Information and Communication Technologies Dissemination in Enhancing Crop Production Capacity: Moderating Role of Country Governance Index

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Information and communication technology enhances crop production by providing farmers with real-time data, market insights, and efficient resource management tools. It raises innovation, improves productivity, and supports sustainable agricultural practices. Therefore, the study objective was to test the impact of information and communication technology on crop production in GCC countries with a moderating effect on the country governance index. Longitudinal quantitative data were collected from six GCC countries from 2005 to 2024 from word development indicators. Unit root, panel cointegration, and panel ARDL statistical analysis were conducted to test the study hypothesis. The study results show the positive and significant influence of information and communication dimensions on crop production of GCC countries. Control variables also positively and statistically significantly influence crop production. Country governance also significantly strengthens the association of information and communication technology and crop production. Research with specific findings highlighted a need for the policymakers of GCC countries to invest in advanced information and communication technologies to enhance agricultural productivity. Strengthening governance frameworks could further optimize the impact of technology on crop production to sustain agricultural growth. This study as per the researchers' knowledge is the first study that explored of role of the corporate governance index between information and communication technology and crop production in the GCC region. The research with this extended framework provides novel insights into how governance enhances the effectiveness of digital advancements in agriculture production.

1. Introduction

Crop production increases food security, sustainable agricultural practices, and also economic stability (Mishra, Mishra, & Santra, 2016). From a general perspective, increasing the capacity of crop production helps to meet population demands in their consumption, sustaining the crop prices in the markets and less focused on food imports (Kar et al., 2024). It also helps to enhance the prosperity of rural farmers by providing employment opportunities to increase their incomes (Upadhyay et al., 2024). Furthermore, improvement in agricultural productivity contributes to environmental sustainability through optimizing land use (Upadhyay et al., 2024). To increase crop production investment in modern technologies, efficient irrigation, and climate-resilient crops is essential to maintaining and improving crop yields globally (Papadopoulos et al., 2024). Specifically, within the developed economies, development in information

and communication technology (ICT) increased crop production by facilitating real-time monitoring of farming, and data-driven decision-making, leading to increased yields (Pasala et al., 2024). In the meantime, ICT is an integral component of increasing crop production in the developing economies.

Over the past decades, developed economies have experienced significant advancements in agricultural technology. These developments include drones, robotics, and farm management software. Consequently, new terms such as digital farming, smart farming, and farming 4.0 have emerged to describe these technological transformations (Singh et al., 2024). The rapid evolution of agricultural technology has led to the expansion and refinement of innovations through cloud computing, and the Internet of Things (Laktionov et al., 2024). All of these technological factors contribute to the consolidation of the fourth agricultural revolution (Laktionov et al., 2024). 4.0 technology in agriculture is centered on the application of digital technologies to manage agricultural production and processes which enables real-time monitoring of essential production variables based on scientific datasets (Elahi et al., 2022). These data-driven techniques optimize food crop cultivation and livestock farming up to the processing stage by reducing production expenses and minimizing waste by ensuring the precise use of inputs (Northrup et al., 2021). Olle (2021) highlighted that digital technologies contribute to promoting sustainable agricultural practices. Furthermore, ICT also played a vital role in the mitigation of uncertainties within the agricultural value chain to increase more precise and sustainable practices in farming (Tiwari, 2022). All of these studies emphasized that over time ICT has been developed to increase crop production in both developed and emerging economies.

Existing research indicated that ICT is crucial in facilitating information exchange in the agriculture sector in developed nations. By bridging information gaps and lowering transaction costs, ICT enhances farmers' access to critical knowledge and resources (Liu et al., 2021). Furthermore, given the increasing challenges posed due to climate change, ICT applications significantly contribute to improving agricultural productivity (Ayisi Nyarko & Kozári, 2021). Despite the recognized benefits of ICT in agriculture, studies estimating the impact of ICT using indicators such as "mobile phone subscriptions, fixed telephone subscriptions, and internet usage" alongside economic variables like net national income per capita and private sector credit have received less

attention with the moderating role of country governance. Previous studies have inconsistent relationships on the relationship between ICT and crop production (Ayisi Nyarko & Kozári, 2021; Ologundudu & Eniola, 2024; Shubhrajyotsna & Aithal, 2024; Tang et al., 2024). This relationship enforced that there is a need for a relationship with the moderating effect which is suggested by Chmura Kraemer et al. (2008). Therefore, this study contributed to country governance as a moderating variable. Country governance could improve ICT in increasing crop production through taking investment actions in digital infrastructure, ensuring farmers have access to high-speed internet and smart agricultural technologies (Chmura Kraemer et al., 2008; Saba et al., 2024). Applying supportive strategies and subsidies can encourage the adoption of ICT that could increase crop production (Wang, Tong, & Fang, 2024). Therefore, the study uses country governance as a moderating variable.

