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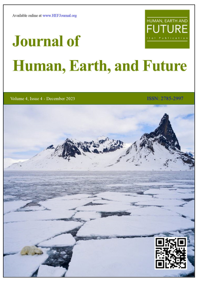

Investigating the Interplay of ICT and Agricultural Inputs on Sustainable Agricultural Production: An ARDL Approach

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Abstract

Sustainable agriculture is an important target of the Sustainable Development Goals (SDGs). Information and communication technologies (ICT) could be an important instrument to assist developing countries in achieving this goal. This study investigates the short- and long-term effects of ICT-related factors (telephone, Internet, mobile phone use) alongside traditional inputs (agricultural land, labor, fertilizer) on sustainable agricultural production in Bangladesh using an autoregressive distributed lag (ARDL) model from 2000 to 2020. In the short term, telephone use and labor involved in agriculture have a positive impact on agricultural production. Conversely, the influence of internet use, mobile phone use, and agricultural land on agricultural production is negative in the short run. In the long run, these relationships have undergone substantial changes. The positive effects of telephone usage and agricultural labor demonstrate a decreasing trend, but the impacts of Internet usage, mobile phone usage, and total agricultural land display a progressively favorable pattern in the long run. Notably, the use of fertilizers has been found to have a positive impact on long-term agricultural production. This study offers valuable insights into the evolving role of ICT in agricultural sustainability, emphasizing the need for context-specific policy interventions that consider both short- and long-term benefits.

Keywords: Information and Communication Technologies; Sustainable Agriculture; Agricultural Inputs; Food Security; Bangladesh.

1. Introduction

1.1. Food Insecurity, Environment, and Sustainable Agriculture

Currently, the world is facing several significant challenges, including hunger, food insecurity, poverty, unplanned agriculture, and environmental damage. While efforts are being made to address the issues of hunger, poverty, and food insecurity, there is a tendency to overlook the impact of these efforts on the environment. In some cases, excessive farming techniques, such as the indiscriminate use of fertilizers and pesticides and over-exploitation of land resources, are employed in the pursuit of short-term gains. However, such practices are not sustainable and pose significant risks

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to future generations. To cater to the diverse needs of current and future generations, it is essential to maintain a mutually beneficial relationship between humans and nature. Sustainable agriculture is key to ensuring the availability of essential resources like water and materials and a healthy environment for both humans and the environment. It is crucial to sustainably use and manage land, fertile soil, clean water, and genetic resources, as they are essential components of food production and are becoming scarce. By increasing yields in current agricultural areas and rehabilitating damaged land through sustainable agricultural techniques, the pressure to remove forests for agricultural production might decrease. The world's agriculture must be more efficient and less wasteful. To achieve sustainable farming, both sustainable production and consumption practices must be pursued [1, 2]. The concept of sustainable agriculture was first introduced through the initial framework by Wes Jackson, who coined the term in his 1980 article "New Roots for Agriculture". Rodale [3] later introduced the concept of "regenerative agriculture" to stress the significance of ecological agricultural practices. Information, communication, and technology (ICT) can be an important instrument for achieving sustainable agriculture by helping in the efficient and planned use of agricultural inputs to improve production and minimize ecological damage.

According to the Food Insecurity Experience Scale, the incidence of moderate-to-severe food insecurity has been gradually increasing worldwide since 2014. In 2020, the anticipated increase was equal to the sum of the increases in the previous five years. In 2020, 2.37 billion people worldwide—nearly one in three—will lack access to food. A third (799 million) live in Africa, 1.2 billion in Asia, and 11% (267 million) in Latin America and the Caribbean, among the 2.37 billion people who are experiencing moderate to severe food insecurity. Around 3 billion people worldwide, particularly the impoverished, were unable to afford nutritious diets in 2019 due to the high expense of such diets and the continued high levels of wealth disparity [4]. According to Sustainable Development Goal (SDG) 2.3, it is crucial to double the production and incomes of small-scale food producers by 2030, particularly for marginalized groups such as indigenous peoples, women, family farmers, pastoralists, and fishermen. Achieving this requires ensuring access to land, resources, information, markets, and value-creation opportunities. In recent times, there has been a shift in farming practices towards the excessive use of fertilizers and pesticides. Global production of pesticides has increased by over 11% annually, from 0.2 million tons in the 1950s to more than 5 million tons by 2000 [5]. Despite the widespread use of pesticides, with three billion kilograms being used annually worldwide, only 1% of these are successfully used to control insect pests on target plants [6]. This excessive use has led to significant quantities of residual pesticides contaminating non-target plants and environmental media, resulting in environmental pollution and adverse health effects [7].

The world is currently grappling with a host of environmental challenges, including rising temperatures, severe weather events, elevated sea levels, global warming, and the depletion of the ozone layer. According to the Mauna Loa Observatory, CO_2 emissions continue to rise unabated, surpassing 415 parts per million, a level not witnessed for thousands of years [8]. The Intergovernmental Panel on Climate Change (IPCC) reported that from 1990 to 2018, global greenhouse gas emissions grew by 50%, exacerbating the heat-trapping effect that drives global warming [9]. This increase in emissions has contributed to the escalating problem of climate change. The average global surface temperature has risen by approximately 1.1 degrees Celsius since the late 19th century, and this increase has had a devastating impact on the world [10]. The implementation of unsustainable agricultural practices may exacerbate the potential negative outcomes of these challenges, emphasizing the need to adopt sustainable agricultural methods. SDG 2.4 aims to establish sustainable food systems, adopt resilient agricultural practices, preserve ecosystems, and improve land quality [11]. Sustainable agriculture meets society's immediate food and clothing needs while preserving resources for future generations [12]. Information and communication technologies (ICTs) can support the attainment of SDG 2 by ensuring sustainable agricultural practices.

1.2. Sustainable Agriculture and Information Communication and Technology (ICT)

Sustainability in agriculture requires economic profitability, environmental responsibility, and social accountability [13, 14]. To ensure the long-term viability of the farm, it is essential that it be profitable. Although sustainable practices may not always result in immediate financial returns, they can have a positive impact on both the environment and society, ultimately leading to a favorable economic outcome for the farm. ICT helps lower the costs of production, transportation, and distribution for agricultural activities, in addition to boosting productivity and profitability. Linking small producers to marketplaces also lowers transaction expenses for food product production and distribution systems. The utilization of natural resources such as water, land, and energy, as well as artificial resources such as pesticides and fertilizers, can be accomplished more efficiently with the aid of ICT. ICT can mitigate the negative environmental impacts and harmful consequences of agriculture and agribusiness in food processing systems. ICT can also reduce water pollution and contribute to the reduction of greenhouse gas emissions [15]. The application of environment-friendly techniques in environmental stewardship has either a neutral or positive effect on the utilization of natural and non-renewable resources on farms. To prevent further degradation of water and land resources, it is crucial to implement conservation measures, even if it means reversing the damage that has already occurred, such as soil erosion or the draining of wetlands. ICT is vital for improving access to information for all parties involved in the food production and distribution chains. Additionally, it increases transparency, strengthens relationships among stakeholders, empowers small-scale farmers, and enhances the efficiency of agribusiness operations. These developments have had a positive impact on promoting social responsibility within the agricultural industry [15].

