Modeling the Relationship between Smart Agriculture and Sustainable Agricultural Development in Algeria: An Econometric Analysis for the Period 1990–2025.

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Abstract:

The aim of this study is to highlight the impact of smart agriculture and its applications in achieving sustainable agricultural development in Algeria during the period 1990-2025. based on the Autoregressive Distributed Lag (**ARDL**) model to analyze the relationships between the study variables and to estimate the extent of the impact of smart irrigation, investment in human resources working in the agricultural sector, and foreign direct investment directed to the agricultural sector on the development of the contribution of the agricultural sector's growth rate to the gross domestic product. The study concluded, through these standard models, that smart agriculture has a positive and significant impact on the agricultural development index in Algeria during the study period, as it focuses on employing modern technology and artificial intelligence in the context of the farming and irrigation process, and even on qualifying human resources in this field, which would enhance the outputs of production processes in the field of agriculture.

Keywords: Smart Agriculture; Smart Irrigation; Smart Agricultural Learning; Agricultural FDI; Sustainable agricultural development.

Jel Classification Codes: Q16, Q18, O13, F21, O33, Q25, C33.

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1. Introduction :

Sustainable agricultural development is one of the strategic issues that tops the economic and development policy agendas in various countries around the world, given its pivotal role in enhancing food security and ensuring the sustainability of agricultural systems in light of the increasing challenges associated with population growth, climate change, and scarcity of natural resources. The growth in the rate of contribution of the agricultural sector to the gross domestic product represents a major challenge for countries of all kinds, as agricultural productivity reflects the extent of control over achieving food security and managing the food basket of the international community, given its direct relationship to achieving self-sufficiency, which requires providing a sustainable food supply system that is sufficient, of high quality and safety, in order to ensure that the nutritional needs of all members of society are met continuously, while preserving the rights of future generations to benefit from natural resources in accordance with the principles of sustainable development.

Smart agriculture has emerged as a development framework based on employing modern technologies and institutional innovation to enhance the efficiency of resource use and improve the productivity of agricultural systems without compromising the requirements of environmental and economic sustainability. This approach is not limited to adopting technological solutions, but is based on a set of integrated determinants, foremost among them smart irrigation, which contributes to rationalizing water consumption and increasing the efficiency of its use, and investment in agricultural human capital through skills development and promoting smart agricultural learning, which supports the assimilation of modern technologies and their adaptation to local characteristics. The flow of foreign direct investment in the agricultural sector also represents an effective channel for the transfer of knowledge, expertise and advanced technologies from leading economies, which accelerates agricultural modernization processes and enhances productive and institutional capacities, which makes smart agriculture one of the basic pillars supporting the path of sustainable agricultural development.

Algeria is among the countries where the agricultural sector occupies a pivotal position in the economic transformation process, given its abundant natural and human resources that can form the basis for enhancing productivity and achieving food security. The vast expanses of arable land and the availability of a skilled workforce at relatively competitive costs represent strategic factors that can be leveraged to build a more efficient agricultural sector capable of generating added value. This, in turn, supports economic diversification efforts and reduces dependence on food imports. However, these potentials still face a number of structural and technological constraints related to resource utilization efficiency, the level of adoption of agricultural innovation, and the ability of the production system to adapt to climatic and economic shifts. These constraints limit the achievement of the desired goals for sustainable agricultural development. Despite the successive reforms and public policies implemented during the period 1990-2025, particularly within the framework of

agricultural and rural renewal programs, the transition to a knowledge-based and technology-driven agricultural model has become a necessity dictated by the demands of the current stage. Smart agriculture emerges as a strategic option for reshaping the agricultural production system by improving resource allocation, enhancing technical efficiency, and supporting the sustainability of the agricultural sector in Algeria.

1.1. Research Problem: In light of the foregoing, the study's central problem revolves around the extent to which smart agriculture determinants can bring about a qualitative shift in the trajectory of sustainable agricultural development in Algeria, given the transformations witnessed by the agricultural sector and the reform efforts aimed at modernizing the production system and enhancing the efficiency of resource utilization. Despite the increasing importance of modern agricultural technologies and the opportunities they offer for improving productivity, optimizing input use, and promoting knowledge transfer, the impact of these determinants on sustainable agricultural development indicators in Algeria still requires measurement and standardized analysis to determine the nature and direction of the relationship during the study period. Therefore, the study's core research question can be formulated as follows:

How do smart agriculture determinants affect the achievement of sustainable agricultural development in Algeria during the period 1990–2025?

1.2. Sub-questions: Based on the research problem posed, the sub-questions of the study can be formulated as follows:

- How do theoretical intellectual contributions explain the relationship between smart agriculture and sustainable agricultural development?
- To what extent has the Algerian agricultural sector adopted the requirements of smart agriculture towards a technology- and knowledge-based agricultural model?
- How have indicators of sustainable agricultural development evolved in Algeria during the study period, and to what extent has the agricultural sector been able to achieve a balance between the requirements of productivity, economic efficiency, and environmental sustainability?
- Is there a long-term relationship between the determinants of smart agriculture and sustainable agricultural development in Algeria during the period 1990–2025?

1.3. Hypotheses: Based on the sub-questions and in order to address the research problem, the following hypotheses can be formulated:

- Previous theoretical studies assume that smart agriculture is one of the drivers of sustainable agricultural development in the event that it incorporates modern agricultural technology applications, improved resource management, and human capital development.

- It is expected that there will be a variation in the level of adoption of smart agriculture requirements by the Algerian agricultural sector during the study period, due to the varying degrees of deployment of modern technologies and development of agricultural skills.
- Sustainable agricultural development indicators in Algeria during the period 1990–2025 witnessed gradual development, but the ability of the agricultural sector to achieve increased productivity and maintain environmental sustainability is still linked to the degree of effectiveness of adopting smart agriculture determinants.
- This study hypothesizes the existence of a statistically significant long-run equilibrium relationship between the determinants of smart agriculture and sustainable agricultural development in Algeria over the period 1990–2025.

1.4. Significance of the Study: The importance of this study stems from its focus on a contemporary shift in agricultural and economic thought: the transition from a traditional agricultural production model to a smart model based on technology, knowledge, and efficient resource management. Its scientific significance lies in its attempt to move beyond prevailing descriptive approaches to smart agriculture by constructing an analytical and benchmark framework that examines the relationship between its determinants and sustainable agricultural development in Algeria during the period 1990-2025. Furthermore, it contributes to bridging a research gap characterized by the limited number of applied studies that measure the dynamic impact of smart agriculture and its components on sustainable agricultural performance within a developing economic context. Its practical importance is highlighted by its provision of quantitative evidence that can support decision-makers in evaluating the effectiveness of agricultural modernization policies and directing investments toward areas with the greatest impact on enhancing food security and sustainability.

1.5. Study Objectives: This study seeks to analyze the role that smart agriculture can play in reshaping the course of sustainable agricultural development in Algeria. Accordingly, the objectives of the study are as follows:

- Establishing the conceptual and theoretical framework of smart agriculture and sustainable agricultural development, and explaining the scientific principles governing the relationship between them.
- Diagnosing the current state of adoption of smart agriculture determinants in Algeria and analyzing their development trends during the period 1990–2025.
- Analyzing the evolution of sustainable agricultural development indicators and evaluating their performance level in Algeria during the study period.
- Explaining the nature of the theoretical and economic relationship between smart agriculture determinants and sustainable agricultural development.

