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Energy literacy and rural economic efficiency: Evaluating the role of energy education in enhancing agricultural productivity

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Abstract: *The transition toward sustainable agriculture requires not only technological innovation but also farmers' capacity to understand and effectively manage energy resources. This study examines how energy literacy contributes to agricultural productivity and rural economic development in Vietnam, with the adoption of energy-efficient technologies considered as a key mediating mechanism. Drawing on Human Capital Theory and the Technology Acceptance Model, the study develops and empirically tests a structural model linking energy literacy, adoption of energy-efficient technologies, agricultural productivity, and rural economic development. Data were collected from 312 farmers and agricultural producers in rural Vietnam using a structured questionnaire and analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM). The findings show that energy literacy has a strong positive effect on the adoption of energy-efficient technologies ($\beta = 0.614$, $p < 0.001$), while technology adoption positively affects agricultural productivity ($\beta = 0.304$, $p < 0.001$). Energy Literacy also has a significant direct effect on Agricultural Productivity ($\beta = 0.320$, $p < 0.001$). Furthermore, agricultural productivity positively influences rural economic development ($\beta = 0.479$, $p < 0.001$). The mediation results indicate that technology adoption mediates the relationship between energy literacy and agricultural productivity, while agricultural productivity mediates the relationships between energy literacy, technology adoption, and rural economic development. A significant serial mediation pathway from energy literacy through technology adoption and agricultural productivity to rural economic development is also identified. The findings highlight energy literacy as an important form of human capital that enables Vietnamese farmers to make more informed technological and production decisions. The study contributes to sustainable agricultural development by demonstrating how knowledge-based capabilities, technological adoption, and productivity improvements can jointly support rural economic development.*

Keywords: Agricultural Productivity; Energy Literacy; Energy-Efficient Technologies; Rural Economic Development; Sustainable Agriculture.

1. INTRODUCTION

Under the combined pressures of climate change, rising energy demand, resource scarcity, and the need for sustainable rural development, improving agricultural productivity while reducing environmental impacts has become a global priority (Liu et al, 2024). Agriculture remains one of the most energy-intensive sectors, relying heavily on electricity, fuel, irrigation systems, machinery, fertilizers, and post-harvest technologies. As developing countries strive to ensure food security and achieve sustainable economic growth, enhancing the efficiency with which energy resources are utilized in agricultural production has become increasingly important. Rural economic efficiency, reflected in higher agricultural productivity, lower production costs, and improved farm profitability, is now recognized as a key component of sustainable agricultural transformation and the achievement of the United Nations Sustainable Development Goals (SDGs) (Ahmed et al., 2022). While investments in modern technologies and renewable energy systems have accelerated agricultural modernization, their effectiveness ultimately depends on farmers' ability to understand, evaluate, and efficiently utilize energy resources.

According to human capital theory, education enhances individuals' knowledge, skills, and decision-making capabilities, thereby improving productivity and economic performance (Khoo et al, 2026). Within the agricultural sector, energy education has emerged as an important instrument for equipping farmers with the competencies required to adopt energy-efficient technologies and sustainable farming practices (Fazeli et al., 2023; Torto et al., 2022). The concept of energy literacy has evolved beyond basic knowledge of energy sources to encompass a multidimensional framework including energy knowledge, attitudes, awareness, behavioral intentions, and responsible energy-use practices (Gladwin & Ellis, 2023). Farmers with higher levels of energy literacy are better positioned to understand energy consumption patterns, evaluate alternative energy technologies, optimize machinery and irrigation systems, reduce unnecessary energy waste, and make environmentally responsible production decisions . Consequently, energy literacy is expected not only to improve energy-use efficiency but also to enhance agricultural productivity and strengthen rural economic performance.

In recent years, education systems worldwide have increasingly adopted interdisciplinary approaches to cultivate the competencies necessary for addressing complex sustainability challenges. Among these, STEM (Science, Technology, Engineering, and Mathematics) education has gained considerable attention as an integrated pedagogical framework capable of developing analytical thinking, technological competence, and real-world problem-solving abilities (Gong et al., 2024). Rather than teaching scientific concepts in isolation, STEM education enables learners to integrate scientific knowledge with engineering design, technological applications, and mathematical reasoning to solve practical problems. Constructivist and application-based learning perspectives further emphasize that learners develop deeper understanding through designing, testing, evaluating, and refining solutions to authentic challenges. Within the context of energy education, STEM-based learning provides an effective platform for developing energy literacy by enabling individuals to analyze the relationships among energy production, consumption, efficiency, environmental impacts, and sustainable resource management. Such competencies are particularly valuable in rural communities, where informed energy-related decisions directly influence agricultural productivity and long-term economic resilience (Sindakis et al., 2024). Previous studies have extensively examined the contributions of renewable energy adoption, energy-efficient technologies, and digital innovations to agricultural development (Thakkar et al., 2021). Existing evidence suggests that improved energy management can reduce production costs, optimize resource allocation, and increase farm productivity . Similarly, educational interventions have been shown to promote environmentally responsible behaviors and facilitate technology adoption among farmers . Nevertheless, current research has largely focused on technological diffusion, energy infrastructure, or policy incentives, while relatively limited attention has been paid to the role of energy literacy as a form of human capital influencing rural economic outcomes. More importantly, although energy education is increasingly recognized as an essential component of sustainable development, little empirical evidence explains the mechanisms through which energy literacy translates into higher agricultural productivity and improved rural economic efficiency. Furthermore, the potential contribution of STEM-based energy education in strengthening farmers' energy literacy remains insufficiently explored.

Against this background, this study investigates the relationship between energy literacy and rural economic efficiency by evaluating the role of energy education in enhancing agricultural productivity. Specifically, the study examines whether improved energy literacy enables farmers to adopt more energy-efficient agricultural practices, optimize resource utilization, and ultimately improve farm productivity and rural economic performance. By integrating perspectives from human capital theory, sustainable agricultural development, and STEM-based energy education, this research contributes to the growing literature on agricultural sustainability in three ways. Firstly, it extends existing studies by positioning energy literacy as a strategic human capital resource influencing agricultural productivity and rural economic efficiency. Secondly, it provides a theoretical framework explaining how energy education enhances farmers’ capacity to make informed energy-related decisions that support sustainable agricultural production. Thirdly, the findings offer practical implications for policymakers and educational institutions seeking to design effective energy education programs that strengthen rural resilience, improve agricultural competitiveness, and accelerate the transition toward sustainable and low-carbon agriculture. The construct of the study consists is divided into five main parts (i) Introduction; (ii) theoretical framework and hypothesis development; (iii) methodology; (iv) results and discussions; (v) implications and conclusion.