Providing essential information to farmers is a significant advantage of ICT in agriculture. Through mobile apps, websites, and SMS services, farmers can access weather forecasts, market prices, agricultural techniques, and best practices, enabling them to make informed decisions and enhance their productivity [16]. Precision agriculture is made possible by ICT, which allows farmers to monitor and manage their crops more effectively using sensors, drones, GPS technology, and data analytics [17]. They can properly apply water, fertilizers, and pesticides, minimizing waste and impact on the environment while increasing crop yields. ICT solutions improve agricultural supply chain management. Direct communication between farmers and consumers may eliminate intermediaries, guarantee fair prices, and improve transparency and traceability. Satellite images and remote sensing technologies track crop health, spot pests and diseases, and measure soil moisture, enabling farmers to take fast action and stop losses. As the effects of climate change on agriculture have worsened, ICT has provided useful instruments for adaptation. Farmers can modify planting schedules, adopt climate-resilient techniques, and prepare for extreme weather events using early warning systems and climate models. Figure 1 shows the links between different ICT tools and sustainable agriculture. It has been proven that agriculture can successfully reduce carbon emissions [18]. By utilizing cost-effective methods of production, high-yielding agriculture can significantly reduce poverty and improve the life standards of poor rural farmers [19].

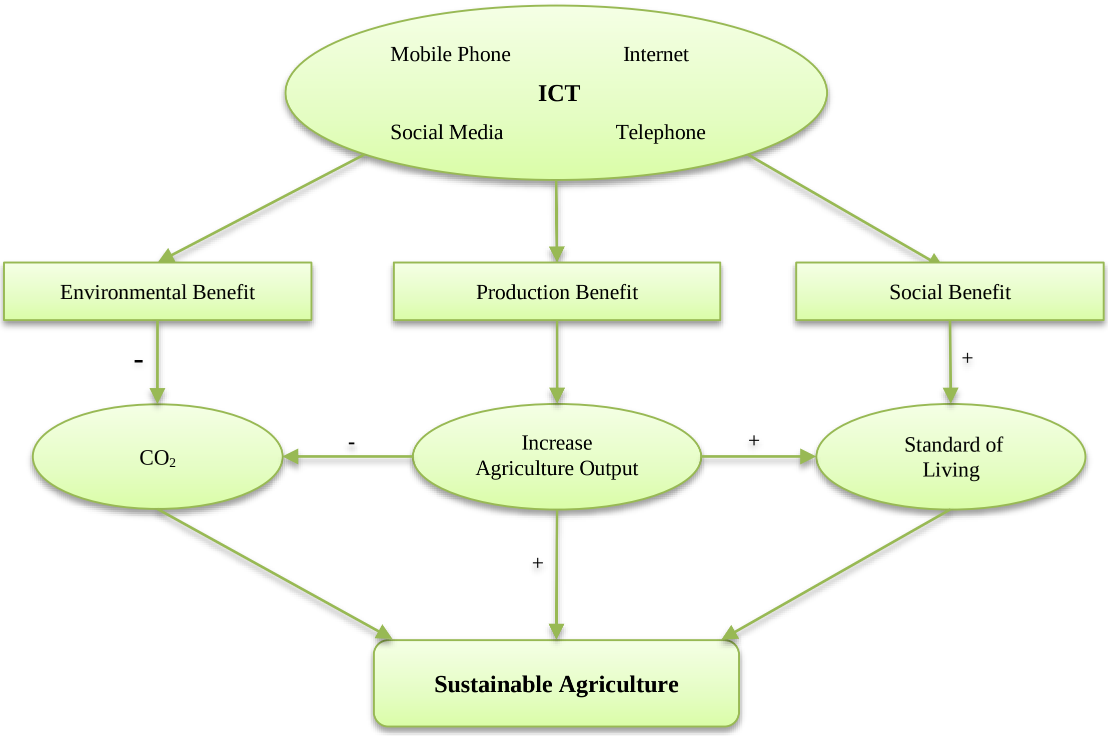

Figure 1. Relationship between ICT and sustainable agriculture

ICT tools provide farmers with insights into managing natural resources and ecosystem dynamics, thereby reducing negative impacts on the environment. Agroforestry techniques and the preservation of natural habitats are encouraged. ICT also increases efficiency, reduces waste, and promotes environment-friendly practices. It is crucial to convert conventional agriculture into a more sustainable system that provides farmers with information and access to markets. Radio remains a common means of communication in remote areas; however, television plays a vital role in agricultural instruction. The gap between farmers and consumers has also narrowed due to mobile devices, which allow farmers to communicate directly with customers and pay for their products.

1.3. Bangladesh, Agriculture, and Information Communication and Technology (ICT):

Agriculture plays a crucial role in Bangladesh's economy as it is the primary source of employment opportunities, accounting for over 41% of the country's employment. The agricultural sector is directly or indirectly responsible for the livelihoods of over 70% of Bangladesh's population. Agriculture remains the primary source of food in Bangladesh despite its relatively low contribution to the country's Gross Domestic Product (GDP) of 13.5%, as reported in the Bangladesh Economic Review 2023. However, this contribution has been steadily declining annually, which can be attributed to various factors, such as shrinking cultivable land, inadequate infrastructure, a shortage of human capital, insufficient focus on agriculture, a lack of proper policies, and technological limitations. The use of modern ICT tools, such as radio, television, telephone, smartphone, Internet, and computers, has improved the condition of Bangladesh's agriculture sector. These tools have helped restore the sector's former prominence [20–22]. Table 1 displays a comparison of ICT development between Bangladesh and its neighboring countries. It is evident from Table 1 that although the growth of ICT in Bangladesh is relatively slow, it is becoming increasingly essential for the daily lives of the population.

Table 1. ICT development index

Country	IDI 2017 Rank (Value)	IDI 2016 Rank (Value)
Bangladesh	147 (2.53)	146 (2.37)
India	134 (3.03)	138 (2.65)
Sri Lanka	117 (3.91)	116 (3.77)
Pakistan	148 (2.46)	148 (2.21)
Nepal	140 (2.88)	139 (2.60)

Source: Global ICT Development Index, 2017

Agriculture has become a top priority in Bangladesh owing to the country's growing population and changing climate, as it is the foundation of environmental protection and food security. The integration of ICT has revolutionized the agricultural industry, providing innovative solutions to the challenges faced by farmers and stakeholders. Bangladesh, with its high population density and limited arable land, relies heavily on the agricultural sector to meet the needs of its people and drive economic growth. However, traditional agricultural practices often lead to resource depletion, land degradation, and environmental pollution, all of which threaten the nation's agricultural sustainability.