1.6. Methodology: To clarify and interpret the relationship between the determinants of smart agriculture and the indicator of the development of the agricultural sector's contribution to the gross domestic product as an indicator expressing sustainable agricultural development in Algeria during the study period, this study relies on the descriptive analytical approach to analyze and explain the study variables, and on the inductive approach to estimate the nature of the relationships between the research variables of the study, using statistical methods.

2. Conceptual and Theoretical Framework of Smart Agriculture and Sustainable Agricultural Development:

Rapid technological transformations have produced a new model for managing agricultural activities, moving beyond the traditional concept of production towards an integrated system that relies on employing digital technologies, automation, data analysis, and artificial intelligence applications in various stages of the agricultural process. This transformation is based on maximizing the efficiency of exploiting natural and human resources, through developing irrigation systems, enhancing the cognitive capabilities of workers in the agricultural sector, and facilitating the transfer of international technology and expertise in a way that reduces the technological gap and accelerates the pace of agricultural innovation. Therefore, we cannot consider smart agriculture as merely a technological option to improve production, but rather it has become a developmental approach that redefines the relationship between technology, human capital, and agricultural institutions, thereby enhancing the competitiveness of the sector and raising its productive efficiency and sustainability. Based on this, this axis aims to establish the conceptual framework of smart agriculture and sustainable agricultural development, and to clarify the theoretical foundations that explain the nature of the interaction between them as a basis for analyzing the relationship that the study will address in a standard manner.

2.1. Theoretical Background of Smart Agriculture

The concept of smart agriculture did not emerge in isolation from the historical development of economic thought. Rather, it represents an extension of a long trajectory of theoretical transformations that have given agricultural activity pivotal importance in explaining the creation of wealth and achieving economic development. The earliest beginnings of this conception were linked to the contributions of the Physiocratic school (1754), which considered land the primary source of economic surplus and agriculture the only productive activity capable of generating real wealth. This granted the agricultural sector a central position in shaping economic policies at the time. With the development of classical thought, Adam Smith (1776) broadened the concept of wealth to include all productive activities, emphasizing that the division of labor, specialization, and increased productive efficiency constitute the true basis for increasing productivity and maximizing added value, including within the agricultural sector. In the same vein, David Ricardo (1817) highlighted the strategic role of agriculture in capital accumulation, resource allocation, and the interpretation of

comparative advantages, thus reinforcing the agricultural sector's contribution to economic growth and international trade. This formed the basis for an important theory: that agriculture is an engine of economic growth.

With the global economy's transition to a technological revolution, agricultural development is no longer solely dependent on expanding the use of traditional production inputs. It now hinges on the sector's ability to absorb knowledge, innovation, and technology as independent factors of production, even those originating from outside the agricultural sector. Robert Solow's (1956) theories of external growth underscored the fact that the accumulation of technological capital significantly impacts the efficiency of production across various sectors, particularly agriculture, which greatly benefits from technological inflows that affect the speed, accuracy, and quality of agricultural outputs.

Theories of endogenous growth and the knowledge economy have led to a reshaping of the concept of agricultural development, particularly the ideas of Paul Romer (1986) and Robert Lucas (1991). These theories consider technological advancements, human capital, institutional innovation, and knowledge transfer as key drivers for improving productivity and enhancing sustainability. In the context of the Fourth Industrial Revolution, the integration of digital technologies and smart systems into agricultural activities has accelerated, giving rise to smart agriculture as a modern production model. This model integrates artificial intelligence, the Internet of Things, remote sensing, big data analytics, and automation to maximize the efficiency of natural resource utilization, improve the quality of production decisions, and enhance resilience to climatic and economic risks.

Based on this theoretical development, smart agriculture can be viewed as an advanced stage in the evolution of agricultural thought. It is no longer limited to improving means of production but has become a developmental framework that reshapes the relationship between technology, human capital, resource management, and knowledge transfer, thereby achieving higher levels of productivity, efficiency, and sustainability. From this perspective, smart agriculture represents the link between digital transformation and sustainable agricultural development, as a mechanism to enhance the competitiveness of the agricultural sector and achieve food security within a more flexible and sustainable production environment.

2.1.1. Definition of Smart Agriculture

The term smart agriculture also known as digital agriculture, is a form of the Fourth Industrial Revolution, which has become easier to implement thanks to modern digital technologies. Digital agriculture also refers to the application of modern digital technologies in the agricultural sector (Abdou Tahir, 2021, p. 23). It can be applied to all aspects of food production systems, reflecting a genuine shift from traditional resource management to a new, efficient, and data-driven approach. Digital smart agriculture provides practical solutions

to address the challenges facing the agricultural sector. Digital technologies enable the achievement of highly efficient and equitable agricultural outcomes characterized by the sustainability of productive resources. Furthermore, data-driven computerized technologies can be used to improve agricultural systems, productivity, and efficiency (Abou Sini & Leblawneh, 2021, p. 26).

Smart agriculture is considered one of the most important modern innovative solutions, primarily aimed at increasing production volume and boosting productivity, in addition to improving the quality of agricultural crops. According to the guidelines of the Food and Agriculture Organization of the United Nations (FAO), the global trend towards adopting smart agriculture approaches and methods not only helps reduce future food security gaps but also contributes to promoting economic diversification and agricultural renewal in farming areas and rural communities (FAO, 2019, p. 10). The scale and level of impact of climate change on agricultural systems and their domains necessitates strengthening the resilience and responsiveness of rural communities, as well as their capacity to protect and ensure global food security.

Smart agriculture is also defined as an agricultural system that relies primarily on the application and use of modern and advanced agricultural technologies with the aim of producing food in healthy ways, while preserving natural resources and using them rationally .the sustainability of resources and increasing the efficiency of water use, reducing production costs and maximizing benefit through the automation of agricultural processes in irrigation and fertilization, pest control, monitoring crops and soil, and searching for, analyzing and processing accurate data, in order to use it to guide agriculture towards abundant production at a lower cost, as well as to make appropriate decisions in the agricultural production process, and to achieve crops of high quality. Among the most important smart technologies and applications are remote control systems, self-operating equipment, supervised by an individual on-site at all times (Bouabdeli & Gherbi, 2023, p. 312). In this case, it is best for farmers to use remote sensing, communication and information technologies, drones, the use of smartphones, robots and robots, and vertical farming (Abu Sini, 2021, p. 26), where drones are used to collect information and automate processes by processing inputs, such as map-based variable yield technology.