2. THEORETICAL FRAMEWORK AND HYPOTHESIS DEVELOPMENT

2.1 Theoretical Foundations

2.1.1 Human Capital Theory (HCT)

Human Capital Theory provides a fundamental theoretical foundation for explaining how education, knowledge, skills, and competencies contribute to individual productivity and broader economic development. Becker (1964) conceptualizes human capital as the knowledge and skills acquired through education, training, and experience that enhance individuals' productive capabilities. Investment in human capital enables individuals to improve their decision making, utilize available resources more efficiently, and increase their productivity, thereby generating economic returns over time. In agricultural contexts, farmers' knowledge and competencies are important determinants of their ability to manage production resources, respond to technological changes, and improve farming practices. Greater levels of human capital can enhance farmers' capacity to make appropriate production decisions and utilize available resources effectively. These improvements in individual productive capabilities can contribute to higher agricultural productivity and, at the broader level, support improvements in rural economic conditions. Human Capital Theory is therefore relevant to the present study because energy education and energy related knowledge can be considered investments in farmers' productive capabilities. Through the acquisition of energy related knowledge and competencies, farmers may become better able to understand energy consumption, manage energy resources, and make more efficient production decisions. These enhanced capabilities may contribute directly to agricultural productivity and may also facilitate the effective use of technologies in agricultural production. Accordingly, Human Capital Theory provides the theoretical basis for examining the role of energy literacy in improving agricultural productivity and its subsequent contribution to rural economic development.

2.1.2 Technology Acceptance Model (TAM)

The Technology Acceptance Model, proposed by Davis (1989), provides a theoretical framework for explaining individuals' acceptance and adoption of technological innovations. The model emphasizes perceived usefulness and

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perceived ease of use as key determinants of technology acceptance. In agricultural contexts, farmers who better understand the benefits and applicability of energy efficient technologies are more likely to recognize their usefulness and adopt them in production activities. Higher levels of Energy Literacy may therefore strengthen farmers' ability to evaluate technological alternatives, reduce uncertainty regarding technology use, and facilitate the adoption of appropriate energy efficient technologies. This is particularly important for technologies that require farmers to understand both their operational requirements and potential economic benefits. Accordingly, the Technology Acceptance Model provides a theoretical basis for explaining the relationship between energy literacy and the adoption of energy efficient technologies, as well as how technological adoption can contribute to improved agricultural production performance through more efficient resource utilization and reduced production inefficiencies.

2.2 Energy Literacy

Energy is a fundamental input for economic development, environmental sustainability, and agricultural production. Rural agricultural activities depend on energy for irrigation, machinery operation, post harvest processing, transportation, and other production processes (Stern, 2011). Increasing concerns about energy security, resource scarcity, and climate change have strengthened the need for adequate knowledge and competencies concerning energy use. Access to energy information supports individuals in understanding consumption patterns, evaluating energy alternatives, assessing environmental consequences, and making informed decisions regarding energy management (Santillán et al., 2023). Energy literacy refers to the knowledge, attitudes, and competencies required to understand energy and make informed decisions concerning its use (DeWaters & Powers, 2011). Although the literature does not provide a universally accepted definition, energy literacy is commonly conceptualized as a multidimensional construct incorporating cognitive, affective, and behavioral components. Jorgenson et al. (2019) define energy literacy as citizens' understanding of energy encompassing broad knowledge together with affective and behavioral dimensions. This conceptualization incorporates energy knowledge, attitudes toward energy conservation, and behavioral capacities related to energy use.

The cognitive and behavioral dimensions of energy literacy have been examined by Van den Broek (2019), who associates energy literacy with understanding energy consumption, identifying opportunities for energy conservation, making energy efficient decisions, and recognizing the relationship between energy use and climate change. Wang et al. (2021) similarly emphasize individuals' ability to understand the role of energy and apply energy related knowledge to promote environmental sustainability. Energy literacy therefore encompasses both knowledge acquisition and the application of energy knowledge in practical decision making.

The economic dimension of energy literacy has also received attention in studies of energy related investment decisions. Brounen et al. (2013) examine individuals' ability to evaluate the economic trade offs associated with energy efficient investments, including initial costs and potential long term savings. Kalmi et al. (2017) further associate energy literacy with awareness of energy consumption, knowledge of energy pricing, energy saving intentions, and the ability to obtain and process energy related information. Blasch et al. (2018) extend this perspective through the concept of energy related financial literacy, emphasizing financial competencies in evaluating energy investments and their expected economic returns.

In agricultural contexts, energy literacy is relevant to the management of energy intensive production activities and the adoption of energy related technologies (Chikaire et al., 2015). Agricultural technologies such as energy efficient machinery, solar powered irrigation systems, and precision agriculture require users to evaluate energy requirements, operating costs, and potential efficiency gains. Farmers with stronger energy related knowledge and decision making competencies may be better equipped to assess these alternatives and manage energy resources efficiently. Energy literacy can therefore represent an important capability for improving resource use efficiency and supporting sustainable agricultural practices (Cavicchi et al., 2022). Despite increasing attention to energy literacy, empirical research has concentrated primarily on household energy consumption (Brounen et al., 2013), energy conservation (Hendinata et al., 2022), environmental behavior (Cha et al., 2024), and energy related decision making. The relationship between energy literacy and energy efficient technology adoption in agricultural production remains less extensively examined, particularly among rural populations. Further investigation of this relationship is warranted given the increasing dependence of agricultural production on energy intensive technologies and the importance of energy efficiency to agricultural productivity and rural economic development

2.3 Energy Efficient Technologies in Agriculture

Agriculture is one of the most energy-intensive sectors of the global economy, requiring substantial inputs of fuel, electricity, and mechanical power for land preparation, irrigation, planting, harvesting, transportation, storage, and post-harvest processing (Benedek et al., 2023). As the demand for food continues to increase alongside population growth and climate-related pressures, improving energy efficiency has become a fundamental requirement for ensuring sustainable agricultural production and rural economic development. Nowadays, the fuel and energy problem has become increasingly critical due to the limited reserves of conventional fossil fuels and the rising costs associated with agricultural production. At the same time, the need to increase food production while reducing environmental degradation has intensified the importance of adopting energy-efficient agricultural technologies (Osman et al., 2025).

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Vol. 10 Issue 8 August - 2026, Pages: 65-79

Energy-efficient technologies refer to technological innovations that reduce energy consumption while maintaining or enhancing agricultural productivity (Daraz et al., 2025). Rather than merely decreasing energy use, these technologies aim to optimize the conversion of energy inputs into agricultural outputs through improved equipment, precision management, renewable energy integration, and intelligent farming systems. Consequently, energy efficiency has become an important criterion for evaluating agricultural production performance because it simultaneously lowers production costs, conserves natural resources, and reduces greenhouse gas emissions (Bojnec et al., 2024). Compared with conventional financial assessments, energy assessment provides a more objective evaluation of production efficiency because it measures the actual energy embodied in agricultural inputs and outputs without being influenced by market price fluctuations or economic conditions. Energy auditing therefore enables researchers and policymakers to identify the most efficient combinations of machinery, production techniques, and resource allocation strategies for different farming systems (Ragazou et al., 2022).

