The ICT-Based Food Security Management of Pakistan

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ABSTRACT

Food security remains a critical development challenge for Pakistan, exacerbated by population pressures, climate vulnerabilities, and systemic inefficiencies within its agrarian economy. In the current research, there is a research question that examines the use of Information and Communication Technology (ICT) as a game changer in terms of advancing food security, other vital determinants such as the agri-food system, greenhouse gas emission, GDP per capita, drinking water provision, and population growth. It is affirmed using the annual data from 2001 to 2023, and with the development of a model of Autoregressive Distributed Lag (ARDL), as a result of the assessment showed that there is indeed a stable long-run co-integrating relationship between the variables. The findings prove that ICT, the agri-food system, and GDP per capita have great positive impacts on long-run food security, and gas emissions are also positively correlated as well, which indicates that there is a complex association between them and agricultural output. The first one is that in the short run, when the error-correction mechanism is efficient, it implies that the adjustment to the equilibrium following a shock is fast. The results highlight the need to have a strategic approach to digital innovation, an effective food value chain, and sustainable economic policies in order to develop a resilient food system. The paper ends by making recommendations on specific investments in ICT infrastructures, climate-sensitive agriculture, and inclusive development to guarantee Pakistan's sustainable food security in the view of changing environmental and demographic conditions.

Keywords: Food Security; Information and Communication Technology; Agri-Food System; Autoregressive Distributed Lag (ARDL); Sustainable Agriculture; Digital Transformation

1. Introduction

Food security has been among the top developmental issues facing Pakistan, a country which is defined by a high population growth rate, climatic instability, inefficiencies in its agricultural sector and its socio-economic imbalances[1]. Despite operating as an agrarian economy where agriculture plays a great role in providing jobs and livelihoods in the rural areas, Pakistan still experiences challenges concerning food availability, food access, food utilization and food stability[2]. Climate change, water shortage, market failure, post-harvest losses and poor institutional coordination are contributing to these issues[3, 4]. As such, the concept of the use of Information and Communication Technology (ICT) in the management of food security has proven to be a transitional approach to improving the productivity of agriculture, market efficiency and policy responsiveness[5, 6]. Food security management is an all-inclusive list of activities, which comprises food production, food storage, and distribution, food pricing, food monitoring, and emergency response[7]. Pakistan has often been relying on incomplete data, tardy reporting, and manual decision-making in the traditional food security systems, which have restricted its responsiveness to shocks like floods, drought, pandemics and international price changes. The lack of real-time data has limited access to the market by the farmers, transparency along the supply

chains, and the effectiveness of the early warning systems. Consequently, the problem of food insecurity remains, especially in rural areas, among the urban poor, and others who are at risk[8].

ICT-food management improves agricultural output by providing farmers with comprehensive information regarding the weather patterns, pest invasion, price of inputs, and the most appropriate farming systems to use[9]. Digital extension platforms and mobile advisory services decrease information asymmetry and enable the small-holder farmers to make well-informed decisions[10]. Moreover, ICT also facilitates precision agriculture by the use of remote sensing and data analytics, which enhances optimal use of resources and controls environmental degradation. Such innovations are especially relevant to Pakistan, where small-scale farmers are the main producers of agricultural products, and they have limited access to knowledge, credit, as well as to the market. In addition to production, ICT is also important in enhancing the food market and distribution[11]. Electronic supply chain management systems, mobile-based price information systems and digital marketplaces would lower the cost of transactions, post-harvest losses, and improve price transparency. ICT also reduces the effects of intermediaries and ensures that income is stabilized by linking the farmer to the buyer[12]. Moreover, online logistics and storage systems have a supportive role in the programs of food distribution by the population, such as strategic grain stocks and local food support programs.

This study offers multiple novel contributions to the food security literature. First, it uniquely integrates information and communication technology (ICT) as a core determinant of national food security in Pakistan, a dimension largely overlooked in prior empirical studies. Second, it expands the analytical scope beyond agricultural production to incorporate environmental, technological, and demographic factors through a multi-dimensional ARDL framework. Third, by utilizing annual time-series data from 2001 to 2023, the study captures the structural impact of digital penetration on food systems over two decades. Fourth, the findings reveal a counter-intuitive positive long-run association between emissions and food security, highlighting complex production–environment trade-offs. Collectively, the study provides original theoretical insights and policy-relevant evidence on how digital transformation can strengthen food system resilience in Pakistan.