To address these challenges, the use of information and communication technology tools and solutions provides unparalleled opportunities to streamline farming operations, boost output, and minimize environmental impacts [23]. Recently, Android apps related to agriculture services and technology have gained immense popularity among low-level laborers in Bangladesh who are employed in the agriculture, equine, and fisheries industries. These applications have brought about a new era of communication and feedback in agriculture, which is crucial for the acceptance and dissemination of new technologies. Producers can easily exchange knowledge, experiences, and concerns with other users through these apps [19]. The graph in Figure 2 illustrates the rising trend of utilizing various communication technology tools in Bangladesh from 1998 to 2021. The graph clearly indicates a significant rise in ICT utilization in Bangladesh over the years.

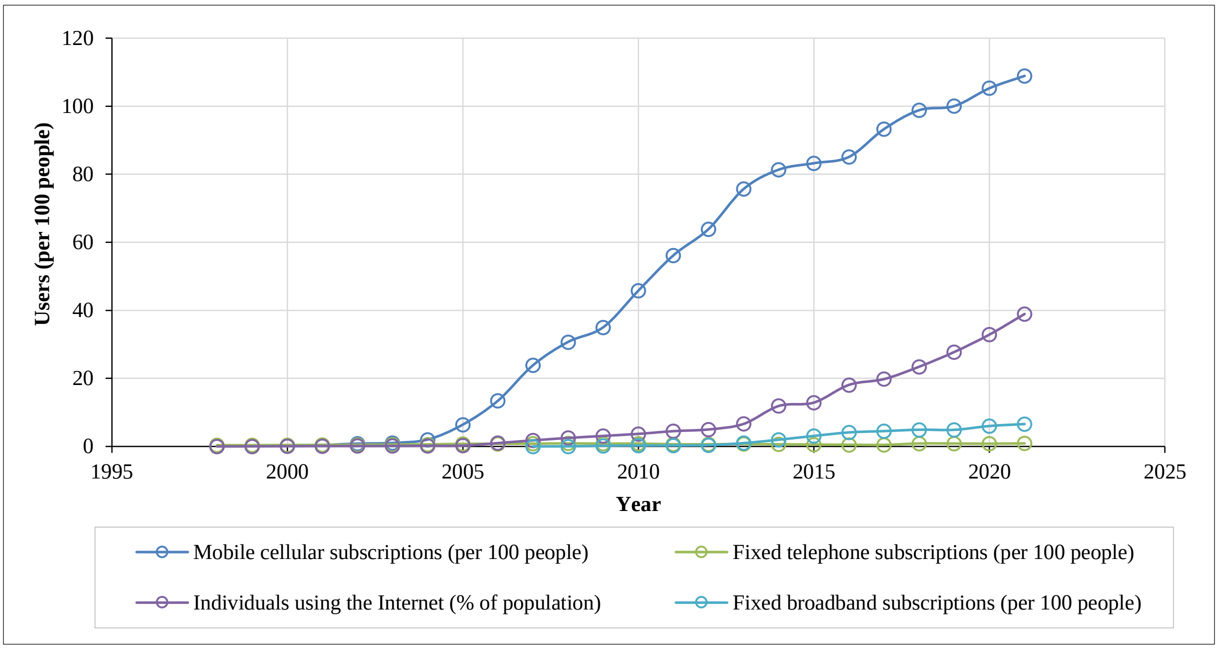

Figure 2. Growth of ICT use in Bangladesh

While prior studies have explored ICT's impact on agricultural productivity, this research goes beyond that by analyzing its dynamic interplay with traditional agricultural inputs such as land, labor, and fertilizer, revealing the evolving nature of their relationships in the context of sustainable food production. Increasing ICT use has a favorable effect on agricultural output, as demonstrated by numerous writers using descriptive approaches. However, no authors have employed a time-series analysis to illustrate this. Thus, to our knowledge, this is the first study to use time-series observations along with qualitative methods to determine the importance of different modern ICT tools in achieving sustainable agriculture. This study aimed to determine the optimal use of ICT tools to boost agricultural production while limiting CO_2 emissions. We strive to identify the association between ICT and agriculture in Bangladesh.

This study follows a systematic organization with distinct sections. An introduction is presented in Section 1, and Section 2 elaborates on the literature review. Section 3 provides insights into the study's data, theoretical framework, and methodology. Section 4 unveils the results, findings, and discussion, and Section 5 presents the conclusions and important policy recommendations. Section 6 addresses the limitations of the study and proposes directions for future research.

2. Literature Review

In addition, according to Deichmann et al. [24], a growing number of people are experiencing life changes owing to the Internet, mobile devices, and other digital technologies that make it easier to access and share data. These technologies are becoming more widespread and can also help agriculture by improving productivity and market transparency [11, 25]. Sishodia et al. [17] stated that new farming methods, such as those used during the Green Revolution, have helped agriculture keep up with the demand for food and other goods. Rising costs, a growing population, and current living standards have put pressure on natural resources. Therefore, there is a need to develop new approaches to address future food needs while reducing environmental impacts. This can be achieved with the help of ICT technologies such as geographic information systems (GIS), the Internet of Things (IoT), artificial intelligence (AI), and big data analysis. According to Walter et al. [26], achieving sustainable agriculture requires smart-farming methods. Chandio et al. [27] applied the D-K-SE and MMQR methods to panel data from 2011–2020 in China to find out the impact of Internet use on rice production, and they found that ICTs play a significant role in ensuring food security and sustainable food production in emerging economies. Alam et al. [28] make the case that several issues facing agri-food systems, such as maintaining accurate farm management, product marketing, and input access, can be resolved with the help of ICTs. In light of the world's increasing demand for food production and to maintain the resilience and sustainability of farming systems, this article highlights the critical need to expand the application of advanced agricultural ICTs to help stakeholders cope with, adapt to, and build resilience in agri-food system networks.

Bangladeshi smallholder farmers have been farming their lands using traditional techniques for centuries. Although their experience provides a solid foundation, many of them need access to updated information, leading to stagnation in their understanding [29]. Digital agriculture may help overcome ICT stagnation in the global food system and enhance sustainability by using digital and geospatial technology to monitor, evaluate, and manage soil, climate, and genetic resources. This approach demonstrates how the complex task of balancing the economic, environmental, and social aspects of sustainable food production can be addressed [23].

