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A Case Study of Korean Farmer's Voluntary Participation in Greenhouse Gas Reduction Programs: Based on In-depth Interview

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ABSTRACT

Amidst evident climate impacts on the Korean peninsula, the Korean government targets carbon neutrality by 2050, extending this commitment to agriculture, aiming to mitigate climate-related impacts and damages. As agriculture's role evolves from emissions source to carbon sink, its responsible role gains importance. Developing low-carbon agricultural methods and technologies becomes crucial. The Korean government backs these efforts through programs for greenhouse gas reduction facilities, energy-saving technologies, and renewable energy installations. Programs incentivizing low-carbon farming practices are also in place. Using a case study method, this paper examines government and agriculture sector efforts toward carbon neutrality, stressing ongoing technique advancements for climate mitigation. A case study on farmers engaged in greenhouse gas reduction initiatives reveals government-backed programs' pivotal role in guiding farmers towards low-carbon practices. Farmers' voluntary participation, incentivized by government policies, coupled with emission-reducing facilities and compensation, yields economic, environmental, and social benefits. Nonetheless, further efforts are needed to address policy barriers, lower technology adoption thresholds, and tailor target strategies for effective participation. Strengthening incentives throughout the agri-food value chain is also crucial. This paper emphasizes continuous policy enhancement and technology promotion for a successful shift to low-carbon agriculture and meeting national climate goals.

Keywords: carbon neutrality, low-carbon agriculture, carbon reduction technology, energy-saving technology

INTRODUCTION

It is widely acknowledged that greenhouse gases (GHG) from the anthropogenic sources including farming, is the main cause of climate change (IPCC 2023; Fahey *et al*., 2017). Given the escalating crisis of climate change, combatting its effects has evolved into a policy challenge of global significance. Among the sectors affected, agriculture stands as one of the most exposed and vulnerable sectors in the face of climate change. This is particularly problematic for farmers, who encounter heightened challenges and costs in their pursuit of crop and livestock production. The Korean peninsula is experiencing a discernible shift as the effects of climate change become more pronounced. Altered weather patterns, characterized by escalating average temperatures and an increase in the frequency and intensity of extreme weather events like heavy rainfall-driven typhoons, heatwaves, droughts, and floods, imperil Korean farmers. This is more evident in the increasing incidence of agricultural disasters attributable to climate change. For example, data from the Rural Development Administration (RDA) reveals a substantial surge in crop insurance payouts due to natural disasters in recent years.

From 2015 to 2018, payments to rice farmers increased by a staggering 19.7 times, rising from KRW580 million (equivalent to US$0.44 million) to KRW11.43 billion (equivalent to US$8.69 million). Similarly, payments for field crops surged by 24.6 times, escalating from KRW470 million (equivalent to US$0.36 million) to KRW11.56 billion (equivalent to US$8.80 million) during the same period. In response, the Korean government is pursuing an array of policies aimed at curbing GHG emissions emanating from the agricultural sector. The objective is to mitigate the adverse effects and damages caused by climate change, ultimately enhancing the climate resilience of the agricultural domain.

To achieve sustainable agricultural development, it is imperative for the agricultural sector to minimize the utilization of energy and chemical materials, recognized as sources of greenhouse gas (GHG) emissions. By doing so, the sector can effectively decrease environmental burden and mitigate GHG emissions (Holka *et al*., 2022). In the pursuit of addressing climate change, the Korean government took a decisive step in 2020 by announcing its commitment to achieve '2050 carbon neutrality'. Subsequently, with a heightened focus on enhanced Nationally Determined Contribution (NDC) targets, the government formulated comprehensive objectives for carbon neutrality, along with corresponding implementation strategies and action plans at both national and industry levels in 2021. Of notable significance, the government has established ambitious goals to curtail GHG emissions originating from the agricultural sector by 30.9% by the year 2050, compared to 2018 levels. This commitment is underpinned by the adoption of targeted strategies and operational plans for carbon reduction (MAFTA, 2021; Kim *et al*., 2022). In the agricultural sector, there is a concerted effort to facilitate a transition towards a low-carbon structure. This is being achieved through the widespread adoption of smart farming practices, the development and dissemination of low-carbon production technologies including low-carbon agricultural machinery and facilities. Moreover, in the livestock sector, there is a highlighted focus on the development of low-methane feed and the expansion of livestock manure utilization. To achieve these objectives, specific plans include the expansion of smart greenhouses and smart livestock facilities from 7,076 hectares in 2022 to 10,000 hectares by 2027. Additionally, there is a target to achieve a 30% distribution of methane-reducing feed by the year 2030 (MOE, 2023).

Through these initiatives, the Korean government aims to diminish the influx of livestock manure into arable land, enhance water management practices within rice paddy fields, and reduce the application of nitrogenous fertilizers. Within the livestock segment, a paramount objective is to transform livestock manure from a waste to a valuable resource such as energy[1], while concurrently regulating feed protein composition through the development of low-methane feed formulations. These endeavors collectively contribute to a reduction in GHG emissions, propelled by the diffusion of innovative smart and precision agriculture technologies. Moreover, in the domain of agricultural energy, the government is actively engaged in the expansion of energy-efficient facilities and the promotion of renewable energy infrastructure. Furthermore, the government is dedicated to the transition of agricultural machinery, currently reliant on fossil fuels, towards environmentally friendly alternatives like electricity and hydrogen.