2. Literature Review and Theoretical Foundation

The theory of food security is based on the framework of the Food and Agriculture Organization (FAO), which frames the concept of food security on 4 pillars related to each other, which include availability, access, utilization, and stability[13, 14]. This is the framework that offers the reviewing lens to the study of food security as a dependent variable that is dependent on economic, environmental, and institutional factors. With reference to the context of Pakistan, the food security results are not only limited to food production but also to systemic efficiencies, environmental sustainability, and information flows within the agri-food system. The Sustainable Livelihoods Framework is another addition that accompanies the theory of food security, and it stresses how assets, institutions, and vulnerability contexts equally combine to ensure household and national food security[15]. All these theories have an incentive to explain why food security should be considered as a consequence of structural and policy-driven factors and not as a condition on its own.

2.1 Agri-Food System and Food Security

The Systems Theory is the most appropriate answer to explain the relationship between the agri-food system and food security in that food production, processing, distribution, and consumption are a part of a larger system[16, 17]. This school of thought postulates that food availability and stability in the agri-food system can be undermined by any disruption or inefficiency in any aspect of this service. According to the literature on agri-food systems in developing economies, integrated and well-coordinated systems lead to an increment in food security through boosted productivity, eliminated losses after harvest, and efficient conversion of market economies. In Pakistan, poor institutional integration and incomplete supply chains underscore the applicability of Systems Theory as to how systemic changes can be made to the agri-food system to result in more sustainable food security.

2.2 Food Security and Gas Emissions

The Environmental Sustainability Theory and Climate Change Theory are theoretically based when it comes to the association between gas emissions and food security[18, 19]. These hypotheses assume that high levels of greenhouse gases will cause imbalances in the ecological aspect, hence causing climate change, loss of resources, and low capacity to produce agricultural products. The literature highlights that agriculture causes as well as is influenced by gas emissions and hence forms a feedback loop that responds to food security. Climate-related risks like floods and droughts in Pakistan are worsened by increased emissions and endanger food security and food stability. The Environmental sustainability theory thus comes in favour of having gas emission as a key determinant of food security, and therefore, low-emission and climate-resistant agriculture should be adopted[20].

2.3 Drinking Water and Food Security

The Human Needs theory and the Ecological Systems theory are theoretically applicable in the relationship between drinking water and food security[21, 22]. According to the Human Needs Theory, the availability of clean water is described as a universal condition of life as well as health, and this directly affects the use of food and nutritional achievements. The Ecological Systems Theory also describes how agricultural productivity and ecosystem health are influenced by water availability and will result in food security. Water scarcity and contamination affect food production as well as human health in Pakistan, which validates the theoretical perspective of water security being a fundamental pillar of sustainable food security.

2.4 Food Security: Information and Communication Technology

Diffusion of Innovation Theory and Information Asymmetry Theory support the role that information and communication technology (ICT) plays in food security[23, 24]. This is due to the diffusion theory as the new technologies permeate the farmers and institutions, increasing the productivity and performance of agriculture over time. The Information Asymmetry Theory is based on the idea that inefficient decisions and market failures are the result of unequal access to information. ICT helps in minimizing these asymmetries by providing the information on weather, prices, and methods of farming as and when it is needed. ICT-assisted advisory services and online platforms in Pakistan improve the efficiency of decision-making and market access, which improves the availability and accessibility of food. These theories give a formidable conceptual rationale of ICT as the primary force of food security.

2.5 GDP per Capita and Population Growth Control Variables

The Economic Development Theory provides a theoretical basis to the concept of GDP per capita, that is, a higher standard of living is associated with higher income, institutional capacity, and development of infrastructure, which leads to better welfare results, such as food security[25, 26]. An increase in GDP per capita indicates an increase in purchasing power, an increase in the availability of food, and an improvement in public service delivery. The fact that GDP per capita is controllable in empirical food security models means that researchers can then control macroeconomic conditions that could have an impact on access to food independent of sector-specific factors. In the case of Pakistan, the differences in economic capacity can be reflected by changes in the GDP per capita, which can indicate changes in food security.