Lio and Liu [30] state that the implementation of modern ICT in agriculture boosts productivity. Infrastructure is critical for the use of contemporary industrial inputs in production. Advances in ICT can result in disparities in agricultural output between nations. Higher resource productivity, reduced inefficiencies, lower management costs, and better food chain coordination are possible benefits of ICTs in the agro-food sustainability transition [31]. According to Mtega & Msungu [32], all forms of ICT are valuable for actors working in the agricultural sector. Mobile phones and radio were preferred as communication channels among farmers, while researchers and extension staff mentioned that they preferred using computers and the Internet [22]. Heang & Khan [33] showed that television and radio had an effective role in increasing farmers' agricultural knowledge, production, and income.

In a study by Das et al. [21] used a sample of 1990 farmers from a population of farmers in Bangladesh using a randomized survey with a questionnaire, interviews, and focus group discussions. The study's findings after counterfactual and difference-in-differences analyses also demonstrated that the application and use of ICTs accelerated agricultural production. This was demonstrated by the degree of increase of ICT to that of counterfactual, which is 0.49, and demonstrated that the production of Boro rice from the ICT-based service area increased more than that of the non-ICT-based area. A questionnaire-based qualitative assessment of Bangladeshi rural agriculture was conducted by Alam and Haque [34]. This study aims to explore how TV channels promote agriculture by broadcasting relevant information to farmers, leading to increased productivity. The results indicated a positive correlation between TV dependence and agricultural improvement.

A study in Zambia found that TV has a positive and statistically significant impact on worker productivity. Younger farmers aged 25-40 who used more labor-saving technology saw higher overall production. Farmers in the 25-40 age group had higher productivity due to increased ICT usage [35].

Aker & Mbiti [36] studied how mobile phones affect African economic growth but were not primarily focused on sustainable agriculture. This study highlights how mobile technology helps small-scale farmers expand their market access and adopt sustainable practices. Abubakari et al. [37] from Ghana used qualitative methods and collected data from 2662 respondents to analyze the impact of mobile phone use on agricultural productivity. They found that mobile phone use significantly increased agricultural production and the income of farmers. ICT plays a vital role in agriculture, and Meena & Singh [38] explored its potential in managing natural resources. Agriculture has a strong presence on social media, including YouTube, Facebook, and Twitter. ICT benefits data collection, monitoring, and decision-making in sustainable agriculture [39]. Deichmann et al. [24] examined the relationship between technology and rural development in India, highlighting the positive impact of ICT initiatives on agricultural output, poverty rates, and rural economies.

According to the findings of Saidu et al. [40], ICT can bring several benefits to agriculture, such as improving market operations, information exchange, profitability, global networks, research, and economic growth strategies for self-sufficiency. Oyelami et al. [41] found that investments in ICT infrastructure have long-term benefits for agricultural sector output, but no short-term sustaining evidence was found. According to Pandey (2017), ICTs, such as mobile phone apps, are changing the way farmers think [42]. Farmers can now communicate with other farmers, market holders, agricultural information call centers, and agricultural extension agents, leading to a shift away from traditional cultivation methods. Hopestone [43] analyzed data from 34 African countries from 2000 to 2011 to show how information and communication technologies impacted agricultural output. The results indicated that ICTs had a significant influence on raising production levels, but mobile phones had no impact, while traditional telephone mainlines still contributed significantly to agricultural development despite the widespread adoption of mobile technologies. According to Milovanovic [44], ICT has a significant potential to aid farmers in enhancing agricultural productivity, efficiency, and effectiveness. Singh et al. [45] suggested that ICT can provide access to useful data on agro-inputs, cultivation methods, crop processing, agro-finance, and farm management. Awuor & Ireri [46] examined the impact of e-agriculture, a subset of ICT in agriculture, on productivity and sustainability. Their study found that ICT interventions can lead to increased crop yields, improved resource management, and enhanced farmer livelihoods. Sishodia et al. [17] highlighted the use of remote sensing technology to improve agricultural operations. Using these technologies, farmers can overcome the impact of geographical heterogeneity, which negatively affects crop growth and yield.

To support agricultural output and agribusiness in Tanzania, Mtega & Msungu [32] evaluated how digital technologies can be used to expand farmers' access to information. They conducted a qualitative study using a questionnaire and found that radio, mobile phones, television, computers, and the internet can significantly impact the industry. Research shows that ICTs improve market accessibility for agricultural products and offer financial services. However, despite the increasing use of ICTs, Tanzania's agricultural sector has not benefited much, which Mtega & Msungu [32] attributed to farmers' limited access to the right ICT tools. Chauhan & Tripathy [47] stated that the Internet of Things (IoT) is an important way to achieve higher productivity. However, it has an important limitation, which is the security and privacy problems.

The influence of ICT on the sustainability of agriculture in Bangladesh is a significant and promising area of research. However, the existing literature has several limitations, including a lack of empirical evidence and its conceptual nature. More comprehensive empirical studies are necessary to assess the practical impacts of ICT interventions on agricultural techniques, productivity, and sustainability in Bangladesh. Although previous research has demonstrated the benefits of ICT for agriculture in a global context, more studies need to be conducted in Bangladesh's specific context. Most studies have relied on cross-sectional data or short-term assessments, requiring an examination of both the short- and long-term implications of ICT adoption [19, 20, 22]. Further investigation is required to understand the specific consequences and barriers of various ICT components, such as mobile applications, weather prediction systems, and market information platforms.

Our study significantly differs from the existing literature by adopting a unique hybrid methodology that combines time-series analysis with qualitative methods, providing a more holistic understanding of the dynamic relationships between ICT, agricultural inputs, and long-term agricultural production in Bangladesh. Unlike previous research, which predominantly focused on specific ICT components or relied on cross-sectional data, our investigation employs an Autoregressive Distributed Lag (ARDL) model to capture both the short- and long-term implications of ICT adoption. In addition, our study delves into the underexplored realm of ICT acceptance and adaptation in rural agriculture, offering practical insights into the challenges and opportunities faced by farmers in Bangladesh. By addressing these gaps in the literature and presenting empirical evidence, our research contributes to a nuanced and context-specific understanding of sustainable agriculture, guiding policymakers and stakeholders in formulating tailored strategies for the unique socioeconomic and environmental dynamics of Bangladesh's agriculture sector.

3. Research Methodology

3.1. Data Description

This study uses an ARDL model to analyze time-series data and gain insights into the long- and short-term dynamics of factors related to ICT and sustainable agriculture in Bangladesh. Data from 2000 to 2020 on various variables such as agricultural production, including crops, forestry and fishery, mobile phone users, telephone users, Internet users, agricultural land, fertilizer use, and labor use in agriculture. Information on these variables was collected from the WDI (Table 2) [48].

