significant level. The results of this study contrary with a study conducted by Simionescu et al. [83] for the European Union, and concluded that greenhouse gases have a positive and significant correlation with cereal production The one-way causality running from fertilizer to cereal food production with 5% significant level was confirmed by the current study. In addition, results also reveal the unidirectional causality correlation from energy consumption to carbon emission from agriculture at a 5% significant level. Ahsan et al [4] also concluded there is a unidirectional causality association between energy consumption and cereal production in Pakistan.

Conclusion and policy implications

This study aims to investigate the asymmetry causality between carbon emission from agriculture, energy consumption, fertilizer consumption, and cereal food production in Pakistan. For this study time-series data from 1976 to 2018 were collected from World Bank indicators and the economic bureau of Pakistan. For estimating the positive and negative asymmetry, this study analyzed the nonlinear autoregressive distributed lag (NARDL) model. For checking the stationarity of the variables, Augmented Dicky-Fuller and Phillip Paroon unit-root tests were employed, and structural breaking year was also investigated by unit-root test. The results of the unit-root test declare all the variables are stationary at the level and first difference. Furthermore, the linear Granger causality test was employed to understand the clear causality between variables. The results of the Granger causality test reveal that fertilizer use does Granger cause cereal food production with a highly significant level. Energy consumption also declares to have significant causality with cereal food production, and the results also confirm the availability of EKC running from the agricultural carbon emission to cereal food production. Moreover, the NARDL model was estimated for the short- and long-run asymmetry association. The results of the NARDL model suggests that both in the long- and short-run by a positive or negative change in agricultural carbon emission cause to change in cereal food production. Considering the energy consumption and fertilizer consumption both in the lon g- and short-run are highly significant and rejected the null hypothesis. This indicates that an increase in energy and fertilizer consumption will cause a negative influence on cereal food production, decrease in the energy consumption and applications of the fertilizer resulting to have a positive and significant effect on cereal food production both in the long- and short-run. Generally, the overall results confirm the short- and long-run asymmetry between variables and reveal that positive and negative changes with time trends in carbon emission, energy consumption, and fertilizer influence cereal food production. Furthere, the NARDL model dynamic multiplier of the regressors were estimated, the results show that the positive and negative change curve reveals that the positive and negative change in agricultural carbon emission does cause to significantly change in cereal food production, but if the asymmetry gives shocks toward the positive does not cause to change in cereal food production. Nevertheless, asymmetry shock towards the decreasing in agricultural carbon emission possible to change in food production because the negative change and asymmetry curve are running in parallel after 5 years trend, and then start fluctuation towards the lower band. Also, NARDL CUSUM and NARDL CUSUMQ were analyzed to know the stability of variables in the long- and short-run. Both represents that the CUSUM and CUSUMQ curve lines are between the upper and lower bound seems the model is stable. In the end, for the asymmetry causality, nonlinear granger causality was applied and results connote that energy consumption and agricultural CO2 confirm to have asymmetry causality with cereal food production at a 10% significant level. Fertilizer consumption also declares to have one-way asymmetry causality running towards the cereal food production.

Possible policy implications are framed based on the estimated results. The government of Pakistan should take initiative for farmers to switch from chemical fertilizer and pesticide as well as consumption of fossil fuel to organic fertilizer and renewable energy. Electricity as renewable energy needs to be accessible to farmers at a low cost per unit of electricity consumption, and urge farmers to use electricity as an energy source. Due to the sudden increase and decrease in temperature, it is recommended that high and low-temperature resistance cereal crop varieties need to be introduced for insurance of food security. The Pakistani government also should pay attention to the burning of agricultural waste such as, rice, wheat, sugarcane straw etc. which leads to an increase in carbon emission from agriculture and reduce soil fertility. The government should provide information regarding the disadvantages of burning agricultural waste and direct them on how to utilize agricultural waste to increase soil fertility and agricultural production with a healthy environment. By adopting of waste management techniques, it does not only can save the cost of chemical fertilizer but also reduce the direct and indirect effect of chemical fertilizer on climate as well as natural resources.

CRediT authorship contribution statement

Mansoor Ahmed Koondhar: Writing - original draft, Conceptualization, Formal analysis. **Edmund Ntom Udemba:** Writing - review & editing. **Ya Cheng:** Data curation, Funding. **Zaid Ashiq Khan:** Software. **Masroor Ali Koondhar:** Revising. **Maria Batool:** Methodology. **Rong Kong:** Supervision.

Declaration of Competing Interest

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

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