Recent advances in agricultural engineering have accelerated the development of energy-efficient technologies across various stages of agricultural production. Modern machinery equipped with fuel-efficient engines, precision farming equipment, variable-rate application systems, conservation tillage technologies, and automated irrigation systems significantly reduce unnecessary energy consumption while improving operational performance. For example, optimizing machinery combinations during land preparation and sowing operations can substantially decrease total energy inputs while improving soil quality and crop establishment. The implementation of improved tillage equipment, advanced seeders, and bio-organic fertilizer application technologies has been shown to enhance production quality while minimizing overall energy costs (Daraz et al., 2024). These innovations demonstrate that technological optimization is not solely a matter of increasing mechanization but also of selecting appropriate technologies that maximize productivity with minimum energy expenditure. Among contemporary agricultural innovations, energy-efficient smart irrigation systems have attracted considerable attention because irrigation represents one of the largest consumers of both water and energy. Traditional irrigation methods frequently rely on fixed schedules, inefficient pumping systems, and excessive groundwater extraction, resulting in significant resource waste and reduced productivity. In contrast, smart irrigation technologies integrate renewable energy sources, sensor networks, automated control systems, and precision water management to optimize irrigation according to actual crop requirements. A typical solar-powered smart irrigation system consists of photovoltaic (PV) panels supplying electricity to water pumps, soil moisture sensors that continuously monitor field conditions, and Internet of Things (IoT)-based controllers that regulate irrigation timing and water volume. By delivering water only when required, these technologies substantially reduce both energy consumption and water losses while improving crop performance (Ingrao et al, 2023).

Another important advantage of energy-efficient irrigation technologies is their capacity to utilize multiple water sources more sustainably. Modern systems can regulate groundwater extraction from deep aquifers, surface reservoirs, and tubewell irrigation networks according to real-time water availability and crop demand. Particularly in water-scarce regions, intelligent pumping systems help prevent excessive groundwater depletion while maintaining reliable irrigation performance. The integration of renewable energy-powered pumping mechanisms further reduces dependence on fossil fuels, decreases operating costs, and minimizes carbon emissions associated with agricultural production (Leal Filho et al, 2024). In consequence, energy-efficient irrigation technologies simultaneously contribute to water conservation, environmental protection, and long-term agricultural sustainability.

Despite the considerable benefits offered by these technologies, their successful implementation depends not only on technological availability but also on farmers' ability to understand, operate, and maintain them effectively. Advanced agricultural equipment, renewable energy systems, and precision farming tools often require users to possess adequate knowledge of energy management, equipment operation, and sustainable farming practices. Without sufficient energy-related knowledge and practical skills, farmers may underutilize available technologies or fail to achieve their expected efficiency gains. Therefore, the effectiveness of energy-efficient agricultural technologies is closely associated with the level of energy literacy, which enables farmers to make informed decisions regarding energy consumption, technology adoption, and resource management. Improving farmers' energy literacy through targeted educational programs is therefore expected to enhance the adoption of energy-efficient technologies, increase agricultural productivity, and ultimately improve rural economic efficiency.

2.4 Agricultural Productivity and Rural Economic Development

Agricultural productivity has long been recognized as a fundamental driver of rural economic development and poverty reduction (Warr & Suphannachart, 2021). Improvements in agricultural productivity increase farm output from a given level of land, labor, and capital, thereby enhancing farmers’ incomes, strengthening food security, and stimulating broader economic growth. Early studies on agricultural productivity emphasized that technological progress alone cannot fully explain productivity growth, as institutional reforms, research and development (R&D), and public investments also play essential roles. Sun et al, (2017) were among the first to argue that omitting R&D investment from production function analyses would substantially overestimate the contribution of institutional reforms. By incorporating research stock into agricultural production functions, they demonstrated that R&D investment significantly contributed to agricultural production growth alongside institutional change and increased input utilization.

Beyond technological innovation, public investments in rural infrastructure including roads, electrification, irrigation systems, education, and extension services, have substantially improved agricultural productivity by facilitating technology diffusion, reducing transaction costs, and improving farmers' access to markets and production resources. Zhou et al, (2021) further emphasized the importance of capital accumulation in promoting rural nonfarm development, although limitations in public capital data constrained their empirical analysis. Moreover, regional disparities in agricultural productivity have been closely associated with unequal infrastructure development, indicating that investments in rural public goods are important determinants of long-term productivity growth and regional economic performance. Utilizing Agricultural Census data, subsequent studies highlighted the importance of infrastructure investment in explaining regional productivity differences while providing more accurate measurements of land and labor inputs than previous statistical sources (Wu et al., 2017).

From a broader development perspective, agricultural productivity contributes to rural economic development through several complementary mechanisms. At the national level, increases in agricultural output generally expand food supply, placing downward pressure on food prices and improving food affordability for consumers. Since low-income households typically allocate a larger proportion of their income to food expenditures, improvements in agricultural productivity often generate relatively greater welfare gains for poorer populations. However, the magnitude of these benefits depends on market conditions, particularly the price elasticity of demand and the degree of market integration. Norton et al. (2020) argued that when agricultural demand is relatively inelastic, increased production leads to larger price reductions, transferring greater benefits to consumers. Conversely, under highly integrated or international markets where demand is more elastic, producers capture a larger share of productivity gains. In regions with weak infrastructure and poorly integrated markets, agricultural products become relatively non-tradable, making domestic productivity growth especially beneficial for low-income consumers (Baloch et al., 2019).

Agricultural productivity also supports structural transformation and long-term economic growth beyond the agricultural sector. Classical dual-economy theories propose that productivity improvements in agriculture generate surplus resources that can be transferred to industrial and service sectors, thereby accelerating national economic development (Sakketa, 2023). Rising agricultural incomes increase household savings and investment capacity, while expanding agricultural exports and reducing food imports strengthen foreign exchange earnings and improve macroeconomic stability. Historically, governments in several developing countries accelerated industrialization by mobilizing surplus resources generated within agriculture through taxation and public investment mechanisms (Roe, 2019). Furthermore, productivity improvements increase output per agricultural worker, enabling labor to transition toward higher-productivity sectors while maintaining agricultural production levels. This structural transformation has been widely recognized as one of the principal drivers of rapid economic growth in East Asian economies .

Within the context of the present study, agricultural productivity represents a crucial pathway linking energy literacy to rural economic efficiency. Farmers with higher levels of energy literacy are more capable of selecting energy-efficient technologies, optimizing machinery operation, improving irrigation management, and reducing unnecessary energy consumption throughout agricultural production. These improvements enhance resource-use efficiency, lower production costs, and increase agricultural productivity, which subsequently strengthens household income, farm profitability, and overall rural economic development. Therefore, agricultural productivity constitutes an essential mechanism through which investments in energy education can generate sustainable economic benefits while simultaneously supporting environmentally responsible agricultural development.