2.1.2. Determinants of Smart Agriculture

The success of the transition to smart agriculture is not solely dependent on the adoption of digital technologies. Rather, it relies on an integrated system of determinants that enhance the agricultural sector's capacity to absorb, localize, and transform technology into productive and developmental value. In this context, smart agriculture is embodied in the interaction of three key determinants: efficient water resource management, the development of agricultural human capital, and the promotion of knowledge and technology flows through foreign direct agricultural investment.

a- Smart Irrigation: An Approach to Maximizing Productive Efficiency and Water Resource Management

Smart irrigation is a fundamental pillar of smart agriculture, as it shifts water management from traditional, estimation-based methods to systems that rely on data, real-time measurement, and automated decision-making. This approach is based on integrating sensing technologies, the Internet of Things, and the analysis of climate and soil data to determine the actual water needs of crops. This increases the efficiency of water resource use, reduces losses, and mitigates environmental pressures. From an economic perspective, the impact of smart irrigation extends beyond water conservation (Sapaev, Arifjanov, & Ramazonov, 2023, p. 6). It improves land productivity, reduces production costs, and enhances the resilience of agricultural systems to climate fluctuations, making it a key determinant of agricultural sustainability.

b- Smart Agricultural Learning and Investment in Human Capital

The efficiency of smart agriculture is not achieved simply by the availability of technology. Rather, it depends on the human resource's ability to absorb and adapt it to the local production environment. Therefore, smart agricultural learning represents an extension of investment in human capital. It focuses on developing digital and technical skills, promoting continuous learning, and expanding the use of smart platforms and digital agricultural extension services to transfer applied knowledge. This contributes to raising the technical efficiency of workers, accelerating the adoption of agricultural innovations, and bridging the knowledge gap among producers. This, in turn, improves productivity, enhances the quality of outputs, and strengthens the competitiveness of the agricultural sector in an environment characterized by rapid technological transformation (Gabriel, Barbosa, & Alexandre, 2025, p. 12).

c- Foreign Agricultural Direct Investment: A Strategic Channel for Knowledge and Technology Transfer

Foreign agricultural direct investment (FDI) is more than just a source of financing for agricultural projects; it is an institutional mechanism for transferring technology, organizational expertise, and advanced production practices to recipient economies. This mechanism is further enhanced when coupled with interaction between investors and local institutions, enabling the transfer of tacit knowledge, the development of technical capabilities, and the promotion of innovation within agricultural value chains. Therefore, the true value of FDI is not measured solely by the volume of capital flows, but also by its ability to build a knowledge and technology base that supports the transition to smart agriculture, improves resource efficiency, and contributes to more sustainable agricultural development.

2.2. Conceptual Foundations of Sustainable Agricultural Development

The concept of development is a dynamic one that has evolved from a mere focus on quantitative economic growth to a multidimensional structural transformation process aimed at improving economic efficiency, social welfare, and human capabilities through the rational use of available resources. Therefore, development is not measured solely by increased production rates, but also by societies' ability to achieve

sustainable qualitative transformations that enhance productivity, innovation, and living standards. (Agung & Trip, 2007, p. 9)

2.2.1. The Concept of Agricultural Development

Agricultural development represents one of the sectoral applications of the concept of development. It is linked to developing the productive capacity of the agricultural sector, improving resource use efficiency, and enhancing its contribution to achieving food security and economic growth. The Food and Agriculture Organization (FAO) defines agricultural development as a process aimed at improving the performance of the agricultural sector by increasing productivity, improving producers' incomes, and ensuring the sustainable management of natural resources in a way that serves food security and rural development (FAO, Sustainable Agricultural Productions : Implication For International Agricultural Researcher, 1989, p. 05).

Todaro and Smith also view it as an economic and institutional transformation process aimed at increasing the productivity of agricultural activity through investment in technology, human capital, and the development of markets and institutions, thereby strengthening the role of agriculture in achieving comprehensive development. Accordingly, agricultural development can be defined as an ongoing process of restructuring the agricultural sector by developing production factors, promoting innovation, and improving the efficiency of resource allocation. This process aims to increase the sector's productivity and support its economic and social role (Baharak, 2023, pp. 169-175).

2.2.2. The Concept of Sustainable Agricultural Development

The concept of sustainable agricultural development emerged as a result of the shift in development thinking from a focus on maximizing production to seeking a model that balances the needs of the present with the rights of future generations. It represents a pattern of agricultural development based on achieving a balance between increasing productivity and economic efficiency on the one hand, and preserving natural resources and ecosystems on the other.

The Food and Agriculture Organization (FAO) defines sustainable agricultural development as the management of natural resources and the guidance of technological and institutional changes in a way that ensures the fulfillment of current and future food needs, while maintaining the long-term productive capacity of agricultural systems.

Therefore, within the framework of this study, sustainable agricultural development can be defined as an integrated development process for the agricultural system. This process relies on improving productivity, rationalizing resource use, developing human capital, and employing technology and innovation to ensure the continuity of agricultural production and achieve food security (mekimeh, ramdane, & harmouch, 2020, p. 183).

2.2.3. Determinants of Sustainable Agricultural Development

The agricultural sector's ability to achieve sustainable development is determined by a set of interconnected factors, which can be categorized into four main determinants:

a- Economic Determinants: These include the size of agricultural investment, the level of productivity, the efficiency of production factor utilization, and the sector's capacity to create added value and support economic growth (Edna, 2022, p. 11).

b- Environmental Determinants: These relate to the sustainable management of natural resources, especially water and soil, and enhancing the resilience of agricultural systems to climate change.

c- Human and Institutional Determinants: These include developing agricultural human capital, improving education, training, and agricultural extension services, as well as the effectiveness of institutions and policies supporting the sector (kerrouch, 2019, p. 527).

d -Technological and Innovative Determinants: These include adopting modern technologies, digitalization, smart agriculture, and the transfer of knowledge and expertise, as these are crucial factors in increasing productivity and enhancing the sustainability of agricultural systems (Spyros, Nikos, Ioannis, & Efthymios, 2020, p. 3).

2.2.4. Agricultural growth as an indicator for measuring sustainable agricultural development

Agricultural growth is a quantitative indicator that reflects the development of the productive performance of the agricultural sector over a specific period of time, often a year, by measuring the change in the volume or value of agricultural outputs. However, its significance within the framework of sustainable agricultural development goes beyond mere increase in production. It indicates the sector's ability to achieve continuous productive expansion based on improving technical efficiency, employing knowledge, rationalizing the use of natural resources, improving the standard of living in the community, and achieving social justice, while ensuring the rational exploitation of resources, as well as ensuring biodiversity and soil fertility. From this perspective, agricultural growth reflects the extent to which the agricultural system is able to transform investments, innovations, and modern technologies into sustainable productive gains, making it a suitable indicator for evaluating the effectiveness of the structural transformations that the agricultural sector is witnessing, especially in light of the transition towards a smart agriculture model based on maximizing productivity while preserving the foundations of economic and environmental sustainability.

3. Evolution Trends of Smart Agriculture Indicators and Sustainable Agricultural Development in Algeria During 1990–2025

The shift towards a smart agriculture model represents one of the structural transformations underway in Algeria's agricultural sector. It serves as a means to enhance production efficiency and optimize the use of natural resources in the face of water scarcity and climate change challenges. The period from 1990 to 2025

witnessed a gradual evolution in smart agriculture indicators, driven by the increasing adoption of modern technologies in agricultural management, the development of stakeholders' knowledge base, and the encouragement of investment flows that support technology transfer. This section examines the evolution of these indicators and their relationship to the dynamics of sustainable agricultural development in Algeria.