Table 2. Variable definition [48]

Variables Type	Variables Name	Symbol	Unit
Dependent Variable	Agriculture production	Y	Current US$
Independent Variables	Telephone use	TP	Person
	Mobile phone use	MP	Person
	Internet use	INT	% of the total population
	Agriculture land	AGRI	Square kilometer
	Labor employed in agriculture	AL	% of total employment
	Fertilizer use in agriculture	FZ	% of fertilizer production

3.2. Theoretical Model Construction

In this study, our goal was to determine trends in ICT and agricultural sector production growth. Therefore, we apply the Cob-Douglas production function of Solow [49], as shown in Equation 1. Romer, Mankiw, and Weil added human resource formation to the Solow growth model, with real output defined as a Cobb-Douglas function of physical capital, human resources, and the effectiveness of the unit of labor [50].

$$Y_t = f(A_t, K_t, L_{t,}) \tag{1}$$

Here, we assume that agricultural output (Y) will depend on capital (K), labor (L), and technology or efficiency of labor (A). We were interested in finding a relationship between ICT and agricultural productivity. ICT is an important part of technology that consists of modern instruments such as radio, television, telephone, smartphone, and Internet, which play a significant role in improving the efficiency of labor. Thus, we can expand the production function in Equation 2 as follows:

$$Y_t = f(TP_t, MP_{t,}INT_t, AGRI_t, FZ_t, AL_t) \tag{2}$$

Here, TP refers to the telephone user, MP refers to the mobile phone user, INT refers to the internet user, AGRI refers to agricultural land, FZ refers to fertilizer consumption by agriculture, and AL refers to the labor employed in agriculture.

In this way, we can determine the effect of different ICT tools on agricultural productivity. Oyelami et al. [41] used a similar strategy and theoretical formwork to analyze the relationship between ICT and agriculture, which was positive in the long run. Both the covariance and variance matrices are more reliable when linear models are converted into natural log versions. Hence, Equation 3 is taken as a natural logarithm.

$$lnY_t = \alpha + \beta_1 lnTP_t + \beta_2 lnMP_t + \beta_3 lnINT_t + \beta_4 AGRI_t + \beta_5 lnFZ_t + \beta_6 lnAL_t + \varepsilon_t \tag{3}$$

The initial purpose of the model, as indicated in Equation 3, is to examine the relationship between the amid variables. In this case, the explanatory variables are represented by the exponents β_1 to β_6 while the error term is denoted by ε.

3.3. Econometric Estimation

The ARDL-bound test proposed by Pesaran et al. [51] was used to determine the cointegration of variables. There are numerous advantages to this method over earlier cointegration methods. This cointegration approach does not require any initial verification, in contrast to other methodologies that require locating a series integration feature beforehand. Additionally, the choice of the ARDL technique for the analysis validates the use of a relatively small sample of 30 observations because, according to Pesaran & Shin [52], the method provides solid results and is more appropriate for statistical assessment with a limited number of samples. The new methodology is adaptable and can potentially be utilized to evaluate the I(0) and I(1) datasets [53, 54]. Additionally, the ARDL technique uses one equation for analysis, which is simple to use and comprehend. In contrast to the conventional method, this model allows the researcher to employ diverse variables with different lag lengths. Finally, the ARDL technique provides a fair estimation of both the short-term and long-term variables simultaneously.

Checking the root of the unit is the initial step in applying the ARDL technique. The sequence of integration cannot be I(2) when performing the bound test; hence, the data must be stationary, either at the level or first difference. If not, this approach is ineffective [51]. To proceed to the next level of analysis and conclusion, it is necessary to confirm the stationarity of all the variables. The analysis of the variables' time-series characteristics, as well as their short- and long-term dynamism and stability, are all part of the unit root issue test. This study employs the Augmented Dickey-Fuller test, commonly referred to as the ADF test, developed by Dickey & Fuller [55], to determine a unit autoregressive root. The long-term variables can be objectively estimated using the ARDL technique. To examine the association between selected variables, one can employ the ARDL regression framework shown in Equation 4.

$$lnY_t = \alpha + \sum_{i=1}^{\rho} \beta_{1i} lnY_{t-i} + \sum_{i=1}^{\rho} \beta_{2i} lnTP_{t-i} + \sum_{i=1}^{\rho} \beta_{3i} lnMP_{t-i} + \sum_{i=1}^{\rho} \beta_{4i} lnINT_{t-i} + \sum_{i=1}^{\rho} \beta_{5i} lnAGRI_{t-i} + \sum_{i=1}^{\rho} \beta_{6i} lnFZ_{t-i} + \sum_{i=1}^{\rho} \beta_{7i} lnAL_{t-i} + \varepsilon_{t1} \tag{4}$$

Rahman & Mamun [56] confirmed the long-standing connection between the variables by performing bound testing. The following in Equation 5 is the framework for cointegration of the ARDL bound check.

$$\Delta lnY_t = \alpha + \sum_{i=1}^{\rho} \beta_{1i} lnY_{t-i} + \sum_{i=1}^{\rho} \beta_{2i} lnTP_{t-i} + \sum_{i=1}^{\rho} \beta_{3i} lnMP_{t-i} + \sum_{i=1}^{\rho} \beta_{4i} lnINT_{t-i} + \sum_{i=1}^{\rho} \beta_{5i} lnLAGRI_{t-i} + \sum_{i=1}^{\rho} \beta_{6i} lnFZ_{t-i} + \sum_{i=1}^{\rho} \beta_{7i} lnAL_{t-i} + \gamma_0 lnY_{t-1} + \gamma_1 lnTP_{t-1} + \gamma_2 lnMP_{t-1} + \gamma_3 lnINT_{t-1} + \gamma_4 lnAGRI_{t-1} + \gamma_5 lnFZ_{t-1} + \gamma_6 lnAL_{t-1} + \varepsilon_{t2} \tag{5}$$

Using the regular error correction mechanism (ECM), short-run parameters can be projected as described in Equation 6.

$$\Delta lnY_t = \alpha + \sum_{i=1}^{\rho} \beta_{1i} lnY_{t-i} + \sum_{i=1}^{\rho} \beta_{2i} lnTP_{t-i} + \sum_{i=1}^{\rho} \beta_{3i} lnMP_{t-i} + \sum_{i=1}^{\rho} \beta_{4i} lnIN_{t-i} + \sum_{i=1}^{\rho} \beta_{5i} lnLN_{t-i} + \sum_{i=1}^{\rho} \beta_{6i} lnFZ_{t-i} + \sum_{i=1}^{\rho} \beta_{7i} lnAL_{t-i} + \tau ECT_{t-1} + \varepsilon_{t3} \tag{6}$$

The ECM findings demonstrate when a short-term shock occurs, alongside how long it is required for the entire system to return to its equilibrium over time. To ensure that no long-run data are lost, the ECM accounts for every short- and long-term variable. According to Shahbaz et al. [57], and Rahman & Manum [56], the statistically significant negative error correction coefficient (ECT) expresses the causation in the long run, whereas all other coefficients represent the short run.