The Malthusian Theory and Demographic Transition Theory are theoretically used to explain population growth[27]. According to the Malthusian theory, the growth of the population can surpass the increase in food production and result in a lack of resources and food insecurity. The theory of demographic transition offers more of a refined perspective whereby the dynamics of population and technological advancement, as well as economic development, interact. In Pakistan, the large population growth exerts pressure particularly on agricultural resources, water, and food systems, which could counter the technological and institutional developments. This is the reason the consideration of population growth as a control variable is theoretically justifiable to consider the demographic pressures on food security. Conceptual framework is shown in figure 1.
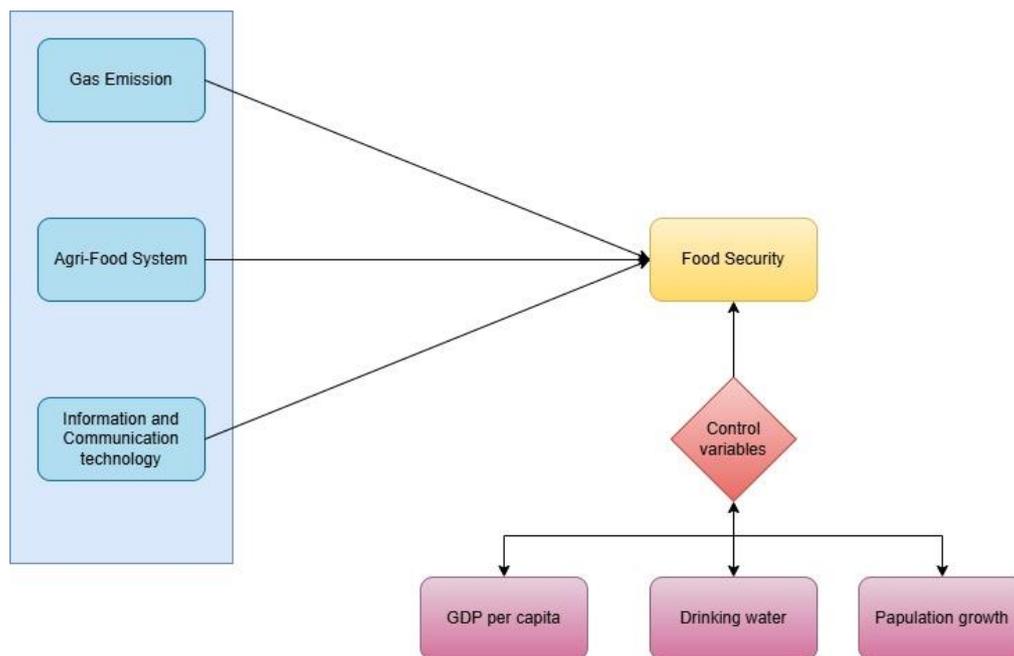
Figure 1: *Conceptual Framework*

3. Materials and Methodology

This study examines annual data for Pakistan from 2001 to 2023, selected based on the availability of a sufficiently long and consistent time series. Food Security (LFS) is the dependent variable, while gas emission (Lemc), agri-food system (Lafs), and information and communication technology (Lict) serve as the primary independent variables. To provide a more comprehensive evaluation of food security, the analysis also incorporates several control variables, including gdp per capita (Lgdp), drinking water (Ldw), and population growth (Lpg), as presented in Table 1. All variables are sourced from publicly available international databases. Data on GDP, information and communication technology, population growth, and drinking water are obtained from the World Bank's World Development Indicators. Data for food security, agri-food system, and gas emission taken from FAO.

Table 1: *List of Variables*

Dependent variable	Food security	Food Production	FAO
Independent variable	Agri food system	Estimated value	FAO
	Gas Emission	Emissions (CO2eq) (AR5)	FAO
	Information and communication technology	Individuals using the Internet (% of population)	WDI
Control variables	GDP per capita	Annual Growth	WDI
	Population growth	Annual growth	WDI
	Drinking water	Availability of clean water to drink	WDI