Table N°1: Evolution of Smart Agriculture Determinants and Agricultural Value Added as a Percentage of GDP in Algeria (1990–1999).

YEAR	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Agricultural Value Added as a Percentage of GDP Yt (AVA-GDP)	%12.36	%11.70	%11.62	%11.47	%11.14	%11.63	%12.10	%11.43	%10.96	%10.42
Smart Irrigation Technology Adoption Rate - X_1 (SITAR)	%1.41	%1.89	%2.03	%2.78	%3.21	%3.87	%4.55	%4.93	%5.24	%5.81
Smart Agricultural Learning Index - X_2 (SALI)	%5.56	%5.97	%6.37	%6.99	%7.05	%7.84	%9.21	%9.66	%10.1	%12.0
Foreign Direct Investment in Agriculture Inflow Rate – X_3 (FDIAIR)	%0.11	%0.39	%0.47	%0.48	%0.48	%0.51	%0.59	%0.61	%0.68	%0.73

Source: Prepared by the researchers based on World Bank reports and National Statistics Office reports.

Table N°1 shows that the period (1990–1999), which coincided with Algeria's implementation of a package of economic reforms aimed at restoring macroeconomic balances and enhancing economic performance, witnessed a gradual improvement in smart agriculture indicators. The adoption rate of smart irrigation technologies, the agricultural learning index, and foreign direct investment flows directed to the agricultural sector all increased at an accelerating pace throughout the period. In contrast, the contribution of agricultural value added to GDP showed a slight downward trend, decreasing from 12.36% in 1990 to 10.42% in 1999. This discrepancy indicates that the determinants of smart agriculture during the reform phase were not yet fully implemented and were still in their initial stages. It can also be concluded that the reforms in the 1990s were more structural than technical, which did not immediately translate into an increase in the agricultural sector's contribution to GDP. Furthermore, the structural imbalances that accompanied the economic transition continued to have an impact.

Table N°2: Evolution of Smart Agriculture Determinants and Agricultural Value Added as a Percentage of GDP in Algeria (2000–2025).

YEAR	Yt (AVA-GDP)	X_1 (SITAR)	X_2 (SALI)	X_3 (FDIAIR)
2000	% 8.40	% 6.29	% 12.01	% 0.82
2001	% 8.9	% 6.43	% 12.37	% 0.88
2002	% 8.4	% 6.69	% 13.21	%0.91
2003	% 8.5	% 7.01	% 13.64	%0.99
2004	% 7.7	% 7.15	% 13.98	%1.22
2005	% 6.6	% 7.32	% 14.01	%1.26
2006	% 6.4	% 7.91	% 14.35	%1.57
2007	% 6.3	% 8.62	% 14.79	%1.92
2008	% 5.5	% 9.36	% 14.86	%2.04
2009	% 8.0	% 12.47	% 14.91	%2.08
2010	% 7.5	% 13.98	% 15.14	%2.44
2011	% 7.1	% 13.16	% 15.99	% 2.97
2012	% 8.0	% 15.02	% 1644	% 3.35
2013	% 9.1	% 15.44	% 16.90	% 3.41
2014	% 9.4	% 16.81	% 17.76	% 3.59
2015	%10.5	% 17.05	% 17.83	% 3.77
2016	% 11.1	% 17.67	% 17.99	% 3.84
2017	% 11.0	% 18.07	% 10.74	% 3.98
2018	% 11.2	% 18.35	% 18.92	% 4.01
2019	% 11.5	% 18.80	% 19.26	% 4.03
2020	% 12.8	% 21.68	% 19.41	% 4.33
2021	% 11.2	% 20.18	% 19.47	% 4.49
2022	% 10.6	% 21.03	% 19.66	% 5.74
2023	% 13.4	% 24.99	% 20.08	% 5.91
2024	% 14.5	% 25.34	% 20.12	% 6.08
2025	% 15.3	% 26.81	% 20.23	% 7.36

Source: Prepared by the researchers based on World Bank reports and National Statistics Office reports.

Based on the statistical data in Table N°2, which analyzes the evolution of smart agriculture determinants in Algeria during the period (2000-2025), a gradual transformation in the nature of the Algerian agricultural model is evident. The sector has shifted from supporting traditional production to seeking a model based on technology and efficient resource use. The adoption rate of Smart Irrigation Technology (SITAR) has seen a continuous increase from 6.29% in 2000 to 26.81% in 2025. This development reflects the growing

interest in integrating modern technologies into agricultural water management, particularly in light of water scarcity and increasing climatic pressures. This improvement was linked to a series of reforms and public policies aimed at modernizing the agricultural sector. These began with the Agricultural Economic Recovery Program (2000-2004), which focused on rehabilitating production infrastructure and supporting investment in agricultural equipment. This was followed by the National Agricultural Development Plan (PNDA), which evolved into the Agricultural and Rural Development Program (PNDAR) in 2002. The PNDAR marked a significant phase in expanding the use of supplemental irrigation techniques, developing collective and individual irrigation systems, and encouraging investment in modern equipment. The Agricultural and Rural Renewal Program (2009-2014) also contributed to strengthening the trend towards more sustainable agriculture by supporting water conservation and expanding the use of water-efficient irrigation systems such as drip irrigation and center-pivot irrigation. These technologies formed the initial foundation for the transition to smart irrigation based on digital monitoring and control. This trend has been reinforced recently by the authorities' focus on agricultural digitalization and the promotion of precision farming techniques within the framework of the government's action plan to develop the agricultural sector and achieve food security. This explains the relative acceleration in the index's growth after 2015. This development coincides with the increased contribution of the agricultural sector to the GDP, with the AVA-GDP ratio rising from 8.4% in 2000 to 15.3% in 2025. This indicates that improving the efficiency of water resource management has been a key factor in increasing the economic value of agricultural activity and enhancing its sustainability.

As for the second determinant, the Smart Agricultural Learning Index (SALI), it has also seen significant growth, increasing from 4.01% in 2000 to 13.23% in 2025. This reflects the gradual shift in Algerian agricultural policy towards considering knowledge and training as essential elements in modernizing the sector. Algeria recognized that the successful integration of agricultural technology depends not only on providing equipment and supplies, but also on having a skilled workforce capable of controlling and utilizing them. This led to the strengthening of agricultural extension and training institutions, most notably the National Institute for Agricultural Extension (INVA), in addition to supporting specialized training in agricultural schools, institutes, and universities. The Agricultural and Rural Renewal Program (2009-2014) contributed to developing mechanisms for transferring knowledge and modern technologies to farmers by expanding extension and training programs and linking scientific research to the agricultural field. Furthermore, the agricultural support policy within the framework of the "Agriculture 2030" plan reinforced the trend towards investing in human capital and encouraging innovation and training in the areas of digitalization, precision agriculture, water conservation, and the valorization of agricultural data. The evolution of the indicator shows that the period following 2016 witnessed further improvement as a result of the expansion of training programs and increased interest in

university specializations related to agricultural sciences, biotechnology, and agricultural artificial intelligence. The accumulation of agricultural knowledge has been reflected in the ability of producers and institutions to absorb modern technologies, contributing to improved agricultural productivity and increased added value for the sector. This explains the positive correlation between the development of agricultural human capital and the improvement in the Sustainable Agricultural Development Index (AVA-GDP).