The faults in Equation 6 should not be serially correlated with one another. They should also be distributed normally. These are the most typical assumptions of the ARDL-bound test method. Therefore, because the "Breusch-Godfrey Serial Correlation LM test" by Breusch [58] and Godfrey [59] is free from the traps of the Durbin-Watson test, it was examined for serial independence [60]. "Jarque-Bera" testing by Jarque & Bera [61] was employed to demonstrate that error terms are regularly distributed. Heteroscedasticity was examined using the "White's General Heteroscedasticity Test" developed by White [62]. A model with autoregressive construction needs to be examined for "dynamic stability." The stability of the model was checked using CUSUMSQ evaluations [63].

4. Empirical Result and Discussion

4.1. Descriptive Statistics

Table 3 provides a statistical overview of the variables evaluated in this model.

Table 2. Summary statistics

Variable	Obs	Mean	Std.Dev.	Min	Max	Variance	Skewness	Kurtosis
lnY	24	23.71987	0.5107774	23.14492	24.60325	0.2608935	0.406472	1.688977
lnTP	24	13.7264	0.391696	12.93025	14.24117	0.1534258	-.6014366	2.305199
lnMP	24	16.71673	2.562916	11.22524	19.03286	6.568538	-.9083268	2.341439
lnINT	24	0.5448818	2.531534	-5.603536	3.661443	6.408664	-.6661898	2.524782
lnAGRI	23	11.44985	.0203765	11.42114	11.50298	0.0004152	1.161373	4.119901
lnFZ	23	5.521548	.6048488	4.712669	6.350829	0.3658421	0.0084814	1.340199
lnAL	24	3.855963	.1494014	3.613348	4.125497	0.0223208	0.2692847	2.358161

Table 4 demonstrates the outcomes of the Augmented Dickey-Fuller (ADF) Test. Here, we observe that all of our selected variables, excluding lnINT and lnMP, are stationary at first difference, whereas lnINT and lnMP are stationary at level. Therefore, the order of integration does not remain the same for all variables. Under these conditions, the ARDL model produced superior results.

Table 3. Results of the Augmented Dickey-Fuller (ADF) test

Variable Name	ADF test at level			ADF test at first difference			Status
	t-statistic	Critical value at 5%	Decision	t-statistic	Critical value at 5%	Decision	
lnY	1.647	-3.000	Non-stationary	-3.214	-3.000	Stationary	I (1)
lnTP	-1.798	-3.000	Non-stationary	-4.499	-3.000	Stationary	I (1)
lnMP	-5.576	-3.000	Stationary	-	-	-	I (0)
lnINT	-3.687	-3.000	Stationary	-	-	-	I (0)
lnAGRI	1.164	-3.000	Non-stationary	-3.105	-3.000	stationary	I (1)
lnFZ	-0.526	-3.000	Non-stationary	-4.474	-3.000	Stationary	I (1)
lnAL	-0.892	-3.000	Non-stationary	-3.337	-3.000	Stationary	I (1)

4.2. ARDL Bound Test Result

Table 5 presents the findings of the ARDL-bound test for cointegration. In this instance, the calculated F statistic of 6.348 was higher than the upper bound critical value at the 5% significance level. Therefore, we can conclude that there is a long-run link between the variables, and the null hypothesis that there is no cointegration can be rejected.

Table 4. ARDL bound test of cointegration

H_0: No Cointegration F-Statistics = 6.348 ***		
Critical Value	**Lower Bound Value**	**Upper Bound Value**
10%	2.26	3.35
5%	2.62	3.79
1%	3.41	4.68

Notes: ***indicates the rejection of the null hypothesis at a 1% level of significance.

4.3. ARDL Estimation Results

The ARDL estimation approach is employed in this analysis to explore both the short- and long-term associations that exist among the variables. According to the long-run estimates in Table 6, all our explanatory variables are statistically significant at the 5% level of significance. The coefficient of lnTP is -0.859, which indicates that agricultural production in Bangladesh will fall by approximately 0.859% for every 1% increase in telephone use, with other things remaining constant. Increased usage of the telephone, particularly for personal or other purposes unrelated to farming, can be a source of distraction for farmers. They may be interrupted more frequently, which will result in a decrease in their capacity to concentrate and overall productivity in their agricultural activities. In Bangladesh, only a few farmers have been introduced to the telephone system. Over the years, the use of telephones has decreased in Bangladesh, but agricultural production has continued owing to overall technological progress. Thus, the degree of its effect on agricultural production in Bangladesh is trivial.

Table 5. Results of the estimated short-run and long-run coefficients

Long run estimates			
Variable	**Coefficient**	**t-Statistic**	**Prob. values**
lnTP	-0.8593665***	-5.25	0.002
lnMP	0.6727838**	4.47	0.011
lnINT	0.0802069**	3.09	0.021
lnAGRI	4.830774***	6.53	0.001
lnFZ	0.2088282**	3.04	0.023
lnAL	-2.242516***	-4.11	0.006
Adjustment lnYL1.	-0.9907161***	-4.49	0.004
Short run estimates			
Variable	**Coefficient**	**t-Statistic**	**Prob. values**
ΔlnTP	0.5618576***	4.65	0.004
LD(lnTP)	0.331211**	3.57	0.012
ΔlnMP	-0.5210298**	4.02	0.016
ΔlnINT	-0.216125***	-4.59	0.004
LD(lnINT)	-0.1371358**	-3.69	0.010
ΔlnAGRI	-5.769707**	-3.20	0.019
ΔlnAL	6.827882***	4.56	0.004
LD(lnAL)	4.660601**	3.65	0.011

Notes: (a) The signs "***" and "**" denote the statistical significance of the estimated coefficients at the 1% and 5% significance levels, respectively. (b) Akaike's information criterion is used to choose the optimal lag length, which is (2,2,2,2,1,0,2).

The use of mobile phones and smartphones has continuously increased in Bangladesh. In the long run, the coefficient of lnMP is 0.6727838, which is statistically significant at the 5% level. This means a 1-unit intensification in mobile phone users will lead to a 0.67 US$ upsurge in agriculture production. The use of mobile phones makes it easy for farmers to communicate and collect information regarding the production process. Using mobile phones, they can collect news on daily weather conditions. Mobile phones also help farmers market their products. This positively contributes to agriculture, which is why mobile phone use has a long-term positive influence on agriculture.