Furthermore, prior mostly studies have relied on panel data or time series analysis but ignored alternative methods like panel ARDL, which remain unexplored (Abdisa, Mehare, & Wakeyo, 2024; Chandio et al., 2024; Rajkhowa & Baumüller, 2024). Therefore, this study contributed literature in the context of ARDLs in the field of ICT and crop production. On the other side, research has been explored on ICT and crop production in other countries with limited attention on Gulf Cooperation Council (GCC) countries. Therefore, this study contributed to a body of literature in the context of GCC countries where there is a lack of adoption of ICT in the agriculture sector (Elzaki, 2024). The slow integration of ICT in agricultural practices across the region is primarily due to structural and infrastructural challenges, including water scarcity, high dependence on food imports, limited arable land, and varying levels of mobile network analysis in rural farming areas (Dabiah, Alotibi, & Azeem, 2024). Additional barriers include high technology costs, policy gaps, and limited technical expertise in utilizing advanced digital tools (Muthuswamy & Krishnan, 2024). Moreover, agricultural digitalization in rural areas lags behind urban regions where ICT infrastructure is more developed (Elzaki, 2024). Literature cited that ICT has emerged as a key enabler in transforming agriculture production (Ali Chandio et al., 2022). Therefore, seeking the significance of ICT and addressing previously unexplored gaps, the study aimed to test the impact of ICT on crop production in GCC countries. The study also explores the moderating role of country governance.

Our research objective provided various insights for

policymakers after understanding the moderating role of country governance in enabling to design of policies that facilitate ICT adoption in agriculture. These insights could also help enhance resource application and encourage sustainable farming practices. Also, the research highlighted the significance of ICT in addressing food security challenges in the region. Through the integration of ICT solutions with effective governance strategies, agricultural sectors could achieve higher production. Eventually, this research serves as a guide for implementing technology-based agricultural policies to enhance long-term sustainability. The study is divided further has four chapters. The second chapter is the literature review which covers the study from theoretical and theoretical and empirical perspectives. The third chapter is the research methodology which discusses the research approach and sampling techniques etc. Forth chapter is data results which interpret the main findings of the study. Discussions and implications discussed the main results and contributions as per the study findings.

2. Literature Review

2.1. Information and Communication Technology and Crop Production

Crop production shows the cultivation of various plants for human needs to fill their hunger (Hasan et al., 2023). Crop production could rise through various farming techniques and technological advancement. This is the reason, information and communication technology (ICT) plays a central role in crop production by providing real-time data and conditions of crops (Ali Chandio et al., 2022). ICT also helps in optimizing the resources to enhance the production of agriculture (Ali Chandio et al., 2022). ICT also provides access to farmers' markets and price information which reduces the reliance on middlemen (Khan et al., 2022b; Saha & Maheswari, 2023). Mobile apps and online platforms offer valuable knowledge, training, and expert advice to enhance farming techniques (Khan et al., 2022b; Spielman et al., 2021). Over the past years, these studies emphasized that ICT significantly contributes to agricultural production. ICT could be conceptualized into three dimensions: "fixed telephone subscriptions, internet using the individuals, and mobile cellular subscriptions" which significantly help to increase crop production (Onyeneke et al., 2023; Spielman et al., 2021).

Various empirical studies conducted on ICT and agricultural production but these studies have primarily focused on two perspectives of methodology. The first involves cross-country analyses utilizing panel data across multiple nations (Ayisi Nyarko & Kozári, 2021), while the second comprises country-specific or localized studies relying on micro-level data (Said Mohamed et al., 2021). Research adopting the latter approach has explored various aspects, including the pathways through which ICT influences agricultural productivity (Karunathilake et al., 2023). Despite these efforts, the availability of quantitative evidence especially cross-country data-driven research remains limited in GCC countries. For example, Rezk et al. (2021) results indicated that mobile phones contributed significantly to agricultural development with mobile phone penetration exhibiting a consistently positive ion crops. Similarly, Yasin et al. (2021) inspected the influence of ICT on agricultural productivity and found that ICT had a positive influence on crop production. Further, Suma (2021) noted that the combined influence of ICT, improved seeds, fertilizers, and credit access which significantly enhanced agricultural productivity.

Over recent years, Sinha & Dhanalakshmi (2022) have further shown the influence of ICT on agriculture production. They found a positive influence of ICT on agriculture production. Further study extended by Hasan et al. (2023) where also observed the role of technology in agricultural production. Their results also found that internet usage significantly improved agricultural production. This study results are further evidenced by the extended results of Gwelo, Feleke, & Manda (2023) who found that SMS-based reminders significantly improved agricultural productivity. Harinath et al. (2024) analyzed data from farmers across rural communities and found a positive role of mobiles in crop production. Conversely, Ayim et al. (2022) conducted a study on primary data sources and found that farmers predominantly used mobile phones for basic communication rather than advanced agricultural applications. They also found that farmers with the latest technology also increase their production capacity which fulfills the needs of individuals and international level.