Regarding the third determinant, the rate of foreign direct investment inflows into the agricultural sector (FDIAIR), it has also witnessed remarkable growth, rising from 0.50% in 2000 to 7.36% in 2025. This reflects a gradual shift in Algeria's view of foreign investment as a means of transferring technology and expertise, not just a source of financing. This development occurred within the framework of reforms aimed at improving the investment climate, particularly after the enactment of investment promotion laws and the establishment of investment support structures, in addition to opening the field to foreign partnerships in certain agricultural activities and food industries. The agricultural land reclamation program in the south and the high plateaus has also been one of the areas that have attracted investor interest, given its reliance on modern irrigation, mechanization, and production management technologies in areas with new agricultural potential. This trend was reinforced with the launch of the National Plan for Desert Agriculture and the encouragement of major investments in cereal production, fodder, and livestock farming. These projects were often linked to the introduction of more advanced production technologies and foreign expertise in agricultural management. The rise in the FDIAIR index in recent years reflects the growing role of foreign investment in transferring technical knowledge and supporting the transition to smart agriculture. However, its impact on sustainable agricultural development remains contingent on the local economy's capacity to absorb this technology and translate it into lasting productivity gains. By linking the development of these three determinants and the rise in AVA-GDP, it becomes clear that the path to smart agriculture in Algeria was not the result of a single factor, but rather the product of an interaction between modernizing production systems, developing human resources, and attracting foreign technology and expertise. These elements have gradually formed the pillars of the transition towards more sustainable agricultural development.

3.1. Variables Definition and Econometric Model Specification

Table N°3 presents the measurement framework of the variables employed in this study, classified according to their analytical roles within the econometric model. It highlights the constructed indicators of smart agriculture and their relationship with sustainable agricultural development in Algeria over the period 1990–2025.

Table N°3: Description of Econometric Study Variables.

Symbol	Indicator	Description
Dependent variable in the standard study		
y_t	**Agricultural Value Added as a Percentage of GDP Yt (AVA-GDP)**	The agricultural value added as a percentage of GDP (AVA-GDP) is the indicator used to measure the level of sustainable agricultural development in this study. This indicator reflects the contribution of the agricultural sector to the national economy by measuring the net economic value added by agricultural activity (including crop production, livestock, and related agricultural activities) as a percentage of the gross domestic product.
Independent variables in the standard study		
X_1	**Smart Irrigation Technology Adoption Rate - X_1 - (SITAR)**	The Smart Irrigation Technology Adoption Rate (SITAR) is a key determinant of smart agriculture and is used in the standard model to measure the prevalence and use of modern irrigation technologies based on digital technology and smart systems in the agricultural sector. These technologies include automated irrigation systems, soil moisture sensors, remote control technologies, and data analytics, all aimed at improving water resource management in Algeria.
X_2	**Smart Agricultural Learning Index - X2 - (SALI)**	The Smart Agricultural Learning Index (SALI) represents the annual rate of change in the development of education and training in the agricultural sector. It is measured by the change in the number of training programs and extension courses organized annually by the Ministry of Agriculture in collaboration with various stakeholders in the agricultural sector. This index reflects the extent to which farmers and other stakeholders in the sector are able to acquire the skills necessary to adopt smart farming practices and technologies.
X_3	**Foreign Direct Investment in Agriculture Inflow Rate. X3 - (FDIAIR)**	This variable (FDIAIR) refers to the percentage change in the flow of foreign direct agricultural investment to the total annual flows in Algeria, and it expresses the transfer of knowledge and technology in the field of smart agriculture in Algeria.

Source: Prepared by the researchers.

3.2 Econometric Model Estimation and Analytical Methodology

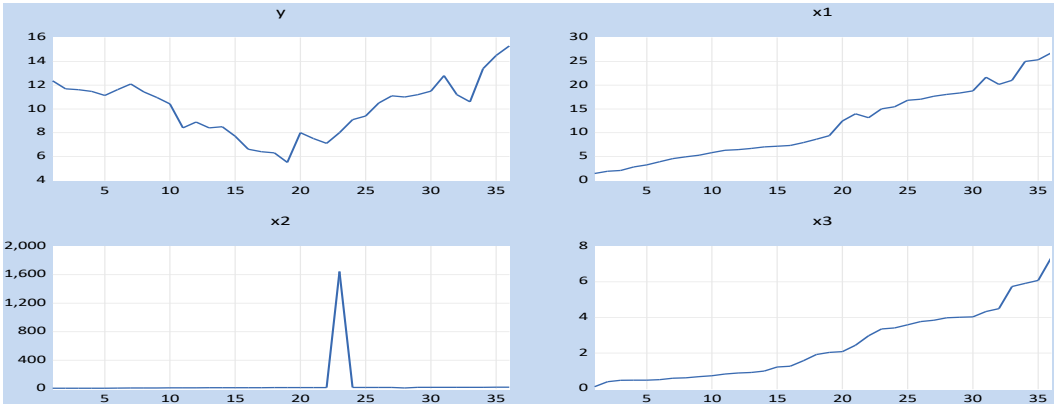
Estimating standard models based on time series data is a crucial step in ensuring the reliability of experimental results. Applying the Ordinary Least Squares (OLS) methodology without verifying data characteristics can lead to misleading estimates and spurious standard relationships. Therefore, a standard approach was adopted, beginning with analyzing the characteristics of the time series, testing their stability, and determining the degree of integration of variables. This allows for the selection of the appropriate model and the provision of more efficient estimates for interpreting the dynamic relationship between the determinants of smart agriculture and sustainable agricultural development in Algeria.

3.3. Time Series Stationarity Testing

Standard time-series models require first verifying the stability of the variables used, as inconsistency in their statistical properties over time can lead to biased estimates and spurious economic relationships. In this context, the Dickey-Fuller extended test (ADF) and the Phillips-Perron test (PP) were employed to determine the

degree of integration of the study variables and to verify their amenability to dynamic analysis. Furthermore, a preliminary graphical analysis of the variables' trajectories over the period (1990-2025) was used to observe their temporal behavior and identify any potential trends or structural changes before estimating the standard relationship between the determinants of smart agriculture and sustainable agricultural development in Algeria.

Fig N° 1: Graphical Representation of Time Series



Source: prepared by the researchers.

Based on the preliminary graphical analysis, the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests are employed to examine the stationarity properties of the time series. The results of these tests are presented in Table N°4.

Table N°4: Unit root test results for time series.