$$FS_t = \int (emc_t, afs_t, ict_t) \tag{1}$$

The explanatory variables included in the model are gas emissions (emc_t), agri-food security (afs_t), and information and communication technology (ict_t). Their respective lagged values are denoted as emc_{t-i}, afs_{t-i}, and ict_{t-i}. The endogenous variable is food security (FS_t), with its lagged term represented by FS_{t-i}. Considering the time-lagged effects involved in enhancing the food security, this study employs an autoregressive distributed lag (ARDL) model to examine the impact of gas emissions, agri-food security, and information and communication technology on food security. The ARDL approach is implemented in two stages. In the first stage, the ARDL bounds testing procedure is applied to assess the existence of a long-run causal relationship among the variables. Based on this procedure, the following model is specified:

$$\Delta lnFS_t = \beta_0 + \beta_1 lnFS_{t-1} + \beta_2 lnemc_{t-1} + \beta_3 lnafs_{t-1} + \beta_4 lnict_{t-1} + \varepsilon_t \tag{2}$$

$$\Delta \ln FS_t = \beta_0 + \beta_1 \ln FS_{t-1} + \beta_2 \ln emc_{t-1} + \beta_3 \ln afs_{t-1} + \beta_4 \ln ict_{t-1} + \beta_5 \ln gdp + \beta_6 \ln dw + \beta_7 \ln pg + \varepsilon_t \quad (3)$$

In the first step, Δ represented a first-order differential operator, ε_t was white noise, and a, b, c, d were the maximum lag orders determined by AIC or BIC. The presence of a long-term equilibrium relationship among the variables was tested using an F-statistic, with the null hypothesis stating that no such long-term equilibrium existed. Step 2 involved estimating the ARDL model to examine both the long-run and short-run relationships between the variables. The long-term relationship was estimated using the ARDL (p_1, p_2, p_3, p_4) model. Methodology flow chart show in figure 2.

$$\Delta \ln FS_t = \beta_0 + \beta_1 \sum_{i=1}^{n} \Delta LFS_{t-i} + \beta_2 \sum_{i=1}^{n} \Delta Lemc_{t-i} + \beta_3 \sum_{i=1}^{n} \Delta Lafs_{t-i} + \beta_4 \sum_{i=1}^{n} \Delta Lict_{t-i} +$$
$$\beta_5 \sum_{i=1}^{n} \Delta Lgdp_{t-i} + \beta_6 \sum_{i=1}^{n} \Delta Ldw_{t-i} + \beta_7 \sum_{i=1}^{n} \Delta Lpg_{t-i} + \varepsilon_t \quad (4)$$

while the short-term relationship was captured using an ARDL-based error correction model (ECM), as specified in Equation (4).

$$\Delta \ln FS_t = \beta_0 + \beta_1 \sum_{i=1}^{n} \Delta LFS_{t-i} + \beta_2 \sum_{i=1}^{n} \Delta Lemc_{t-i} + \beta_3 \sum_{i=1}^{n} \Delta Lafs_{t-i} + \beta_4 \sum_{i=1}^{n} \Delta Lict_{t-i} +$$
$$\beta_5 \sum_{i=1}^{n} \Delta Lgdp_{t-i} + \beta_6 \sum_{i=1}^{n} \Delta Ldw_{t-i} + \beta_7 \sum_{i=1}^{n} \Delta Lpg_{t-i} + + \lambda ECM_{t-1} + \varepsilon_t \quad (5)$$
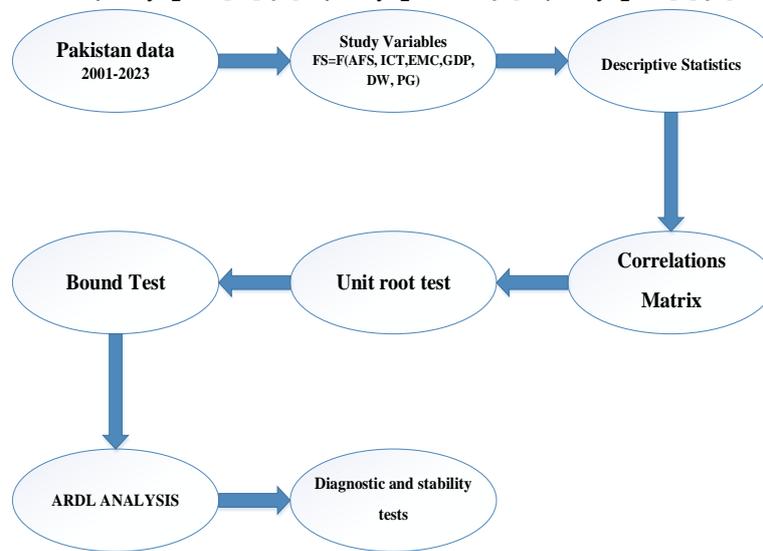