Additional research has explored the specific ways in which farmers use mobile phones in agricultural activities. For instance, Krell et al. (2021) studied farmers and found that mobile phones were utilized for advisory services, market information, weather forecasts, and financial transactions, enabling farmers to make better decisions while reducing transportation costs. Likewise, Mdoda & Mdiya (2022) found that found that more educated farmers in technology significantly increase the crop production. Ayisi Nyarko & Kozári (2021) further

analyzed ICT use among youth in agriculture where they emphasized the role of social media, SMS, and voice messages in disseminating farming knowledge and facilitating financial transactions. Some of the studies from other developing regions have similarly highlighted ICT's role in agriculture. In Pakistan, Khan et al. (2022b) explore the effect of mobile phones on crop production. They found that ICT adoption significantly improved sales efficiency and agricultural profitability. Likewise, Khan et al. (2022a) utilized a national dataset where they found that mobile phone policies contributed to reduced inorganic fertilizer use, promoting sustainable agricultural practices. Ali Chandio et al. (2022) analyzed panel data and observed that internet access enhances total agricultural production due to improved fertilizer efficiency, particularly among younger households. Bhupenchandra et al. (2024) also found that internet adoption significantly increased rural household income and expenditure. Similarly, Haggag (2021) established that internet use enhanced the technical efficiency of farmers. Chamara et al. (2022) demonstrated that IOT helps to reduce the loss which increases the profitability and also decreases the volatility in prices of production. These previous studies emphasized that the transformative potential of ICT in agriculture is an important concern in increasing production capacity. However, despite growing evidence, research on ICT's role in agricultural productivity within GCC nations remains scarce, necessitating further investigation to bridge this knowledge gap. Therefore, to address previous gaps, the study has the following research hypothesis below,

H1: Fixed telephone subscriptions significantly improve the agricultural crop production.

H2: Internet using the individuals significantly improve the agricultural crop production.

H3: Mobile cellular subscription significantly improve the agricultural crop production.

2.2. The Moderating Role of the Country Governance Index

Previous studies on the relationship between ICT and crop production have inconsistent findings. Some studies found that ICT played an integral role in increasing production (Chamara et al., 2022). Conversely, another study found that ICT adoption did not significantly improve crop production due to challenges such as infrastructure limitations, and economic constraints (Ahmad et al., 2024). These discrepancies indicated that the impact of ICT on agriculture may depend on additional country-level variables. As a result, there is a need to investigate moderating variables that can influence the ICT and crop production relationship (Fountas et al., 2024). One such variable is country governance, which can generate an environment aimed at ICT integration in the agricultural sector (Saba et al., 2024). Governance structures that promote transparency, investment, and institutional support may enhance the effectiveness of ICT in improving crop yields (Spielman et al., 2021). Therefore, this study contributed to country governance as a moderating variable between the relationship of ICT and crop production.

The country's governance played a significant role in increasing the investment toward ICT resources in the agriculture sector (Saba et al., 2024). Better governance infrastructure develops policies that support digital infrastructure development, and financial incentives for farmers to facilitate technological advancements (Shou et al., 2025). Through prioritizing ICT-based agricultural solutions, governments can encourage digital literacy programs, improve rural connectivity, and provide subsidies for precision farming technologies (Bakhoum, Gonzalez Otero, & Hoffmann, 2024; Patel, 2025). Additionally, strong governance ensures regulatory frameworks that protect digital platforms, enhancing trust and participation among farmers (Patel, 2025). Improved governance mechanisms also promote research and development in agricultural technologies, leading to innovations that optimize farming efficiency (Joseph & Pandey, 2025). As governance strengthens ICT adoption, farmers gain better access to weather forecasts, pest control information, and market trends that could lead to increased crop production (Boachie & Mensah, 2022; Rezaee et al., 2021; Spielman et al., 2021). In previous empirical studies, country governance has been also used as a moderating variable and found a significant moderating effect (Saba & Pretorius, 2024; Saha et al., 2024), which strengthens the moderating variable effectiveness for the current study. Therefore, integrating country governance as a moderating factor can bridge the gap between ICT investment and its practical effectiveness in agriculture. Based on preceding empirical supports, the study has articulated the following hypothesis below,

H4: Fixed telephone subscriptions significantly improve the agricultural crop production with moderating effect of the country governance index.

H5: Internet using the individuals significantly improve the agricultural crop production with moderating effect of the country governance index.