UNIT ROOT TEST TABLE (PP)

			Y	X1	X2	X3
At Level						
With Cons...	t-Statistic		-0.5901	1.8969	-5.8978	3.3213
	Prob.		***0.8602***	***0.9997***	***0.0000***	***1.0000***
			n0	n0	***	n0
With Cons...	t-Statistic		-0.6241	-1.4948	-5.8484	0.7304
	Prob.		***0.9711***	***0.8123***	***0.0001***	***0.9995***
			n0	n0	***	n0
Without C...	t-Statistic		0.3509	5.4646	-5.7006	6.0953
	Prob.		***0.7808***	***1.0000***	***0.0000***	***1.0000***
			n0	n0	***	n0
At First Difference						
			d(Y)	d(X1)	d(X2)	d(X3)
With Cons...	t-Statistic		-5.3939	-6.9027	-33.3513	-4.3296
	Prob.		***0.0001***	***0.0000***	***0.0001***	***0.0017***
			***	***	***	***
With Cons...	t-Statistic		-6.1822	-7.4176	-34.1536	-5.1303
	Prob.		***0.0001***	***0.0000***	***0.0000***	***0.0011***
			***	***	***	***
Without C...	t-Statistic		-5.4225	-4.8294	-33.9446	-2.6686
	Prob.		***0.0000***	***0.0000***	***0.0000***	***0.0092***
			***	***	***	***

UNIT ROOT TEST TABLE (ADF)

			Y	X1	X2	X3
At Level						
With Cons...	t-Statistic		-0.4254	1.1391	-5.8979	2.9409
	Prob.		***0.8938***	***0.9971***	***0.0000***	***1.0000***
			n0	n0	***	n0
With Cons...	t-Statistic		-0.6241	-1.7092	-5.8489	0.4349
	Prob.		***0.9711***	***0.7258***	***0.0001***	***0.9986***
			n0	n0	***	n0
Without C...	t-Statistic		0.3945	4.2058	-5.7006	5.5195
	Prob.		***0.7923***	***1.0000***	***0.0000***	***1.0000***
			n0	n0	***	n0
At First Difference						
			d(Y)	d(X1)	d(X2)	d(X3)
With Cons...	t-Statistic		-5.4030	-6.8632	-9.7980	-0.8800
	Prob.		***0.0001***	***0.0000***	***0.0000***	***0.7815***
			***	***	***	n0
With Cons...	t-Statistic		-6.1777	-7.3377	-9.6468	-5.1303
	Prob.		***0.0001***	***0.0000***	***0.0000***	***0.0011***
			***	***	***	***
Without C...	t-Statistic		-5.4303	-0.5083	-9.9499	0.0397
	Prob.		***0.0000***	***0.0001***	***0.0000***	***0.0000***
			***	***	***	***

Source: prepared by the researchers based on the output of Eviews 12 - (*) Significant at the 10%; (**) Significant at the 5%; (***) Significant at the 1%. and (no) Not Significant.

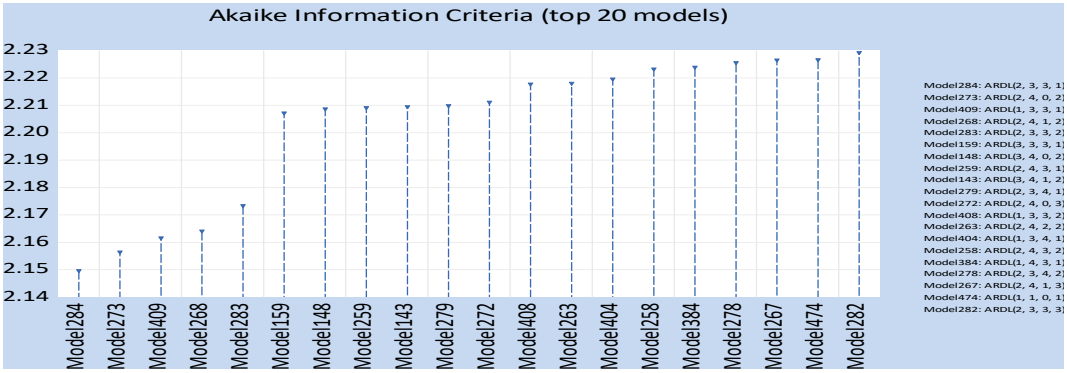
The results shown in the table above, using the Dickey-Fuller test and to check for the existence of a unit root in the time series indicate that the series" **Yt (AVA-GDP), X_1 (SITAR), X_3 (FDIAIR)**" become stationary after taking the first difference (**I_1**), while the series" **X_2 (SALI)**" is stationary at the level (**I_0**). Based on the hypothesis of **Pesarane and al**, the optimal model for estimating the short-term and long-term effects of smart agriculture determinants on sustainable agricultural development in Algeria during the period 1990-2025 is the Autoregressive Distributed Lag (ARDL) model.

3.4 Determination of the Optimal Lag Structure for the ARDL Model

In light of the fulfillment of the integration conditions necessary for implementing the ARDL model, the study moves to determining the optimal deceleration structure, as it is a crucial element in characterizing the model's temporal dynamics and ensuring estimation efficiency. To achieve this, the Akaiki Information Criterion (AIC) was adopted to select the deceleration specification that achieves the best balance between fit quality and providing an optimal number of parameters.

The results indicate that the optimal lag specification selected according to the Akaike Information Criterion (AIC) is **ARDL(2, 3, 3, 1)**.

Fig N° 2: Optimal Lag Structure for the ARDL Model - (AIC).



Source: prepared by the researchers based on the output of Eviews 12.

3.5 Bounds Testing Approach

After determining the optimal hysteresis specification, the" **Bounds Test**" methodology is performed to verify the existence of a long-term equilibrium relationship between the model variables within the **ARDL** framework. This step is crucial in distinguishing between short-term dynamic correlations and cointegration relationships. The test results are presented in the following table.

Table N°5: Results of the Co integration Test Using the Bounds Test.

F-Bounds Test			Null Hypothesis: No levels relationship	
Test Statistic	Value	Signif.	I(0)	I(1)
			Asymptotic: n=1000	
F-statistic	4.818136	10%	2.37	3.2
k	3	5%	2.79	3.67
		2.5%	3.15	4.08
		1%	3.65	4.66
Actual Sample Size	33		Finite Sample: n=35	
		10%	2.618	3.532
		5%	3.164	4.194
		1%	4.428	5.816
			Finite Sample: n=30	
		10%	2.676	3.586
		5%	3.272	4.306
		1%	4.614	5.966

Source: prepared by the researchers based on the output of Eviews 12.

Based on the results in Table N°5, the calculated value of the F-Statistic, estimated at 4.818, is higher than the critical values at the lower and upper bounds for the 1%, 2.5%, 5%, and 10% significance levels. From this, we conclude the existence of a long-run equi-librium relationship between the dependent variable

(Agricultural Value Added as a Percentage of GDP in Algeria) and the explanatory variables in our econometric study model.

3.6 Estimation of Model Parameters and Model Validation

After verifying the existence of a long-term equilibrium relationship, the analysis moved on to estimating the short-term dynamics and long-term equilibrium coefficients according to the **ARDL** model and the results are presented below.

3.6.1 Long-Run Parameter Estimation

After verifying the existence of a long-term equilibrium relationship between the study variables, the long-term ARDL model coefficients were estimated to derive long-term elasticities and determine the magnitude and direction of the sustained impact of the explanatory variables in the study—smart irrigation, smart agricultural learning, and foreign direct agricultural investment in Algeria—on the dependent variable, sustainable agricultural development, expressed as the agricultural value added index as a percentage of GDP. The estimation results are shown in the following table.

Table N°6: Results of Long-Run Parameter Estimation.