Figure 2: Flow Chart of Methodology

4. Analysis and Results

The empirical analysis will begin with the descriptive statistics shown in table 2, which will provide an overview of the dynamics of the variable over the study period. Food security (LFS) exhibits a high mean and low variance, which means that food security conditions did not fluctuate as much over the period during which this study was conducted. GDP per capita (LGDP), on the other hand, is highly variable, with a temporary change in the increased economic performance. The dispersion among all the variables is the highest among information and communication technology (ICT), which indicates uneven growth and digital infrastructure adoption. The agri-food system, gas emissions (LEMC), drinking water access (LDW), and population growth (LPG) variables show moderate variability, which means that there are no intense structural changes but gradual ones. All in all, the descriptive results show that the dataset is properly organized and can be analyzed using time series.

Table 2: Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
lfs	23	7.583	.084	7.43	7.73
lgdp	23	1.919	2.253	-3.04	5.2
lemc	23	3.403	.067	3.28	3.52
lafs	23	4.395	.052	4.3	4.46
lict	23	11.037	6.817	1.32	27.38
ldw	23	1.603	.06	1.49	1.71
lpg	23	2.038	.479	1.3	2.8

The table 3 correlation matrix determines that there are strong initial relationships between the

variables under study. The relationship between food security and gas emission, agri-food system, information and communication technologies (ICT), and access to drinking water depicts a good and positive correlation, meaning that agricultural infrastructure, technological, and basic utilities improvement accompany a high level of food security. On the other hand, the relationship between population growth and food security is characterized by a negative relationship and is thus in an inverse manner, whereby the growth of population will tend to weaken the food availability and distribution systems. The gross domestic product per capita has poor associations with most variables, indicating that its impact on food security is indirect, as it acts via other structural factors. These correlations provide preliminary information, but they are not causal.

Table 3: Matrix of correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)
(1) lfs	1.000					
(2) lgdp	-0.044	1.000				
(3) lemc	0.997	-0.056	1.000			
(4) lafs	0.884	-0.091	0.883	1.000		
(5) lict	0.917	-0.097	0.908	0.690	1.000	
(6) ldw	0.640	0.203	0.633	0.662	0.531	1.000
(7) lpg	-0.750	-0.199	-0.749	-0.791	-0.654	-0.612

Before the estimation process, unit-root diagnostics were conducted to determine the stationarity properties of the series under investigation. The diagnostics show that the non-stationary variables are food security, information and communication technology (ICT), gross domestic product per capita, drinking water and population growth all of which satisfies the criterion of non-stationarity when first differenced and thus attain stationarity when first differenced; hence, these can be termed as the integrated of order one (I(1)). On the other hand, agri-food system variable is stationary that is integrated of order zero (I (0)). This heterogeneity of integration warrants the employment of the Autoregressive Search Lag (ARDL) modeling framework that is appropriate whenever there is a need to incorporate variables that are integrated both at I (0), and I (1) as shown in table 4.

Table 4: Unit Root test

Variables	T statistic	p-value	Integration
LFS	-9.060	0.000	I (1)
LICT	-4.325	0.001	I (1)
LAFS	-4.088	0.001	I (0)
LEMC	-9.386	0.000	I (1)
LGDP	-3.190	0.021	I (1)
LDW	-3.756	0.011	I (1)
LPG	-3.560	0.000	I (1)

The ARDL bounds testing (table 5) process supports the presence of a long-run relationship between the variables. The computed F-statistically significantly exceeds the upper bound figures at all traditional levels of significance, thus permitting us to reject the null hypothesis that there is no cointegration. This finding provides solid proof of a long-run equilibrium relationship between food security and the chosen agri-food, environmental, technological, and macroeconomic variables.