The coefficient of lnINT is 0.08, indicating that agricultural production in Bangladesh will be boosted by approximately 0.08% for every 1% increase in internet use. The availability of Internet connectivity offers farmers an extensive range of agricultural information, including weather predictions, market valuations, crop administration methodologies, and tactics for pest regulation. With increased accessibility to this information, agricultural practitioners can make better educated decisions regarding the optimal timing for planting, harvesting, and selling their products. This phenomenon has the potential to enhance agricultural strategies and increase crop productivity. Suroso et al. [64] also found a positive effect of Internet use on agriculture in Africa, Asia, and Oceania. Ma & Wang [65] also found a favorable influence of Internet use on sustainable agricultural practices in China.

The coefficient of lnAGRI is 4.83, which means that agricultural production in Bangladesh will increase by approximately 4.83% for every 1% increase in total agricultural land. Bangladesh has a high population density and a scarcity of agricultural land. An increase in aggregate agricultural land signifies a greater allocation of land for agricultural activities. The increased availability of land facilitates the cultivation of additional crops and enables farmers to participate in agricultural endeavors. Farmers can increase crop diversity if they have access to more farmland. They can grow subsistence and cash crops. Due to the decreased dependence on any one crop, increased output is an expected outcome of diversification.

According to the coefficient of lnFZ, it can be inferred that agricultural production is projected to exhibit a growth of around 0.21% for each 1% increment in fertilizer usage. Crops acquire vital nutrients such as nitrogen, phosphorus, and potassium from fertilizers such as manure and compost. When farmers apply the required fertilizers, they contribute to the enrichment of the soil with these nutrients. This enrichment results in healthier plants and increased production.

The obtained coefficient lnAL was -2.2425. This signifies that a 1% increase in labor employed in agriculture will result in a 2.2425% decrease in agricultural production in Bangladesh. The law of diminishing marginal returns states that as more units of a single input (labor) are added while holding other inputs constant, the resulting increase in production will eventually decrease. In agriculture, it is observed that additional labor may not result in proportional production increments beyond a certain threshold and that inefficiencies might arise if the workforce is unskilled or uses antiquated farming practices. In such cases, increasing workforce size with corresponding improvements may prevent production from falling. Finally, the adjustment coefficient quantifies the degree to which the adjustment errors from the preceding period are rectified in the current period.

In ARDL models, a negative adjustment coefficient indicates the variables' tendency to return to their long-term equilibrium state after deviations or shocks. Our study found an observed magnitude of -0.99, indicating rapid convergence towards the equilibrium state. The deviation from equilibrium decreased by nearly 99% with each passing period.

The short-run coefficients of telephone users and labor employed in agriculture are positive. By contrast, the short-run coefficients of Internet users, mobile phone users, and total agricultural land are negative. In the short run, the coefficients of lnINT and lnMP exhibit a negative relationship. Several farmers are currently adjusting to the use of the Internet and mobile phone technologies for agricultural purposes, which presents initial challenges. Obtaining productive outcomes from Internet and mobile phone usage may require a significant amount of time, as it is difficult for illiterate farmers to learn user manual guidelines within a short period of time. Additionally, in the short run, the installation costs of smartphones and the internet adversely affect farmers in Bangladesh, as most farmers are poor. Therefore, in the short run, internet and mobile phone use hurt agricultural production. A similar conclusion was drawn by Oyelami et al. [41]. Using a panel ARDL technique, they examined the impact of ICT infrastructure on the agricultural sector's performance in SSA. 39 SSA countries provided panel data for 23 years (1995–2017). The findings of the estimation offer compelling evidence that the ICT structure has a long-term positive effect on agricultural performance. However, they found little evidence to support this claim in the short run.

The negative short-run coefficient of lnAGRI suggests that increasing arable land could require a period for land preparation, adaptation, and resource allocation. These concerns may temporarily nullify the benefits. A positive short-term coefficient of labor employed in agriculture suggests that the introduction of additional labor can result in enhanced cultivation practices in harvesting within a short period of time. Farmers may opt to employ additional labor during the peak season to achieve immediate benefits.

4.4. Ramsey Reset Test

As the p-value is greater than 0.05, the Ramsey [66] reset test presented in Table 7 suggests that the model of the study is correctly specified.

Table 6. Ramsey reset test

H_0: The Model has no omitted variables	
F(3,3)	1.83
Prob>F	0.3155

4.5. The Breusch–Godfrey Test

The Breusch-Godfrey test determines whether the errors in a regression model are autocorrelated with one another. Because our p-value is greater than 0.05, we cannot reject the null hypothesis. Therefore, there was no autocorrelation problem in our regression model, as shown in Table 8.

Table 7. Breusch-Godfrey LM test for autocorrelation

lags(p)	chi2	df	Prob>chi2
1	2.788	1	0.0950
H_0: no serial correlation			

4.6. White Test

White's test was performed to check if the variance of the residuals in our regression model was constant. In Table 9, the p-value is 0.3971, which is greater than 0.05. Therefore, the variance of the residuals in our regression model is homoscedasticity, and there is no problem of heteroscedasticity in our model.

Table 8. White's test

H_0: Homoskedasticity Ha: Unrestricted heteroskedasticity	
chi2(20)	21.00
Prob>chi2	0.3971

4.7. Jarque-Bera Test

The Jarque-Bera normality test was used to determine whether a dataset had a normal distribution, as shown in Table 10. The test statistic had a value of 0.7258, which was below the critical value when compared to a chi-square distribution with two degrees of freedom (Chi(2)), which had a value of 0.6957. Based on the test results, the null hypothesis that the data are normally distributed cannot be rejected.

Table 9. Jarque-Bera normality test

Jarque-Bera test for Ho: normality	
Jarque-Bera normality test	0.7258
Chi(2)	0.6957

4.8. CUSUM Square Test

The stability test results for the model are shown in Figure 3. This was performed to ensure the reliability of the conclusions. The analysis uses an assessment for the stability of the structure of the long-run variables that is based on the mathematical modeling of the cumulative sum of squares of recursive residuals (CUSUMSQ) tests. The plot demonstrates that CUSUMSQ does not cross the line that runs parallel (produced at the 5% level of significance); that is, the CUSUMSQ graph is within the boundaries of the straight lines (represented by the black dashed lines). These figures demonstrate the model's consistency and that, during the investigation, there was no detectable systematic shift in the coefficients at the 5% level of significance.