2.5 Hypothesis Development

2.5.1. The Impact of In-store Audio-Visual Advertising on Perceived Financial Value

Energy literacy refers to an individual's knowledge, awareness, attitudes, and behavioral competencies related to energy production, consumption, conservation, and sustainable energy use. As a multidimensional construct, energy literacy enables individuals to understand energy related issues, evaluate alternative energy solutions, and make informed decisions regarding energy use in both daily and professional contexts. Kellberg et al. (2025) suggest that energy literacy develops through the interaction of prior knowledge, individual interest, and learning experiences, which enhances individuals' capacity to understand complex energy systems and apply energy related knowledge in practical contexts. In the agricultural sector, the adoption of energy efficient technologies, including solar powered irrigation systems, energy efficient machinery, precision irrigation, renewable energy applications, and intelligent energy management systems, requires farmers to possess adequate knowledge of energy use and technological applications. Farmers with higher levels of energy literacy may be better equipped to understand the functional characteristics and potential benefits of such technologies, evaluate available alternatives, and assess their relevance to agricultural production. Santillán & Cedano (2023) emphasize the importance of energy related knowledge and awareness in shaping energy related decision making and sustainable practices. Conversely, insufficient energy literacy may constrain farmers' ability to assess technological alternatives and make informed decisions regarding the adoption of energy efficient solutions.

Existing literature further indicates that energy related knowledge and awareness constitute important foundations for energy conscious behavior and sustainable decision making. Energy literacy can facilitate the translation of energy related knowledge into practical actions and support individuals' engagement with innovative energy solutions. Duan et al. (2026) demonstrate that energy literacy enhances individuals' capacity to apply energy related knowledge in practical contexts and engage in energy related actions. In agricultural settings, these competencies may enable farmers to more effectively evaluate and adopt energy efficient technologies that improve resource use efficiency and reduce energy related costs.

H1: Energy literacy has a positive effect on the adoption of energy-efficient technologies.

The adoption of energy-efficient technologies has become an important approach to improving agricultural productivity in the context of increasing resource constraints, rising energy costs, and the need for more sustainable agricultural production. Energy-efficient technologies encompass a range of applications, including solar-powered irrigation systems, precision irrigation, energy-efficient agricultural machinery, automated monitoring systems, and renewable energy technologies. By improving the efficiency of energy and other production inputs, these technologies can reduce resource losses, lower operational costs, and enhance the efficiency of agricultural production processes, thereby contributing to improved farm performance (Gasa et al., 2026). The productivity-enhancing effects of energy-efficient technologies are particularly evident through improved resource-use efficiency and more precise management of agricultural inputs. For example, smart irrigation systems can integrate renewable energy sources with sensors, automated controllers, and Internet of Things (IoT) technologies to provide water according to crop requirements. Such systems can reduce unnecessary energy consumption and water losses while improving irrigation efficiency, which may contribute to higher agricultural output and more efficient production processes (Daraz et al., 2025).

Furthermore, the adoption of advanced technologies can facilitate the modernization of agricultural production processes and improve the allocation of production inputs. Xu et al. (2026) emphasize that the adoption of agricultural technologies can enhance production efficiency through improved resource management, greater technological utilization, and more effective farming practices. The integration of such technologies can therefore enable farmers to manage production resources more efficiently and improve overall production performance. Within the context of this study, the adoption of energy-efficient technologies is expected to improve the efficiency of energy, water, and other agricultural inputs while reducing operational inefficiencies. More efficient resource utilization can enhance production processes and contribute to improved agricultural output and productivity. Therefore, farmers with higher levels of adoption of energy-efficient technologies are expected to achieve higher levels of agricultural productivity.

H2: The adoption of energy-efficient technologies has a positive effect on agricultural productivity.

Energy literacy encompasses individuals’ knowledge, awareness, attitudes, and behavioral competencies concerning energy production, consumption, conservation, and sustainable energy management. Beyond the acquisition of energy-related knowledge, energy literacy involves the capacity to interpret energy-related information, make informed decisions, and apply appropriate energy practices in practical contexts (Zhao et al., 2022). In agricultural production, where energy is an important input for activities such as irrigation, mechanization, post-harvest processing, and transportation, farmers’ energy literacy may influence the efficiency with which energy resources are managed and utilized. Farmers with higher levels of energy literacy are more likely to recognize the relationship between energy use and agricultural production outcomes. Such knowledge can support more informed decisions regarding the allocation and utilization of energy inputs, reduce inefficient energy consumption, and improve the management of energy-intensive production activities. Manono et al. (2026) suggest that greater energy-related knowledge can enhance individuals’ ability to make appropriate decisions concerning energy use and resource management. From this perspective, energy literacy represents a form of knowledge-based capacity that may contribute to more efficient agricultural management and production practices.

Agricultural productivity is closely associated with the effective utilization of production inputs, including energy, land, labor, and other resources. Chen (2025) highlights that improvements in agricultural production practices and technological applications can enhance productivity through more efficient resource utilization, improved production processes, and optimized use of agricultural inputs. Although technological adoption constitutes a distinct mechanism within the present research framework, the ability of farmers to understand and manage energy inputs remains relevant to agricultural production efficiency. Farmers who possess greater energy-related knowledge may be better positioned to identify inefficient energy use, allocate production resources appropriately, and implement energy-saving practices within their existing farming activities. Accordingly, higher levels of energy literacy are expected to improve the efficiency of energy and resource management in agricultural production. More informed energy-related decisions may reduce unnecessary resource consumption, improve operational efficiency, and support more effective production practices. These improvements are expected to contribute to enhanced agricultural productivity.

H3: Energy literacy has a positive effect on agricultural productivity.

Energy literacy equips farmers with the knowledge, awareness, and practical competencies necessary to understand energy use, evaluate technological alternatives, and make informed decisions regarding energy related practices. Farmers with higher levels of energy literacy are better positioned to recognize the potential economic and operational benefits of energy efficient technologies and assess their suitability for agricultural production. Consequently, higher levels of energy literacy may encourage farmers to adopt technologies such as solar powered irrigation systems, precision irrigation, energy efficient agricultural machinery, and renewable energy applications (Daraz et al., 2025). The adoption of energy efficient technologies can subsequently enhance agricultural productivity by improving the utilization of energy and other production resources. Such technologies can reduce unnecessary energy consumption, improve irrigation efficiency, optimize machinery performance, and reduce production inefficiencies (Duan et al., 2026). Daraz et al. (2025) demonstrate that energy efficient smart irrigation technologies can improve water and energy efficiency in agricultural production. Similarly, Xu et al. (2026) emphasize that agricultural technology adoption can enhance production efficiency through improved resource management and more effective farming practices.

H4: The adoption of energy-efficient technologies mediates the positive relationship between energy literacy and agricultural productivity.

Agricultural productivity is widely recognized as one of the principal drivers of rural economic development, particularly in developing economies where agriculture remains a primary source of employment, income, and livelihood. Higher agricultural productivity enables farmers to generate greater output from existing production inputs, thereby increasing farm income, improving resource-use efficiency, and strengthening the overall resilience of rural economies (Gao et al ,2023). As agricultural production expands, higher household earnings stimulate local consumption, investment, employment opportunities, and the development of supporting industries, creating positive spillover effects throughout rural communities.