Table 5: BOUND TEST

Model	F-stat	Sig. level	I (0)	I (1)	Decision
	106.970	10%	2.12	3.23	Rejected H0
		5%	2.45	3.61	
		2.5%	2.75	3.99	
K	6	1%	3.15	4.43	

There is a long-run estimation that gas emissions have a negative and insignificant impact on food security. The agri-food system has a significant positive impact on food security, and so the development of efficient agricultural structures and food systems is quite important in ensuring sustainable access to food. There is a high positive effect of information and communication

technology, which implies that online connectivity will enhance food security by increasing market presence, flow of information, and agricultural productivity. The same was found with GDP per capita, whose effect is also positive and significant, supporting the fact that economic growth facilitates the attainment of food security through increasing the purchasing power and investment potential. Conversely, the availability of drinking water and population increase can have no statistically significant influence in the long term, which implies that the two factors can contribute to food security indirectly or contextually. The dynamic processes in the short run also indicate a salient adjustment process. The reactions of ICT and GDP per capita to change have a negative, but weakly significant response, implying that in the short term, there are transitional costs or lagged advantages of technological growth and economic alterations. The value of the error-correction term is negative, but very significant, and this confirms that there is a valid process of adjustment in association with the long-run equilibrium. The size of the coefficient implies a quick rate of adjustment, which means that disequilibria are eliminated in a short period of time. All long- and short-term results shown in table 6.

Table 6: ARDL Analysis results

D.lfs	Coefficient	Std. err.	t	P>t	95% conf.	interval]
ADJ						
lfs						
L1.	-1.152	0.066	-17.500	0.000	-1.296	-1.009
LR						
lemc	-0.849	0.082	-10.330	0.099	-0.670	-1.029
lafs	0.228	0.076	3.010	0.011	0.063	0.392
ldw	0.027	0.020	1.360	0.198	-0.016	0.070
lict	0.003	0.001	4.730	0.000	0.002	0.004
lgdp	0.002	0.001	2.860	0.014	0.000	0.003
lpg	0.005	0.005	1.060	0.311	-0.005	0.015
SR						
lict						
D1.	-0.005	0.003	-1.790	0.099	-0.012	0.001
lgdp						
D1.	-0.001	0.001	-1.760	0.103	-0.002	0.000
_cons	4.154	0.370	11.240	0.000	3.349	4.959

The diagnostic and stability tests (table 7) are used, which justifies the strength of the estimated model. The estimated standard errors are credible due to the absence of serial correlation and heteroskedasticity, unlike the Ramsey RESET test, which supports the correct functional form. Normal tests reveal that the residual is normally distributed, and the CUSUM square test shows that the parameter has not changed over the years. All these results confirm the sufficiency of the ARDL specification and the soundness of the estimated relationships. The CUSUM graph shown in figure 3.

Table 7: Diagnostic and stability tests

Model		
Test	Chi2/F-value	Probability
Breusch–Godfrey LM test	0.060	0.8072
Breusch–Pagan/Cook–Weisberg test for heteroskedasticity	0.02	0.8974
Ramsey RESET test	1.12	0.3774
Skewness and kurtosis tests for normality	0.60	0.7402
Shapiro–Wilk W test	-0.819	0.7935
Jarque-Bera normality test	2.54	0.2808
CUSUM Square Test	Stable	

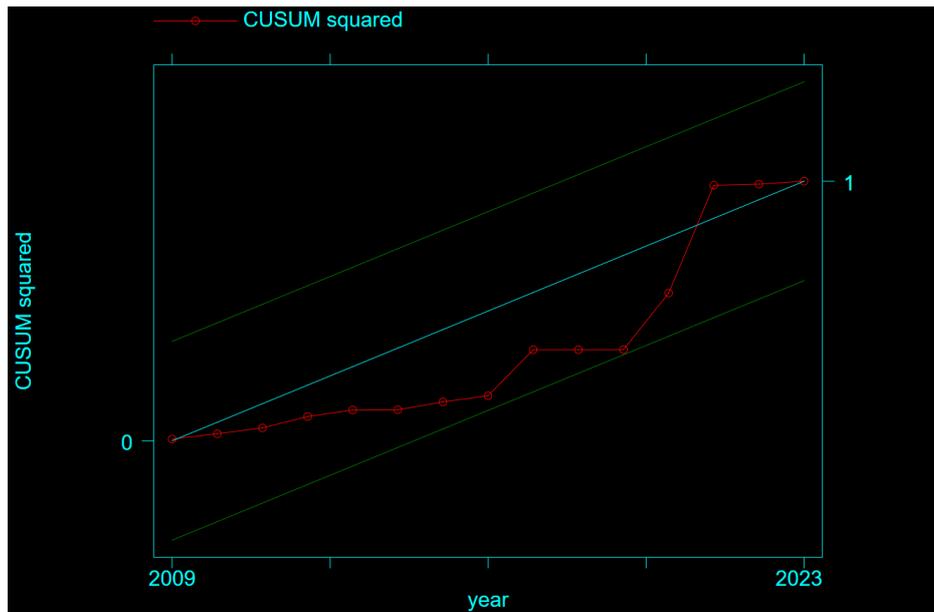***Figure 3:*** *CUSUM Graph of Analysis*