Levels Equation
Case 2: Restricted Constant and No Trend

Variable	Coefficient	Std. Error	t-Statistic	Prob.
X1	1.335905	2.334706	0.136145	0.0031
X2	0.131444	1.044838	0.125804	0.0011
X3	2.370519	4.115401	0.135965	0.0022
C	-1.438629	2.240010	-0.115970	0.0049

Source: prepared by the researchers based on the output of Eviews 12.

3.6.2 Estimating Short-Run Dynamics and Error Correction Modeling (ECM)

After confirming the existence of a long-run equilibrium relationship, short-run dynamics were estimated using an error correction model derived from the ARDL. This allowed for the estimation of the Error Correction Coefficient (ECT), which measures the rate at which short-run imbalances are corrected and the gradual return to the long-run equilibrium path occurs. The following table presents the results of the short-run coefficient estimation, along with the value of the Error Correction Coefficient and its statistical significance.

Table N°7: Results of Short Run - Parameter Estimation.

ARDL Error Correction Regression
Dependent Variable: D(Y)
Selected Model: ARDL(2, 3, 3, 1)
Case 2: Restricted Constant and No Trend
Date: 07/20/26 Time: 22:28
Sample: 1990 2025
Included observations: 33

ECM Regression
Case 2: Restricted Constant and No Trend

Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(Y(-1))	-0.237173	0.151994	-1.560413	0.1343
D(X1)	0.703093	0.093856	7.491176	0.0000
D(X1(-1))	0.197546	0.135337	1.459663	0.1599
D(X1(-2))	0.466206	0.176328	2.643966	0.0156
D(X2)	-4.16E-05	0.000322	-0.129325	0.8984
D(X2(-1))	-0.000290	0.000357	-0.812363	0.4261
D(X2(-2))	-0.000743	0.000308	-2.416451	0.0254
D(X3)	-1.808405	0.582985	-3.101973	0.0056
CointEq(-1)*	-0.008468	0.001575	-5.376692	0.0000

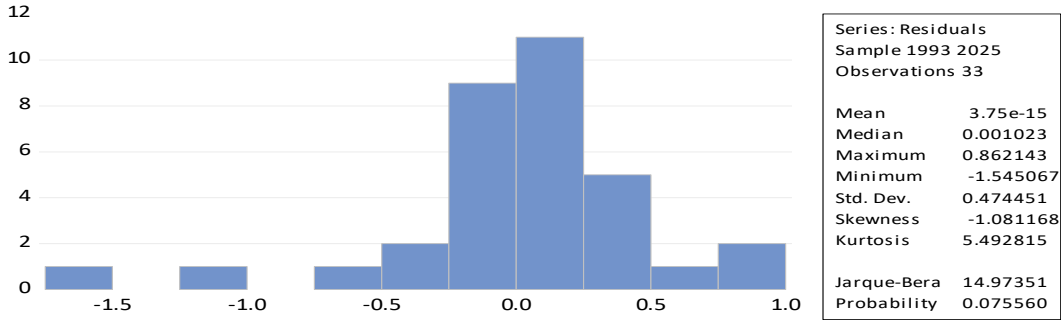
Source: prepared by the researchers based on the output of Eviews 12.

As shown in Table N°7, the error correction coefficient (ECT) was negative and statistically significant at a significance level of 5%, confirming the existence of a self-correcting mechanism that gradually returns the system to long-term equilibrium after short-term shocks. The estimated value of the coefficient (-0.008) indicates that approximately 0.8% of the imbalance from long-term equilibrium is corrected during each time period, reflecting a relatively slow rate of adaptation to equilibrium.

3.6.3 Diagnostic Evaluation of the Estimated Model

a- Residual Distribution: To test the extent to which the model satisfies the normality hypothesis, the distribution of the estimating residuals was examined using the Jarque-Bera test, whose null hypothesis is based on the residuals following a normal distribution. The test results are shown in the following figure.

Fig N° 3: Optimal Lag Structure for the ARDL Model - (AIC).



Source: prepared by the researchers based on the output of Eviews 12.

As depicted in the figure, the histogram of the estimated residuals closely follows the bellshaped curve typical of a normal distribution. Additionally, since the p-value of the Jarque-Bera test (0.075) exceeds the 5% significance level, we fail to reject the null hypothesis, suggesting that the residuals are normally distributed.

b- Test for Autocorrelation of Errors: Autocorrelation of model residuals is a crucial diagnostic test for the validity of standard estimation, as its presence indicates a violation of the assumption of the independence of random errors, which can negatively impact the efficiency of estimates and the accuracy of statistical inference. Within the framework of ARDL models and bounds testing, the **Breusch–Godfrey test** is used to detect autocorrelation in residuals and verify whether the model meets this standard assumption. The test results are presented in the following table.

Table N°8: Results of the Autocorrelation Problem Test for the Estimated Residuals.

Breusch-Godfrey Serial Correlation LM Test:
Null hypothesis: No serial correlation at up to 2 lags

F-statistic	0.588657	Prob. F(2,18)	0.5654
Obs*R-squared	2.025902	Prob. Chi-Square(2)	0.3631

Source: prepared by the researchers based on the output of Eviews 12.

According to the results in the table, the calculated F-statistic value was (0.58), which is not statistically significant at a significance level of (5%), which does not provide sufficient evidence to reject the null hypothesis. Therefore, it is inferred that the remnants of the model are free from the autocorrelation problem, which confirms that one of the basic assumptions necessary for the validity of the standard estimate is met.

c- Testing for homogeneity of variance: Homogeneity of the error boundary variance is a fundamental assumption for ensuring the efficiency of model estimators and the validity of statistical inference. To verify this assumption, the **Breusch–Pagan–Godfrey test** was applied to detect heterogeneity in the residual variance, and the results are presented in the following table.

Table N°9: Breusch-Pagan-Godfrey.

Heteroskedasticity Test: Breusch-Pagan-Godfrey
Null hypothesis: Homoskedasticity

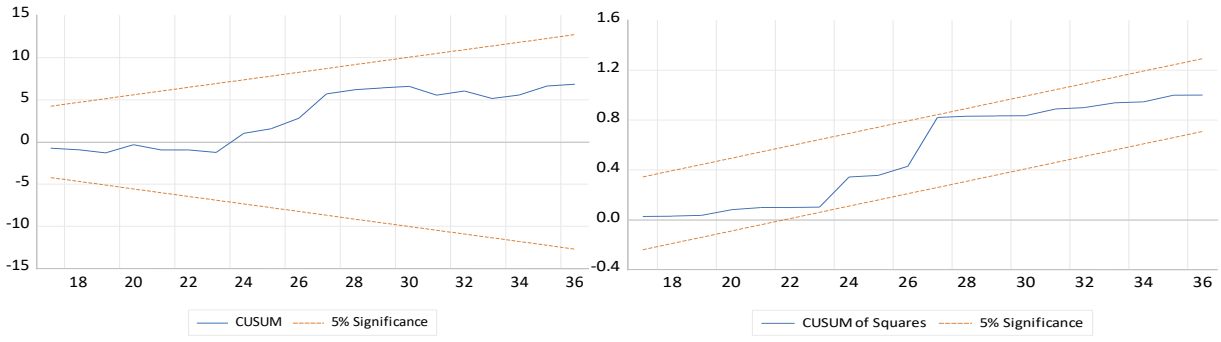
F-statistic	0.289065	Prob. F(12,20)	0.9843
Obs*R-squared	4.877536	Prob. Chi-Square(12)	0.9619
Scaled explained SS	4.024586	Prob. Chi-Square(12)	0.9830

Source: prepared by the researchers based on the output of Eviews 12.