H6: Mobile cellular subscription significantly improve

the agricultural crop production with moderating effect of the country governance index.`

3. Research Methodology

The study objective was to test the impact of ICT on crop production in GCC countries with a moderating effect of the country governance index. For this objective, quantitative longitudinal data was collected from 2005 to 2024 from world development indicators from 6 GCC countries. These countries were selected because they have good strength in agricultural production and vary based on their climatic conditions and technological advancements. Saudi Arabia has developed large-scale desert agriculture using modern irrigation systems and government support, making it a leader in wheat, date, and dairy production (Fiaz, Noor, & Aldosri, 2018). The UAE excels in hydroponics, vertical farming, and controlled-environment agriculture which is enhancing food security through agri-tech investments (Murad, 2010). Qatar has rapidly expanded local food production with hydroponic greenhouses and desalination-based irrigation, particularly after the 2017 blockade (Ben Hassen & El Bilali, 2022). Kuwait focuses on greenhouse farming, precision agriculture, and sustainable water use to improve vegetable and fodder crop production (Omar Asem, 2024). Oman benefits from traditional farming in coastal and mountainous regions, excelling in date palm cultivation and fisheries while promoting sustainable farming practices. Bahrain leverages urban farming to maximize limited arable land, adopting

innovative solutions to boost agricultural output (Al-Ammary & Ghanem, 2024). As these countries have different approaches in agricultural strategies which are employed by GCC nations to overcome arid conditions and enhance food security. Therefore, these countries are selected for the study setting.

3.1. Variables Measurement and Regression Model

In the below model and in Table.1, crop production index is the dependent variable, fixed telephone subscription, individual using internet of population percentage and mobile cellular subscription are independent variables. The country governance index is a moderating variable. Domestic credit for private banks, per capital-adjusted national income, and rural population are the control variables. The research used auto-regressive distributed lag (ARDL) to evaluate the aforementioned variables using STATA software for analysis. Determining long-term correlations between exogenous and endogenous variables and avoiding the endogenous problem are two key characteristics of the panel ARDL framework (Bildirici, 2014). The Pesaran Cross-sectional Augmented Dickey-Fuller (CADF) test was utilized to ascertain whether unit roots existed among the variables or not which is recommended by Bildirici (2014). The long- and short-term effects of the independent factors on the dependent variable were calculated using the panel autoregressive distributed lag. Study variables are predicted in Table.1 below,

Table 1: Data Sources and Variables.

Variables	Source
Dependent Variable	
Crop production index (% of total crop in GCC countries)	(WDI, 2005-2024)
Independent Variable	
Fixed telephone subscriptions (number of persons)	(WDI, 2005-2024)
Internet using the individuals (% of the population)	(WDI, 2005-2024)
Mobile cellular subscriptions (number of persons)	(WDI, 2005-2024)
Moderating Variable	
Country Governance Index The aggregate score is derived from national governance mechanisms, including government effectiveness, regulatory quality, and the rule of law, as reported by the Worldwide Governance Indicators. It is expressed as a percentage, ranging from 0% to 100%	(WDI, 2005-2024)
Control Variables	
Per capita adjusted net income (current US$)	(WDI, 2005-2024)
Domestic credit to private sector by banks (percentage of GDP)	(WDI, 2005-2024)
Rural population (percentage of total population)	(WDI, 2005-2024)

Following econometric model of the study which are presented in equations below,

$$Y_{it} = \beta0 + \beta1 IUI_{it} + \beta2\ MCS_t + \beta3\ FTS_{it} + \beta4\ ANPC_{it} + \beta5\ DCPS_{it} + \beta6\ RP_{it} + \varepsilon it \quad (2)$$

$$Y_{it} = \beta0 + \beta1\ IUI_{it} + \beta2\ MCS_t + \beta3\ FTS_{it} + \beta4 IUI^*CGI + \beta5 MCS^*CGI + \beta6 FTS^*CGI + \beta7 ANPC_{it} + \beta8\ DCPS_{it} + \beta9 RP_{it} + \varepsilon it$$

Yit = crop production; *IUI*-internet using the individuals;

MCS = mobile cellular subscription; FTS = fixed telephone subscriptions; $ANPC$ = per capita adjusted net income RP=rural population, e = error term, CGI-corporate governance index. These variables are predicted in Figure.1
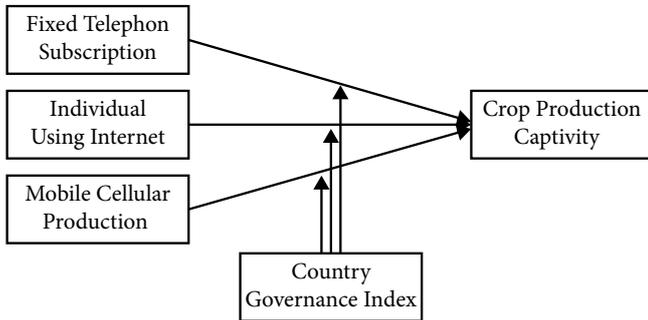

Figure 1: Research Framework.