Improvements in agricultural productivity also contribute to structural transformation by increasing production efficiency and reducing the costs associated with agricultural activities. Higher productivity enhances the competitiveness of agricultural products, strengthens food security, and provides greater opportunities for value addition through processing, marketing, and agribusiness development. These improvements ultimately promote rural economic growth by expanding agricultural markets, increasing household welfare, and supporting sustainable regional development. Recent studies further highlight that technological advancement and innovation are important mechanisms through which productivity contributes to broader economic development. Takhumova, O. (2020) argues that modern agricultural technologies improve agricultural productivity by enhancing production efficiency, optimizing land utilization, and promoting more sustainable resource management. Increased productivity generated through technological modernization provides a stronger economic foundation for rural development by improving production performance and increasing farmers' incomes.

Similarly, Chen & Xing (2025) emphasize that technological innovation and green transformation serve as critical drivers of high-quality economic development. Their findings suggest that productivity improvements achieved through innovation enhance economic efficiency, optimize resource allocation, and promote sustainable development outcomes. Within rural economies, agricultural productivity therefore not only generates direct economic benefits for farming households but also supports broader regional development through increased investment capacity, improved market competitiveness, and more sustainable economic growth. In the context of this study, higher agricultural productivity is expected to strengthen rural economic development by improving farmers' income, increasing production efficiency, stimulating rural economic activities, and enhancing the long-term sustainability of agricultural production systems. Consequently, improvements in agricultural productivity provide an essential pathway through which energy literacy and energy-efficient technologies can contribute to rural economic prosperity.

H5: Agricultural productivity has a positive effect on rural economic development.

Energy literacy extends beyond knowledge of energy resources to include individuals' ability to understand energy-related issues, make informed decisions, and adopt sustainable energy practices. In rural communities, higher levels of energy literacy contribute not only to more responsible energy consumption but also to stronger community resilience and sustainable local development. Chodkowska-Miszczuk et al. (2021) argue that energy literacy enhances rural resilience by improving communities' capacity to manage energy resources, strengthen local participation, and support sustainable rural development. These improvements in energy-related knowledge and resource management can help farmers use production inputs more effectively and create favorable conditions for improving agricultural productivity. Similarly, Zhao et al. (2022) demonstrate that higher levels of literacy significantly influence rural households' adoption of greener energy consumption behaviors. Their findings suggest that knowledge and awareness encourage individuals to make more sustainable energy decisions, which ultimately contribute to broader socio-economic and environmental improvements within rural communities. In the agricultural context, greater energy literacy can encourage farmers to manage energy resources more efficiently and make informed decisions regarding agricultural production, thereby supporting improvements in agricultural productivity. Agricultural productivity, in turn, plays an important role in rural economic development. Higher agricultural productivity

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can increase agricultural output, improve resource-use efficiency, strengthen farmers' income-generating capacity, and create greater economic opportunities within rural communities. Therefore, the benefits of energy literacy may extend beyond individual energy-related practices to broader rural economic outcomes through improvements in agricultural productivity. In this sense, agricultural productivity may serve as an important mechanism linking energy literacy with rural economic development, whereby higher energy literacy contributes to improved agricultural productivity, which subsequently supports rural economic development.

H6: Agricultural productivity mediates the positive relationship between energy literacy and rural economic development.

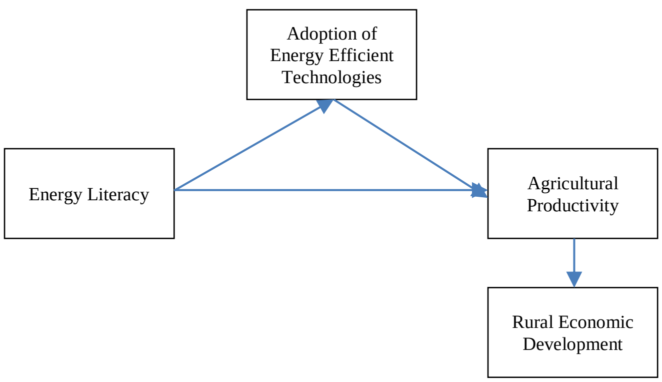

Figure 1: Research Model

3. METHODOLOGY

3.1 Measures and Questionnaire Design

The measurement instrument was designed to examine the relationships among energy literacy, the adoption of energy-efficient technologies, agricultural productivity, and rural economic development in the agricultural sector of rural Vietnam. All constructs were operationalized using measurement items adapted from established and relevant studies in the literature. Responses were collected using a five-point Likert scale, ranging from 1 = Strongly disagree to 5 = Strongly agree.

Energy Literacy (EL) was measured using four items adapted from Kellberg et al. (2025) and informed by the systematic literature review of Santillán and Cedano (2023), capturing respondents' knowledge, awareness, and understanding of energy use and energy-related issues. Adoption of Energy-Efficient Technologies (AEET) was assessed using four items adapted from Daraz et al. (2025) and Xu et al. (2026), reflecting the extent to which farmers adopt and use energy-efficient technologies in agricultural activities. Agricultural Productivity (AP) was measured using five items adapted from Chen (2025), focusing on improvements in agricultural output and the efficiency of agricultural resource use. Rural Economic Development (RED) was measured using five items adapted from Chen and Xing (2025), capturing improvements in economic conditions and development associated with agricultural and rural economic activities. All measurement items were slightly contextualized to reflect the characteristics of rural agricultural production and energy use in Vietnam.

The questionnaire was originally developed in English and subsequently translated into Vietnamese to ensure that the items were understandable and appropriate for local farmers and agricultural producers. A back-translation procedure was applied to ensure semantic equivalence between the English and Vietnamese versions. The Vietnamese questionnaire was also reviewed to ensure the clarity, relevance, and contextual appropriateness of the measurement items for respondents involved in agricultural production.

3.2 Data Collection and Analysis

The data were collected through a structured questionnaire administered to farmers and agricultural producers in rural areas of Vietnam. Both online and offline methods were employed to reach respondents with different agricultural backgrounds and levels of experience. The sampling strategy targeted individuals directly involved in agricultural production and familiar with energy use, energy-efficient technologies, and agricultural production practices.

The final sample of 312 valid respondents captured diversity in demographic and agricultural member characteristics, including gender, age (below 30, 31–40, 41–50, and above 50 years), education level (high school or below, college/bachelor's degree, and postgraduate), and farming experience (≤5, 6–10, 11–20, and >20 years). The respondents represented different types of agricultural production, including crop production, livestock, aquaculture, and mixed farming, as well as different levels of participation in energy education or training. The sample also included farmers with and without experience in adopting energy-efficient technologies, which is relevant to evaluating how energy literacy can be translated into more efficient agricultural practices.

Regarding economic conditions, respondents were categorized by annual agricultural income, ranging from less than USD 2,000 to more than USD 5,000. These characteristics allowed the study to capture variation in farmers' energy-related knowledge, exposure to energy education, technology adoption, agricultural experience, and economic conditions. Overall, the sample provides an appropriate basis for evaluating the role of energy education in developing energy literacy, enhancing agricultural productivity, and contributing to rural economic efficiency. Data analysis was conducted using Partial Least Squares Structural Equation Modeling (PLS-SEM) with SmartPLS.