5. Discussion

This research has provided clear evidence of what defines food security in Pakistan. These demonstrate that all these factors-structure, technology, and macroeconomic are important. A long-term co-integration test ascertains that food security is not a lone outcome, but it is determined by the interrelation of the agri-food system, the environmental factors, digital infrastructures, and economic performance in the long-run. This is one of the main findings, which justifies applying an ARDL framework and suggests an argumentation concerning the particular long- and short-run processes that the model reveals. Information and Communication Technology (ICT) produce a positive, statistically significant impact on food security in the long run. It is in favour of the Diffusion of Innovation and Information Asymmetry theories. In Pakistan, ICT can enhance access to markets, provide real-time weather and pricing, and enhance agricultural productivity using digital advisory services. A positive impact on the agri-food system is also significant, in which the efficiency of production, processing, and distribution channels has been brought to the fore through the Systems Theory. Gas emissions have a negative long-run coefficient. It could be a sign of the connection between the emissions and increased agricultural and industrial activity already sustaining the consumption of food, yet it brings concerns of environmental sustainability in the long term. Economic Development Theory is also adequately demonstrated by a strong positive impact of the GDP per capita, since economic growth increases the purchasing power and public investment. The long-run model did not show a statistically significant effect of drinking water access and population growth, which can possibly mean that these variables have an indirect or mediating impact.

Short-run analysis displays crucial information and patterns of adjustments. Indicated strong initial adjustment costs or implementation lags are weakly significant negative coefficients of ICT and GDP per capita. The existence of benefits brought about by the technology adoption or economic policy adjustments may not surface quickly, perhaps due to infrastructure constraints, skill differences or the disruption of the transitional markets. Most importantly, the error-correction term is negative and has great significance. This ascertains a stationary, comparatively rapid process that adjusts brief fluctuations of deviations in the long-run equilibrium. Therefore, the food security system is vulnerable to shocks, but internally driven in Pakistan, which gets back to its long-term course as determined by underlying determinants. These conclusions are strong as they are backed by numerous diagnostic tests and stability tests. This model does not indicate any signs of serial correlation or heteroscedasticity, and the Ramsey RESET test makes sure the functional form is correct. The distribution of residuals is

normally distributed, and the CUSUM of squares test confirms there are no changes in the parameters within the study. Combined, both of these diagnostics attest to the received ARDL and to the validity of the relationships inferred between food security and elements that explain it.

6. Conclusion

This study conclusively demonstrates that achieving sustainable food security in Pakistan hinges on the strategic integration of digital technology, systemic agri-food efficiency, and supportive macroeconomic policies. The empirical evidence confirms a robust long-run relationship where Information and Communication Technology (ICT) serve as a transformative force, enhancing market access, information flow, and agricultural productivity, while a resilient agri-food system and rising GDP per capita further solidify the foundation for national food security. These findings validate a forward-looking policy approach that prioritizes ICT infrastructure in rural areas, modernizes supply chains, and fosters inclusive economic growth to build a more resilient food ecosystem. Ultimately, Pakistan's path to food security must balance immediate productivity gains with long-term sustainability. While emissions were negatively linked to food output in this analysis, this signals an urgent need to adopt green agricultural practices and climate-resilient strategies to avoid future trade-offs between food production and environmental health. By embracing technology-driven, system-wide, and ecologically conscious policies, Pakistan can transform its food security challenges into opportunities for sustainable development, ensuring equitable access to food for all its citizens in the decades to come.

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