The Standard panel regressions model which shown in Equation 1 and Equation 2. These models show that if some of the variables are stationary on level 1 while others become stationary at first difference then a dynamic panel data model that accounts for cointegration is required. Suitable approaches in this case include the Pooled Mean Group (PMG) and Dynamic Fixed Effects (DFE) models (De Hoyos & Sarafidis, 2006).

4. Data Analysis and Results

Table 2 results show the descriptive statistics results where analysis reveals significant variations in economic, technological, and demographic factors affecting crop production in GCC countries. Fixed Telephone Subscriptions (FTS) have a high mean (800,452.25) but is highly dispersed, indicating that while some countries still rely on traditional communication, others have shifted to mobile technology. This is further supported by Mobile Cellular Subscriptions (MCS), with a mean of 17,532,890.74, reflecting widespread mobile adoption that enhances communication and digital agricultural solutions. However, internet-using individuals (IUI) have a relatively low mean (18.54 which suggests limited digital infrastructure that may restrict access to online agricultural knowledge, market prices, and weather forecasts. Corporate Governance Index (CGI) has a mean of 0.8912, indicating moderate governance quality that can influence agricultural policies, investments, and regulatory support.

Meanwhile, economic factors are also playing an important role in increasing agricultural production. Among these, per capita adjusted net income (ANPC)

has a mean of 2,045.78, highlighting disparities in economic well-being, which could impact access to modern farming technologies and financial resources. Domestic credit to the private sector (DCPS) averages 28.9 which indicates that financial support is available but may not be uniformly accessible, potentially limiting investments in advanced farming techniques. Rural population (RP) along with a mean of 55.83 suggests that a significant portion of the population still resides in rural areas which emphasizes the continued importance of agriculture in economic development. skewness and kurtosis results show that most variables have asymmetric distributions, with some extreme values affecting the overall trends. The high skewness in FTS, MCS, and ANPC suggests that a few countries have very high values, while others remain significantly lower. In contrast, the moderate distribution of CPI and RP indicates relatively balanced levels across CC countries. These variations imply that while technological and economic advancements are improving, disparities still exist, influencing agricultural productivity and access to resources differently across countries. Below Table 2 represents the descriptive statistics.

Table 2: Descriptive Analysis.

Variables	Mean	Std. Deviation	Skewness	Kurtosis
FTS	800,452.25	1,850,312.75	3.712	14.892
CPI	95.2145	20.56321	-0.012	0.978
CGI	0.8912	0.87455	-0.175	0.624
IUI	18.54	18.32	1.325	0.658
MCS	17,532,890.74	27,101,453.65	3.118	11.672
ANPC	2,045.78	1,932.75	1.926	4.312
DCPS	28.92	21.36	1.573	1.934
RP	55.83	18.24	-0.182	-0.526

4.1. Diagnostics Tests

Table 3 results show the diagnostics test results. Three main tests were conducted on diagnostics namely cross-sectional dependence test, unit root test, and panel cointegration test. Among these tests, cross-sectional dependence shows a strong level of cross-sectional dependence among the variables because all variables are significant at p-values (p = 0.000). The presence of cross-sectional dependence suggests that shocks affecting one cross-section unit are likely to impact others, which is common in macroeconomic and financial panel data due to shared economic, technological, or policy-related factors (De Hoyos & Sarafidis, 2006). Such dependence can lead to biased and inconsistent estimates if not properly accounted for in econometric modeling (Baltagi & Baltagi, 2008). Given the high CD-test values, it is essential to apply robust estimators, such as the Common Correlated Effects

(CCE) estimator or the Driscoll-Kraay standard errors, to mitigate the impact of cross-sectional dependence (Baltagi & Baltagi, 2008). These findings emphasized the necessity of considering cross-sectional dependence in panel data analysis to increase results reliability.

Furthermore, to assess the potential collinearity among the independent variables in this study multicollinearity tests through variable inflation factor (VIF) were conducted. The results displayed in Table 3 indicated no significant multicollinearity, as all VIF values remained below 5. This cutoff is widely considered acceptable for detecting multicollinearity. Therefore, these results show that there is no issue of multicollinearity. Additionally, a unit root test was conducted through the Pesaran cross-sectional augmented Dickey-Fuller (CADF). The Pesaran Cross-sectional Augmented Dickey-Fuller (CADF) unit root test results show that several variables in the dataset exhibit different orders of integration. Variables such as CPI, FTS, IUI, DCPS, and RP are stationary at their levels (I(0)) at various significance levels (1% or 5%) which indicates no unit root and this is suggesting that these variables do not require differencing for further analysis. In contrast, CGI, MCS, and ANPC are non-stationary at the level and are integrated of order 1 (I(1)) at the 1% significance level, implying that they exhibit a unit root and require differencing to achieve stationarity. These results are important for correct model selection, such as differencing for non-stationary variables and potentially conducting cointegration tests for the integrated series, ensuring valid and reliable analysis in subsequent steps.