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4. RESULTS AND DISCUSSIONS

4.1 Demographics of Respondents

Table 1 presents the demographic characteristics of the 312 respondents included in the study. The sample was predominantly male, accounting for 76.3%, while female respondents represented 23.7%. Regarding age, the largest proportion of respondents was between 41 and 50 years old, accounting for 36.2%, followed by those aged 31–40 years and above 50 years, both representing 26.3%. Respondents under 30 years old accounted for 11.2%. In terms of education, 54.5% of respondents had a high school education or below, while 35.9% held a college or bachelor's degree and 9.6% had postgraduate qualifications. Regarding farming experience, the largest group had 11–20 years of experience, accounting for 33.0%, followed by those with 6–10 years at 28.2%, more than 20 years at 19.2%, and 5 years or less at 19.6%.

Table 1: Demographics of Respondents

Demographics		**Frequency**	**Percent (%)**
Gender	Male	238	76.3
	Female	74	23.7
Age	< 30 years	35	11.2
	31–40 years	82	26.3
	41–50 years	113	36.2
	> 50 years	82	26.3
Educational Level	High school or below	170	54.5
	College/Bachelor's degree	112	35.9
	Postgraduate	30	9.6
Farming experience	≤ 5 years	61	19.6
	6–10 years	88	28.2
	11–20 years	103	33.0
	> 20 years	60	19.2
Type of agricultural production	Crop production	145	46.5
	Livestock	58	18.6
	Aquaculture	34	10.9
	Mixed farming	75	24.0
Energy-related education/training	Yes	126	40.4
	No	186	59.6
Energy-efficient technology adoption	Yes	139	44.6
	No	173	55.4
Annual agricultural income	< 2000 USD	105	33.7
	2000 – 3000 USD	89	28.5
	3000 – 5000 USD	74	23.7
	> 5000 USD	44	14.1
Total		**312**	**100**

Regarding agricultural production, crop production was the most common type, accounting for 46.5% of respondents, followed by mixed farming at 24.0%, livestock production at 18.6%, and aquaculture at 10.9%. With respect to energy education or training, 40.4% of respondents had received energy related education or training, whereas 59.6% had not. In terms of energy efficient technology adoption, 44.6% of respondents reported having adopted energy efficient technologies, while 55.4% had not. Regarding annual agricultural income, 33.7% of respondents reported an annual income below USD 2,000, followed by 28.5% with USD 2,000–3,000, 23.7% with USD 3,000–5,000, and 14.1% with more than USD 5,000.

The sample consists mainly of experienced rural farmers, with a substantial proportion having 11–20 years of farming experience. More than half of the respondents had not received energy education or training, and a similar proportion had not adopted energy efficient technologies. The demographic profile provides a relevant context for examining the role of Energy Literacy and energy education in technology adoption and Agricultural Productivity, as well as their implications for Rural Economic Development

4.2 Scale Reliability and Validity Assessment

Table 2 presents the results of the construct reliability and convergent validity assessment for Adoption of Energy-Efficient Technologies (AEET), Agricultural Productivity (AP), Energy Literacy (EL), and Rural Economic Development (RED). The results indicate that all constructs demonstrate satisfactory internal consistency reliability. Cronbach's alpha values range from 0.914 to 0.957, which are substantially above the recommended threshold of 0.70. Specifically, the Cronbach's alpha coefficients are 0.946 for AEET, 0.940 for AP, 0.914 for EL, and 0.957 for RED. These results indicate that the measurement items within each construct are highly consistent in measuring their respective underlying concepts.

Table 2: Construct Reliability and Validity

	Cronbach's Alpha	**rho_A**	**Composite**	**AVE**

International Journal of Academic Management Science Research (IJAMSR)
ISSN: 2643-900X
Vol. 10 Issue 8 August - 2026, Pages: 65-79

			Reliability	
AEET	0.946	0.953	0.961	0.861
AP	0.940	0.941	0.955	0.808
EL	0.914	0.916	0.939	0.795
RED	0.957	0.959	0.967	0.853

Source: Data analysis by SmartPLS3

The rho_A and composite reliability (CR) results further support the reliability of the measurement scales. The rho_A values range from 0.916 to 0.959, while the composite reliability values range from 0.939 to 0.967, all exceeding the commonly accepted threshold of 0.70. Specifically, AEET records a rho_A of 0.953 and CR of 0.961, AP records 0.941 and 0.955, EL records 0.916 and 0.939, and RED records 0.959 and 0.967, respectively. These findings provide further evidence that the indicators associated with each construct exhibit adequate internal consistency and reliably represent their respective latent variables.

Convergent validity was assessed using the Average Variance Extracted (AVE). As shown in Table 2, the AVE values range from 0.795 to 0.861, exceeding the recommended minimum threshold of 0.50 for all constructs. AEET has an AVE of 0.861, followed by RED at 0.853, AP at 0.808, and EL at 0.795. These findings indicate that each construct explains a substantial proportion of the variance in its corresponding indicators. Therefore, the results provide strong evidence of convergent validity and confirm that the measurement items adequately converge on their intended constructs.

Table 3: Fornell-Larcker Criterion and Heterotrait-Monotrait Ratio (HTMT)

	Fornell-Larcker Criterion				Heterotrait-Monotrait Ratio (HTMT)			
	AEET	AP	EL	RED	AEET	AP	EL	RED
AEET	0.928							
AP	0.500	0.899			0.527			
EL	0.614	0.506	0.892		0.654	0.543		
RED	0.426	0.479	0.536	0.924	0.444	0.501	0.570	

Source: Data analysis by SmartPLS3

Table 3 further evaluates discriminant validity using the Fornell–Larcker criterion. The square roots of the AVE values, presented on the diagonal of the matrix, are 0.928 for AEET, 0.899 for AP, 0.892 for EL, and 0.924 for RED. These values are greater than the correlations between each construct and the other constructs in the model. For example, the square root of the AVE for EL is 0.892, which is higher than its correlations with AEET (0.614), AP (0.506), and RED (0.536). Similarly, the diagonal values for AEET, AP, and RED are greater than their respective inter-construct correlations. Thus, the Fornell–Larcker criterion is satisfied, indicating that each construct is empirically distinct from the other constructs in the research model.

In addition to the Fornell–Larcker criterion, the Heterotrait–Monotrait ratio (HTMT) was examined to provide further evidence of discriminant validity. The HTMT values range from 0.444 to 0.654, with the highest value observed between AEET and EL (HTMT = 0.654). All HTMT values are below the conservative threshold of 0.85 and substantially below the more liberal threshold of 0.90. This indicates that there are no serious discriminant validity concerns among the constructs. Although AEET and EL exhibit the strongest association, their HTMT value remains sufficiently below the recommended threshold, confirming that energy literacy and the adoption of energy-efficient technologies represent empirically distinguishable constructs.