The calculated F-statistic (0.28) is not statistically significant at the 5% significance level, providing insufficient evidence to reject the null hypothesis of **homoskedasticity**. Accordingly, the residuals exhibit constant variance, indicating that the model satisfies the homoskedasticity assumption.

d- Stability of the ARDL Model: To verify the structural stability of the model's parameters over the study period, the CUSUM and CUSUM of Squares tests were applied. The results shown in Figure (4) indicate that the curves of both tests remained within the critical limits at a significance level of (5%), indicating the stability of the ARDL model's parameters and the absence of statistical evidence of structural instability during the analysis period. This reinforces the reliability of the results and the validity of the model for inference and analysis related to identifying the shocks and impacts of smart agriculture determinants in Algeria on the dimensions of sustainable agricultural development, particularly concerning the added value generated by this sector and its contribution to Algeria's GDP during the period 1990-2025.

Fig N° 4: Cumulative Sum of Residuals and Cumulative Sum of Squared Residuals.



Source: prepared by the researchers based on the output of Eviews 12.

4. Economic analysis of the estimation results

Based on the ARDL model estimation results presented in Table N° 6, the estimation formula for the adopted standard model was derived. This formula reflects the dynamic relationship between the dependent variable and its determinants in both the short and long term. This equation serves as the basis for analyzing and interpreting the economic impacts of the independent variables and assessing their contribution to explaining the evolution of the phenomenon under study in Algeria. The equation for the estimated model can be expressed as follows:

$$Yt = C + \beta_1 X1 + \beta_2 X2 + \beta_3 X3 + \cdots \ldots \ldots + \beta_n Xn + \varepsilon_t$$

$$\text{AVA} - \text{GDP} = -1.43 + 1.33\ \text{SITAR} + 0.13\ \text{SALI} + 2.37\ \text{FDIAIR}$$

- The results of the regression model estimation support the study's first hypothesis, which posits a positive impact of adopting smart irrigation technologies on the development of the agricultural sector's added value in Algeria's GDP during the period 1990–2025. The estimated value of the smart irrigation index indicates that promoting the use of irrigation water management technologies based on operational efficiency and rationalizing water consumption is associated with a higher contribution of the agricultural sector to GDP. According to the estimates obtained, a 1% increase in the smart irrigation index leads to an increase in agricultural added value of approximately 1.33%, all other factors being constant. This reflects the positive economic impact of transitioning to more efficient irrigation systems in supporting agricultural productivity and promoting sustainable agricultural development in Algeria.
- The long-term estimation results of the ARDL model reveal a positive impact of the Smart Agriculture Learning Index (SALI) on the added value contributed by the agricultural sector to Algeria's GDP, thus supporting the study's second hypothesis. The estimated coefficient for this index reached 0.13, indicating that a 1% increase in the level of smart agriculture learning is associated with an increase in agricultural added value of approximately 0.13%, assuming the other explanatory variables in the model remain constant. This impact reflects the economic role of agricultural knowledge capital in enhancing the ability of sector stakeholders to adopt modern technologies, improve production methods, and increase the efficiency of knowledge- and data-driven agricultural decision-making. Despite the relatively small numerical value of the coefficient compared to some other smart agriculture determinants, its impact is of strategic importance as it represents a long-term, cumulative mechanism that supports agricultural innovation and contributes to creating the necessary institutional and human environment for achieving the transition to smart and sustainable agriculture in Algeria.
- Standard long-term correlation estimates confirm that foreign direct investment in agriculture (FDIAIR) is a key driver for increasing the value added that the agricultural sector contributes to Algeria's GDP, which aligns with the study's third hypothesis. The coefficient for this variable registered a significant positive value

of 2.37, meaning that a 1% increase in agricultural FDI inflows is associated with a 2.37% increase in agricultural value added, assuming all other explanatory variables remain constant. This strong effect reflects the role of foreign investment in supporting technological modernization, providing financing and production expertise, and accelerating the adoption of smart farming practices. Therefore, this result highlights that enhancing the attractiveness of the agricultural sector to foreign investment is a strategic lever for improving agricultural performance and achieving a sustainable transformation based on innovation and production efficiency in Algeria.

5. Conclusion:

The study entitled "The Dynamic Role of Smart Agriculture Determinants in Enhancing the Added Value of the Agricultural Sector in Algeria during the Period (1990-2025): A Standard Approach Using the ARDL Model" yielded a set of theoretical and empirical findings that highlighted the importance of transitioning to a knowledge-based and technology-driven agricultural model in supporting the economic performance of the agricultural sector. The study analyzed the dynamic relationship between smart agriculture indicators and agricultural added value by assessing the impact of key determinants, namely smart irrigation technologies, smart agricultural learning, and foreign direct investment flows directed to the agricultural sector. The results demonstrated a long-term positive relationship between these determinants and the agricultural sector's contribution to GDP, confirming that enhancing technological, knowledge-based, and investment capacities is a crucial path to improving agricultural productivity and achieving sustainable agricultural performance in Algeria.

The study concluded with a number of key findings related to both theoretical and experimental aspects, the most important of which are summarized below:

- The results of the econometric estimation using the ARDL model demonstrated a positive and stable relationship between the determinants of smart agriculture and the added value contributed by the agricultural sector to Algeria's GDP. This confirms that technological transformation in the agricultural sector is a modern determinant for enhancing agricultural growth and improving long-term productivity.
- The results highlighted that the smart irrigation index is an effective mechanism for improving agricultural performance. The positive impact of this variable reflects the importance of transitioning from traditional irrigation systems to more efficient water resource management technologies, especially given the climatic constraints and water scarcity facing the Algerian agricultural economy.
- The estimates revealed that smart agricultural learning is a supporting element for structural transformation in the agricultural sector. The accumulation of agricultural knowledge and the acquisition of skills related to modern technologies contribute to enhancing producers' ability to adopt innovations and improve the efficiency

of production decisions, although its impact appears gradually compared to other investment and technological determinants.

- The results showed that foreign direct investment flows directed towards the agricultural sector represent the most influential determinant within the standard model, as a major channel for transferring technology and expertise and providing the necessary financing for modernizing the sector, which confirms the importance of building an investment climate capable of attracting capital that supports the shift towards smart agriculture.

Based on these results, the following recommendations can be made to help policymakers and decision-makers support the contribution of smart agriculture to achieving sustainable agricultural development in Algeria:

- Develop a comprehensive national strategy to accelerate the adoption of smart irrigation and digital farming technologies through targeted public investment in water-efficient agricultural infrastructure.
- Strengthen smart agricultural learning by enhancing collaboration among universities, research institutions, extension services, and farmers to facilitate knowledge transfer and technology adoption.
- Improve the regulatory and investment framework to attract technology-oriented foreign direct investment that supports agricultural modernization and the diffusion of smart farming technologies

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