Additionally, panel cointegration tests were also conducted to test the study hypothesis. For this purpose, two tests were conducted namely, Modified Phillips–Perron t-statistic and Augmented Dickey-Fuller t-statistic which are recommended by Baltagi & Baltagi (2008). The results of the Pedroni cointegration test designate a strong cointegration among the variables in the panel data model. Specifically, both the Modified Phillips–Perron t-statistic (7.6234) and the Augmented Dickey-Fuller t-statistic (–13.8666) have p-values of 0.0000, which are highly significant at conventional levels (e.g., 1%, 5%, or 10%). The Modified Phillips–Perron t-statistic being positive and significant suggests that the null hypothesis of no cointegration is rejected, indicating that variables are cointegrated in the panel which shows the long-run relationship. Similarly, the Augmented Dickey-Fuller t-statistic which is negative and significant, further supports the rejection of the null hypothesis of no cointegration. These findings suggest that despite potential short-term dynamics, the variables move together in the long run, meaning they share a stable long-term relationship. This result is important for further analysis, as it justifies the use of error correction models (ECM) or other methods that account for long-term relationships in panel data analysis. The above results are predicted in the table.3 below,

Table 3: Diagnostics Tests.

Variable	CD-Test	*p*- Value	*VIF*	Result	Accepted	*Ho*
CPI	34.00	0.000	…..	I(0) at 1 %	At level	Rejected
FTS	43.01	0.000	2.32	I(0) at 5 %	At level	Rejected
CGI	56.04	0.000	2.00	I(1) at 5 %	At difference	Rejected
IUI	67.02	0.000	1.92	I(0) at 1 %	At level	Rejected
MCS	8.09	0.000	2.893	I(1) at 1 %	At difference	Rejected
ANPC	78.91	0.000	1.89	I(1) at 1 %	At difference	Rejected
DCPS	23.08	0.000	1.772	I(0) at 1 %	At level	Rejected
RP	34.19	0.000	2.891	I(0) at 1 %	At level	Rejected
Cointegration Pedroni Test						
	Statistic	*p*-Value				
Modified Phillips–Perron t	7.6234	0.0000				
Augmented Dickey-Fuller t	–13.8666	0.0000				

4.2. ARDL Regression Results

After performing a diagnostics test, the next step is to test the study hypothesis. For this purpose, the Hausman test was used in identifying the misspecification and endogenous variable specification. In the context of panel ARDL estimations, dynamic fixed effect (DFE), pooled mean group (PMG), and dynamic fixed effect (DFE) estimators were used. The results of the Hausman test suggest that the PMG estimator is the more appropriate choice for the analysis. However, when analyzing the crop production category (y), the DFE estimator proved to be the preferred option. As a result, the DFE estimator is considered the most efficient estimator for this study, especially when comparing it to the PMG estimator. The results obtained using the DFE

estimator, as presented in Table 4, are more reliable and accurate in both the long-run and short-run estimations of the ARDL model. The results from both of long and short run were significant in all hypothesis testing.

Direct influence in long of each independent variable namely mobile cellular subscriptions (MCS), fixed telephone subscriptions (FTS), and internet using the individuals (IUI) demonstrated significant positive influences on crop production. These results suggest that, over time, improvements in communication infrastructure, internet access, and access to financial services help increase agricultural productivity. The long-term benefits of these variables reflect a deeper integration of technology and financial services in agricultural practices, leading to better resource management, access to markets, and information flow. On the other hand, control variables have a significant influence on crop production in the run. Further moderating effect results in the long run also show that CGI positively and significantly moderates FTS, IUI, MCS, and crop production relationships.

In the short run, the direct effects also remain positive and statistically significant, though the magnitudes of their impacts are generally smaller compared to the long run. MCS and IUI still exhibit positive impacts, but these effects are more limited in the short term, possibly due to the time required for technology adoption and infrastructure development. Similarly, DCPS and FTS show reduced effects in the short term, suggesting that the immediate impact of these variables is not as strong as in the long run, likely due to the lag between investment and realization of benefits. Despite the weaker short-run effects, the moderating effects of these variables remain significant, particularly for MCS and IUI, which continue to enhance the relationships between other factors and crop production, even if the impact is less pronounced in the short term. These results emphasize that while the short-run benefits of technological advancements and financial services are still apparent, their full potential is realized only over time as farmers and agricultural systems become more integrated with these innovations. The above results are predicted in Table.4 below.