4.3 Model Assessment and Discussion

The structural equation modelling results presented in Table 4 indicate that all proposed direct and mediating relationships are statistically significant, with all p values below 0.001. The findings therefore provide empirical support for the proposed relationships among Energy Literacy, the Adoption of Energy Efficient Technologies, Agricultural Productivity, and Rural Economic Development.

Regarding the explanatory power of the structural model, the adjusted R^2 values indicate that the model explains 37.4% of the variance in the Adoption of Energy Efficient Technologies, 30.9% of the variance in Agricultural Productivity, and 20.7% of the variance in Rural Economic Development. These results demonstrate that the proposed model provides meaningful explanatory power for the three endogenous constructs. In particular, the relatively higher adjusted R^2 for the Adoption of Energy Efficient Technologies suggests that Energy Literacy has substantial explanatory relevance for farmers' technology adoption decisions.

Table 4: Structural Equation Modelling Results Estimates

Paths	Original Sample (O)	S.D (STDEV)	T Statistics (|O/STDEV|)	P Values
AEET -> AP	0.304	0.305	0.060	5.092
AP -> RED	0.479	0.476	0.053	8.994
EL -> AEET	0.614	0.611	0.039	15.809
EL -> AP	0.320	0.318	0.069	4.622

EL -> AEET -> AP	0.186	0.186	0.039	4.826
AEET -> AP -> RED	0.145	0.145	0.032	4.483
EL -> AEET -> AP -> RED	0.089	0.089	0.021	4.203
EL -> AP -> RED	0.153	0.152	0.041	3.753
Adjusted R^2: AEET = 0.374; AP = 0.309; RED = 0.207				

Source: Data analysis by SmartPLS3

First, Energy Literacy has a positive and significant effect on the Adoption of Energy Efficient Technologies (β = 0.614, t = 15.809, $p < 0.001$), supporting H1. This is the strongest direct relationship identified in the structural model, indicating that farmers with higher levels of energy literacy are more likely to adopt energy efficient technologies. The finding suggests that knowledge and awareness of energy use can enhance farmers' ability to recognize the benefits, suitability, and potential economic value of technological alternatives. This result is consistent with Kellberg et al. (2025), who emphasize the importance of prior energy knowledge and learning experiences in the development of energy literacy. It is also consistent with Santillán and Cedano (2023), who identify knowledge and awareness as important components of energy literacy. Therefore, strengthening farmers' energy related knowledge may contribute to greater acceptance and adoption of energy efficient technologies in agricultural production.

Second, the Adoption of Energy Efficient Technologies has a positive and significant effect on Agricultural Productivity (β = 0.304, t = 5.092, $p < 0.001$), supporting H2. This finding indicates that farmers who adopt energy efficient technologies tend to achieve higher levels of agricultural productivity. The positive relationship can be explained by the ability of such technologies to improve the efficiency of energy and other production inputs, reduce operational inefficiencies, and support more effective production practices. Daraz et al. (2025) demonstrate that energy efficient smart irrigation technologies can improve water and energy efficiency in agricultural production. Similarly, Xu et al. (2026) emphasize that agricultural technology adoption can enhance production efficiency through improved resource management and more effective farming practices. The present finding therefore reinforces the importance of technological adoption in improving agricultural production outcomes.

The results further demonstrate that Energy Literacy has a positive and significant effect on Agricultural Productivity (β = 0.320, t = 4.622, $p < 0.001$), supporting H3. This finding indicates that energy literacy contributes to agricultural productivity beyond its influence through technology adoption. Farmers with higher levels of energy literacy may be better able to understand energy consumption patterns, identify inefficient resource use, and make more appropriate production decisions. In this regard, energy literacy can strengthen farmers' capacity to manage production resources more effectively and integrate energy considerations into agricultural decision making. The finding extends the literature on energy literacy by suggesting that its benefits may extend beyond energy related behavior to broader agricultural performance outcomes.

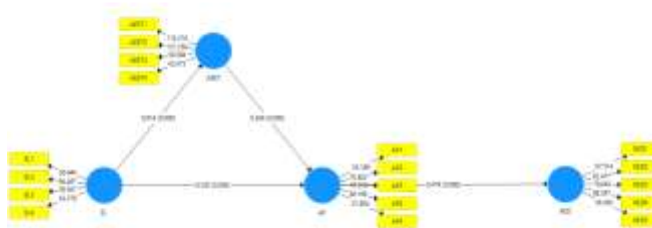

Figure 2: PLS Bootstrapping Model

Source: Data analysis by SmartPLS3

Regarding the mediating relationship, the indirect effect of Energy Literacy on Agricultural Productivity through the Adoption of Energy Efficient Technologies is positive and statistically significant (β = 0.186, t = 4.826, $p < 0.001$), supporting H4. This result confirms that the Adoption of Energy Efficient Technologies serves as an important mechanism through which Energy Literacy contributes to Agricultural Productivity. Farmers with greater energy literacy are more capable of recognizing and evaluating appropriate energy efficient technologies, while the adoption of these technologies allows their knowledge and awareness to be translated into more efficient production practices. Since the direct effect of Energy Literacy on Agricultural Productivity remains significant (β = 0.320, $p < 0.001$), the mediation is partial rather than full. This indicates that Energy Literacy affects Agricultural Productivity through both a direct pathway and an indirect pathway through technology adoption.

Furthermore, Agricultural Productivity has a positive and significant effect on Rural Economic Development (β = 0.479, t = 8.994, $p < 0.001$), supporting H5. This is the strongest direct predictor of Rural Economic Development in the proposed model, highlighting the important role of agricultural performance in strengthening rural economic conditions. Higher agricultural productivity can increase agricultural output and household income while stimulating employment, investment, consumption, and supporting economic activities within rural communities. This finding is consistent with Chen (2025), who emphasizes the contribution of modern agricultural technologies to agricultural productivity and land use efficiency. It also aligns with Chen and Xing (2025), who highlight the importance of technological advancement, innovation, and improved economic efficiency in supporting high quality economic development. Therefore, improvements in agricultural productivity can provide an important economic foundation for rural development.

International Journal of Academic Management Science Research (IJAMSR)
ISSN: 2643-900X
Vol. 10 Issue 8 August - 2026, Pages: 65-79

Furthermore, Agricultural Productivity significantly mediates the positive relationship between the Adoption of Energy Efficient Technologies and Rural Economic Development ($\beta = 0.145$, $t = 4.483$, $p < 0.001$), supporting H6. This finding indicates that the adoption of energy efficient technologies contributes to Rural Economic Development through improvements in Agricultural Productivity. When farmers adopt energy efficient technologies, improved resource utilization and production efficiency can enhance agricultural output and economic returns, which subsequently contribute to broader economic activities and development in rural communities. This result is consistent with Daraz et al. (2025), who highlight the contribution of energy efficient technologies to agricultural resource use efficiency, and Xu et al. (2026), who emphasize the role of agricultural technology adoption in improving production efficiency. Therefore, the findings confirm that Agricultural Productivity serves as an important mediating mechanism linking the Adoption of Energy Efficient Technologies with Rural Economic Development.