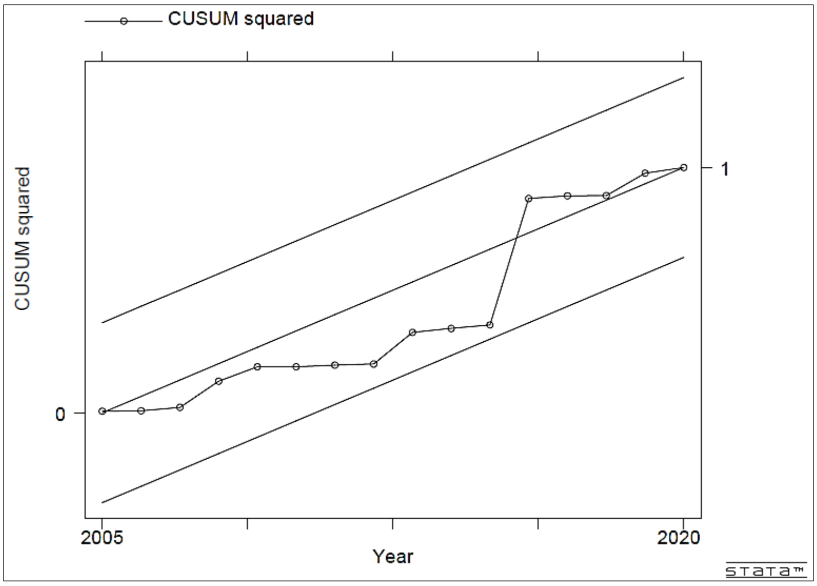

Figure 3. CUSUMSQ Test

Figure 4 shows the relationship between dependent and independent variables. The figure shows that mobile users, internet users, agricultural land use, and fertilizer use exhilarate agricultural production. In contrast, telephone users and labor employed in agriculture decrease agricultural production.

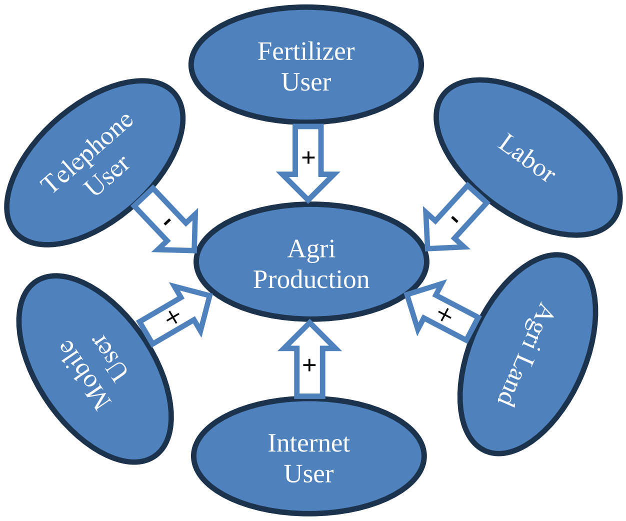

Figure 4. Results of the study

5. Conclusion and Policy Recommendations

The current era of technological advancement has led to significant convergence between technology and agriculture, resulting in remarkable transformations within the global farming sector. In nations such as Bangladesh, where agriculture performs a vital function in both the economy and the sustenance of a significant population, the integration of ICT farming has significant possibilities and prospects. Therefore, this study examines how ICT can help ensure the long-term viability of Bangladesh's agricultural sector. By utilizing data from 1971 to 2022, this study employs an ARDL model to determine the long- and short-run dynamics of variables related to ICT and sustainable agriculture in Bangladesh. According to the ADF unit root test, all variables in our study exhibit stationarity, either at the label or through the first difference.

The results of the ARDL-bound cointegration test suggest long-term correlations among the variables. In the short term, it has been discovered that variables such as telephone usage and labor utilized in agriculture exhibit a beneficial influence on agricultural production. Nevertheless, the beneficial impact of this phenomenon tends to decrease over the long run. In contrast, the utilization of the Internet, mobile phones, and the overall extent of agricultural land display adverse immediate impacts but gradually transform into favorable factors that enhance agricultural productivity over the long run. Moreover, the utilization of fertilizers has consistently demonstrated a positive influence on agricultural output over an extended period. Using the Ramsey Reset Test, we show that our model has been specified appropriately. Moreover, Breusch-Godfrey and White's tests are used to prove that our model is free from autocorrelation and heteroscedasticity problems. To improve agricultural output in Bangladesh, we provide the following policy recommendations based on our research:

- One proposed strategy is to allocate resources for the expansion and enhancement of rural information and communication technology (ICT) infrastructure. This would involve investing in the development of broadband internet access and mobile networks in remote locations to ensure that farmers residing in these regions have access to consistent connectivity.
- To improve the digital literacy and ICT abilities of farmers, it is important to deliver them through training programs and workshops. These courses can improve students' capability to locate useful data, make good use of agricultural apps, and efficiently apply digital tools.
- It is crucial to provide farmers with access to climate information services via ICT so that they can better adapt to shifting weather patterns and reduce their vulnerability to climate-related hazards.
- To maximize land utilization and reduce the short-term negative effects of land expansion, sustainable land management approaches should be encouraged.
- To reduce long-term dependence on chemical fertilizers, it is necessary to encourage the use of organic farming techniques and instruct farmers on maximizing the effectiveness of their fertilizer applications.
- Labor productivity can be enhanced by implementing skill-development programs aimed at improving the efficiency of agricultural labor. Additionally, investing in agricultural mechanization and technology can contribute to long-term improvements in labor productivity.
- Maintaining consistent agricultural policies that strike a balance between short-run and long-run objectives is required to secure both food security and economic stability.

5.1. Limitations and Future Research

This study can be used as a reference point by future academics interested in exploring sustainable agriculture's potential growth in tandem with information and communication technology. Only three ICT-related instruments were employed as independent variables in this study, with a shorter time range (2000 FY–2020 FY) because of a shortage of time and resources. However, future studies with sufficient funding might employ more ICT-related variables and a wider period to investigate the connection between ICT and the development of sustainable agriculture more thoroughly. Time series data were employed in our analysis; however, panel datasets and comparisons between emerging and developed nations using sophisticated econometric approaches can lead to more precise estimations.

6. Abbreviation

ARDL	Auto-Regressive Distributed Lag	G7	Group of Seven
CSD	Cross-Sectional Dependence	ICTs	Information and communication technologies
CO_2	Carbon Dioxide	MG	Mean Group
EF	Ecological Footprint	PMG	Pool Mean Group
FD	Financial Development	SDGs	Sustainable Development Goals
GDP	Gross Domestic Product	WB	World Bank

7. Declarations

7.1. Author Contributions

Conceptualization, M.A.H. and M.A.E.; methodology, M.A.H. and M.A.E.; software, M.B.M. and M.A.H.; validation, L.C.V., M.R., and M.A.H.; formal analysis, L.C.V.; investigation, M.A.H.; resources, M.A.H.; data curation, M.B.M.; writing—original draft preparation, M.A.H.; writing—review and editing, M.A.H.; visualization, M.A.E.; supervision, M.A.E.; project administration, M.R.; funding acquisition, M.A.E. and M.R. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in the article.

7.3. Funding

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7.4. Institutional Review Board Statement

Not applicable.

7.5. Informed Consent Statement

Not applicable.

7.6. Declaration of Competing Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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