Table 4: ARDL Results.

Variables	Direct Effect (Long-Run)	Moderating Effect (Long-Run)	Direct Effect (Short-Run)	Moderating Effect (Short-Run)
FTS	0.302 (0.0782)***	0.412 (0.068)***	0.248 (0.0675)***	0.396 (0.073)***
MCS	0.392 (0.0893)***	0.472 (0.0823)***	0.345 (0.0786)***	0.425 (0.079)***
IUI	0.431 (0.083)***	0.521 (0.093)***	0.377 (0.0812)***	0.490 (0.085)***
DCPS	0.452 (0.0672)***	0.241 (0.071)***	0.389 (0.0638)***	0.278 (0.065)***
ANPC	0.232 (0.082)***	0.312 (0.091)***	0.197 (0.079)***	0.284 (0.083)***
RP	0.312 (0.072)***	0.355 (0.0831)***	0.268 (0.070)***	0.320 (0.078)***

5. Discussion

Information and Communication Technology (ICT) enhances crop production through providing farmers by real-time data, market insights, and efficient resource management tools. It raises innovation, improves productivity, and supports sustainable agricultural practices. Therefore, **the** study objective was to test the impact of ICT on crop production in GCC countries. The findings of these objectives demonstrated that ICT positively and statistically significantly affects to crop production of GCC countries. The study reveals that ICT adoption, especially mobile cellular subscriptions, fixed telephone infrastructure, and internet usage significantly enhances crop production in the GCC region. Furthermore, the corporate governance index (CGI) plays a significant moderating effect between ICT dimensions and crop production. These findings highlight that ICT adoption and effective CGI is important for driving crop production to gain sustainable growth in the agricultural sector.

In the dimensions of ICT, FTS significantly increases the crop production of GCC countries. These findings indicated that reliable fixed telephone services play a key role in enhancing communication within the agricultural sector. Meanwhile, with the widespread adoption of mobile technologies fixed-line communication remains a better tool for maintaining sustainable communication among the farmers in the GCC countries. Therefore, these findings support the agriculture sector of the GCC because these countries often depend on large-scale operations and government intervention for resource management. The study findings are supported by several studies (Chandio et al., 2024; Singh et al., 2024) where they found that countries with strong fixed-line telecommunication systems tend to have more efficient agricultural production systems because farmers can connect with suppliers, access advice, and stay informed about market prices. These findings emphasized that there should be a proper investment in technology infrastructure in GCC countries' agriculture that could raise more coordinated agricultural practices, enhance market transparency, and that could

increase food production which is vital for reducing reliance on food imports.

Further outcomes demonstrated that MCS also positively and statistically significantly affects to crop production of GCC countries. These results highlighted the transformative role of mobile technology in modern agriculture increasing economic growth. These findings show that in GCC countries mobile phones are playing an important role in providing farmers with quick access to vital information such as prices of crops as per markets, pest control methods, and best practices in farming. Historically, it has been observed that agriculture in GCC has been plasticized in harsh weather conditions, and in this environment, mobile solutions enable farmers to make decisions that could affectedly improve yields. These findings on mobile technology could also support to contribute financial inclusion by enabling farmers to access mobile banking and digital systems which is important for small-scale farmers to increase their production. These arguments and empirical results are supported by other regions (Ahmad et al., 2024; Sekabira & Qaim, 2016) where they found that increased mobile phone usage leads to better productivity particularly when used for market access, crop management, and information sharing. Therefore, based on the evidence, expanding the availability and use of mobile phones for agricultural services in GCC countries would significantly enhance agricultural productivity which helps farmers in adopting smart farming techniques that align with the region's economic growth.

Further results show that IUI also significantly increases crop production in the GCC countries. These results demonstrated the significance of internet access in revolutionizing agricultural practices in the GCC. With internet access, farmers can leverage accuracy agriculture tools, data-driven decision-making platforms, and online agricultural education resources to increase yields while conserving resources. These findings are important for the GCC where the scarcity of water is a major issue and therefore use of internet-based technologies such as automated irrigation and remote sensing tools can optimize water use, a critical factor in sustainable farming. Furthermore, increasing penetration in the rural areas of GCC countries could also create a shift towards high-tech that could reduce the region's reliance on food imports and strengthen its economic resilience. Meanwhile, with the expansion of internet access to rural agricultural communities, GCC nations could achieve food security, support agribusiness growth, and promote economic diversification within the non-oil

sectors. Therefore, based on the findings it is enforced that agricultural sector in GCC should have good IUI system to enhance their crop production. The results are similar with several empirical studies (Kuradusenge et al., 2024; Mushtaq, 2011) where they found that internet access accelerates agricultural innovation, particularly through enabling the use of drones, AI for pest detection, and cloud-based data management.