5. IMPLICATIONS AND CONCLUSION

This study brings several theoretical contributions to the literature on sustainable agriculture and energy management. It extends Human Capital Theory by positioning energy literacy as a form of productive human capital that enhances farmers' knowledge, decision-making capabilities, and resource-use efficiency. Second, drawing on the Technology Acceptance Model, the study demonstrates that energy literacy facilitates the adoption of energy-efficient agricultural technologies, which subsequently contributes to higher agricultural productivity. Third, the findings provide empirical evidence for the mediating role of technology adoption and agricultural productivity in linking energy literacy with broader rural economic outcomes. Overall, the study integrates human capital, technology adoption, and agricultural productivity perspectives into a unified framework, thereby providing a clearer theoretical explanation of how energy-related knowledge can contribute to sustainable agricultural and rural economic development.

The findings of this study suggest that improving rural economic development in Vietnam requires more than simply increasing farmers' access to modern agricultural technologies. The strong positive relationship between energy literacy and the adoption of energy-efficient technologies ($\beta = 0.614$) indicates that farmers' knowledge, awareness, and ability to make informed energy-related decisions are fundamental to the effective use of technological innovations. In the Vietnamese agricultural context, where many farming households increasingly depend on electricity, fuel, irrigation pumps, machinery, refrigeration, drying systems, and other energy-intensive inputs, strengthening farmers' capacity to understand and manage energy should therefore become an important component of agricultural modernization policies.

A particularly important implication is that energy literacy should be incorporated into the existing agricultural extension and farmer-training system in Vietnam. Energy education should not be limited to general information about energy conservation or renewable energy, but should be closely connected with the everyday production decisions that farmers make. Farmers need to understand how much energy is consumed during irrigation, land preparation, harvesting, drying, storage, and transportation; how inefficient equipment increases production costs; and how alternative technologies can improve both energy efficiency and economic returns. Training that enables farmers to compare fuel consumption, estimate operating costs, identify unnecessary energy losses, and evaluate the long-term benefits of technological investments would make energy literacy directly relevant to farm management. In this way, energy education can function as a form of practical human capital that improves the quality of farmers' production decisions rather than simply increasing their theoretical knowledge.

The findings also indicate that technology adoption should be accompanied by adequate knowledge and technical support. The positive effect of energy literacy on technology adoption suggests that farmers are more likely to use energy-efficient technologies when they understand their usefulness, suitability, and economic value. Consequently, agricultural modernization programs in Vietnam should move beyond the simple provision or subsidization of equipment. Technologies such as solar-powered irrigation systems, efficient water pumps, precision irrigation, automated monitoring systems, and energy-efficient machinery are more likely to generate meaningful productivity gains when farmers understand how to select, operate, maintain, and evaluate them. Demonstration farms, practical field training, and locally accessible technical assistance could therefore be particularly valuable, allowing farmers to observe the actual differences in energy consumption, operating costs, water use, and productivity under Vietnamese farming conditions. This implication is especially important because Vietnam's rural agricultural sector is highly diverse. Energy requirements and technological priorities differ considerably across production systems and regions. Crop farmers may benefit primarily from efficient irrigation, pumping, mechanization, drying, and storage technologies, while livestock producers may have greater demand for efficient cooling, ventilation, feeding, and waste-management systems. In aquaculture, electricity-efficient pumping and aeration technologies can be particularly important. Likewise, the agricultural conditions of the Mekong Delta, Central Highlands, Red River Delta, and other regions create different energy and resource-management challenges. Energy education and technology-support programs should therefore be adapted to local production conditions rather than applying a uniform model across rural Vietnam. Such contextualization would increase the practical relevance of energy education and improve the likelihood that farmers adopt technologies that are technically appropriate and economically beneficial.

The results further highlight the importance of agricultural cooperatives and local institutions in translating energy knowledge into practice. For many smallholder farmers, the challenge is not only a lack of willingness to adopt new technologies but also limited financial resources, technical knowledge, and access to reliable information. Cooperatives can help overcome these constraints by facilitating collective training, technology demonstrations, shared machinery services, and group investment in renewable-energy or energy-efficient infrastructure. Collective adoption can also reduce investment costs and provide farmers with greater access to maintenance and technical support. In this respect, cooperatives can become an important bridge connecting government policies, technological providers, agricultural extension services, and individual farming households.

The significant positive effect of energy-efficient technology adoption on agricultural productivity ($\beta = 0.304$) also suggests that technology policies should be evaluated according to their actual contribution to production efficiency rather than simply the number of technologies adopted. In practice, the success of agricultural modernization should be reflected in whether farmers can produce greater output with less energy, water, fuel, and other production inputs. Agricultural development programs could therefore pay greater attention to indicators such as energy consumption per unit of agricultural output, fuel use per hectare, irrigation efficiency, production-cost savings, and productivity improvements following technology adoption. This would encourage a shift from technology adoption as an end in itself toward technology as a means of achieving more efficient and sustainable agricultural production.

More broadly, the finding that agricultural productivity has the strongest direct relationship with rural economic development in the model ($\beta = 0.479$) emphasizes that energy-related interventions ultimately need to generate tangible economic benefits for rural households. Energy literacy becomes particularly valuable when it helps farmers reduce unnecessary production costs, improve resource allocation, increase output, and strengthen farm profitability. For Vietnamese policymakers, this means that energy education, agricultural technology programs, rural infrastructure development, and farmer-support policies should be designed as interconnected components rather than isolated interventions. Improving farmers' energy-related capabilities can support better technology adoption; better technology adoption can improve productivity; and higher productivity can strengthen household income and wider rural economic activity.

Finally, these findings provide a broader policy perspective for Vietnam's transition toward greener and more resilient agriculture. Energy efficiency should not be regarded solely as an environmental objective. In rural agricultural communities, it is also closely connected to production costs, competitiveness, income generation, and long-term economic resilience. Strengthening energy literacy can therefore serve both environmental and economic objectives by enabling farmers to make better-informed decisions about energy use and technological investment. A rural development strategy that combines practical energy education, STEM-oriented learning, appropriate technological solutions, agricultural extension, and locally responsive institutional support could help Vietnamese farmers move toward a production model in which higher productivity is achieved not simply through greater resource consumption, but through smarter, more efficient, and more sustainable use of available resources.

This study has several limitations that should be considered when interpreting its findings. Firstly, the cross-sectional design and self-reported data limit the ability to establish causal relationships and may introduce common method bias. Future research could employ longitudinal designs and objective measures of energy consumption, technology adoption, and agricultural productivity to provide stronger causal evidence. Secondly, the study focuses on rural Vietnam, which may limit the generalizability of the findings to other countries or agricultural contexts. Comparative studies across regions and countries could provide further insight into the applicability of the proposed model. Future research could extend the model by incorporating factors such as access to finance, government support, digital literacy, environmental awareness, and energy education as additional explanatory or moderating variables. Such extensions would provide a more comprehensive understanding of how energy literacy can contribute to sustainable agricultural and rural economic development.

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None

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