Further, a moderating effect also strengthens the relationship between ICT and agricultural production in the GCC countries. These findings emphasized that CGI played an integral role in enhancing the effectiveness of ICT on agricultural productivity that is showing that strong governance amplifies the positive impacts of ICT infrastructure on farming outcomes. This finding suggests that governance-related factors, such as policy transparency, regulatory quality, and public-private collaboration are key to ensuring that investments in digital technologies for agriculture are successfully implemented and maximized. These findings are more relevant for the GCC countries where governance structures are typically strong but require further alignment with technological advancements. In general, it has been observed that good governance can help optimize the benefits of ICT by increasing a conducive regulatory environment for digital solutions. Well-governed institutions can ensure that policies supporting rural ICT infrastructure reach the farmers who need them most, thereby improving their access to information, financial services, and technical support. Therefore, it is argued that GCC countries should have a good governance environment because by enhancing governance mechanisms, GCC countries can increase ICT adoption, which in turn will boost agricultural productivity and contribute to economic growth in both rural and urban areas. The findings are supported by the relevant studies where they found good governance in ICT implementation leads to more inclusive agricultural development, particularly in improving rural livelihoods and facilitating equitable access to technology. These results are also supported by previous studies (Saba & Pretorius, 2024; Saha et al., 2024), where the moderating effect of CGI also has been tested and found to strengthen the relationship. Therefore, this moderating effect is considered to be a big contribution to the study.

5.1. Implications

Theoretical implications are following given below. Firstly, research contributed to the literature by introducing a moderating effect of CGI on the relationship between ICT

and agricultural productivity in the GCC countries, an area largely unexplored in existing research. While many studies have focused on individual GCC countries, this research fills a gap by examining the collective impact of ICT on agricultural production across the region which offers a more strong perspective. Secondly, a study with the extended model provides empirical evidence of the significant and positive role of ICT specifically mobile technology, fixed telephone services, and internet usage in enhancing crop production in the GCC countries. This contributes to the broader literature on agricultural development by emphasizing the transformative potential of ICT in regions with challenging climates and limited agricultural land. Thirdly, a study with the moderating effect of CGI on the relationship between ICT and agricultural productivity is a unique contribution which is showing how strong governance can strengthen the impact of ICT in increasing crop production. This contribution is crucial as it demonstrates the need for alignment between governance structures and technological initiatives to achieve optimal agricultural outcomes. Lastly, the study offers insights into the specific ICT needs of GCC countries which is informing future investments and policies to improve agricultural practices in the region that could increase sustainable growth.

The study has the following practical implications with the study findings which offers valuable insights for the policymakers and regulatory bodies in the GCC countries. Firstly, policymakers should recognize the critical role of ICT infrastructure particularly mobile cellular subscriptions, internet usage, and fixed telephone services in increasing agricultural productivity. Investing in these technologies could be important in driving the sector's growth. Secondly, the study emphasized the importance of effective governance in ensuring the success of ICT implementation in agriculture. Strong governance mechanisms, including transparency, regulatory quality, and public-private partnerships can create a conducive environment for technology adoption. For agriculture developers, these findings suggest that they should work closely with policymakers to design ICT solutions that align with local governance structures and agricultural needs which ensures better access to technology for farmers, especially in rural areas.

The research has various limitations that could be fulfilled in further research. Firstly, the study was limited only to crop production while ignoring other livestock production, etc. Therefore, further research could be explored on livestock production to increase the strength of the study. Secondly, the study focused on country-level study, further research could be conducted on the firm level to enhance study generalizability. Thirdly, a methodology study was conducted on the ARDL model which limited the study to other panel data tests, further study could be explored on dynamic panel data for study generalizability enhancement. Lastly, study findings were limited to a quantitative approach which limited the scope for triangulation. Consequently, future studies can explore mixed methods.

6. Conclusion

The study objective was to test the impact of ICT on crop production in GCC countries with a moderating effect on the country governance index. For this purpose, longitudinal quantitative data were collected from six GCC countries from 2005 to 2024 from word development indicators. Unit root, panel cointegration, and panel ARDL statistical analysis were conducted to test the study hypothesis. We found the positive and significant influence of ICT dimensions on crop production in GCC countries. The country governance index also significantly strengthens the association between ICT and crop production. Research with specific findings highlighted a need for the policymakers of GCC countries to invest in advanced ICT to enhance agricultural productivity. Strengthening governance frameworks can further optimize the impact of technology on crop production, ensuring sustainable agricultural growth.

6.1. Acknowledgement

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