As of 2018, the agricultural sector's greenhouse gas (GHG) emissions in Korea accounted for approximately 2.9% of the total emissions, and this share is on a declining trend (MOE, 2020). GHG emissions from the agricultural sector increased from 21.0 million tons of carbon dioxide equivalents (CO_2eq.) in 1990 to 21.2 million tons CO_2eq. in 2018, showing a slight increase in comparison to emissions from other industries. Meanwhile, the total GHG emissions surged significantly from 292.2 million tons CO_2eq. to 727.6 million tons CO_2eq. during the same period. These emissions in the agricultural non-energy sector stem from both crop and livestock activities. The primary types of GHG emissions are methane (CH_4) and nitrous oxide (N_2O), with methane and nitrous oxide emissions linked to rice cultivation and livestock manure management processes. Methane emissions are also associated with the intestinal fermentation of ruminants like cattle. Additionally, the emissions in the agricultural energy sector are associated with the use of fossil fuels (MOE, 2020).

As previously stated, the Korean agricultural sector has exhibited a passive stance in response to

[1] Instead of the traditional linear economy, which is based on single-use resource consumption, a circular economy focuses on recycling waste materials back into resources, aiming to enhance environmental sustainability.

climate change since agricultural sector has generated significantly lower greenhouse gas (GHG) emissions compared to other industries, and the sector's overall capacity to reduce GHG emissions has been lacking. Moreover, its connection to national food security has rendered its approach to climate change mitigation somewhat reserved. However, considering the imperative to achieve national carbon neutrality, the Korean agricultural sector has been assigned more robust reduction targets than ever before. Consequently, a more proactive role in both absorbing and diminishing GHG emissions is imperative.

Furthermore, the government's initiative toward carbon neutrality should be viewed as an opportunity rather than a crisis. Consequently, the agricultural sector urgently needs to transition from prevalent high-input agricultural practices to a low-input, low-carbon agricultural system. Additionally, considering Korea's participation in the International Methane Pledge (IMP) in 2021, further efforts are necessary to mitigate methane emissions in the agriculture and livestock sector, which constitutes 43.6% of domestic methane emissions. Hence, it is vital to practice environmentally friendly and low-carbon agriculture that contributes to GHG reduction and energy efficiency. Above all, investments in R&D are particularly crucial to spread clean technologies within agricultural contexts. Clean technology R&D in the agricultural sector has been consistently undertaken under the auspices of the Rural Development Administration (RDA) under the Ministry of Agriculture, Food and Rural Affairs (MAFRA). In alignment with this, diverse government support programs are being actively promoted to facilitate the provision of energy-efficient facilities and renewable energy infrastructure.

However, the carbon reduction technologies in the agricultural sector require higher unit costs compared to conventional methods, posing a challenge that without incentives to adopt these measures, there is no guarantee that the government's goals for dissemination and reduction will be achieved. Thus, the government is considering various support policies that compensate for reduced greenhouse gas emissions or promote production methods and practices that lead to emissions reduction. However, the actual effectiveness of these policies needs to be analyzed not only from an economic perspective but also from various angles. Especially in the field of agriculture, studies on the effectiveness of energy-saving and renewable energy-related measures have often been limited to experiments in controlled environments (Kwon *et al*., 2013; Lee *et al*., 2016; Kim *et al*., 2017), and only a few recent studies (Kim *et al*., 2013 ; Kang *et al*., 2015) have extended their analysis to the application of these technologies on actual farms and their impact on operational performance. Nonetheless, most studies have focused on the effects of energy-saving and renewable energy technology adoption, primarily in terms of heating cost reduction, productivity enhancement, and greenhouse gas emission reduction. However, to comprehensively evaluate individual farm experiences from diverse social aspects, there is a need to assess these effects through the lens of various factors.

In light of this, this study aims to analyze the effects of the government's greenhouse gas reduction initiatives, particularly energy-saving and renewable energy technology support programs, from various perspectives through a study of farm cases. Additionally, the study seeks to address the practical outcomes and challenges faced by farmers in adopting such technologies in the agricultural sector. For this purpose, the study conducted a case study on farmers who voluntarily participated in the government's agricultural sector greenhouse gas reduction support and compensation programs. Through this, the economic, environmental, and social impacts of these government-led programs were analyzed. Additionally, by identifying the challenges that farmers face during program participation, the study aimed to derive policy suggestions for the enhancement of government voluntary programs and the promotion of low-carbon agriculture. This study provides valuable insights into voluntary carbon reduction policies that can effectively encourage behavioral changes among farmers in a more sustainable manner. The remainder of this study is structured as follows: Section 2 reviews voluntary carbon reduction programs in the Korean agricultural sector. Section 3 describes the case study methodology and results and addresses their implications. Finally, Section 4 concludes with policy recommendations.

MAJOR POLICIES TO REDUCE GHG EMISSIONS IN AGRICULTURAL SECTOR

The Korean government has undertaken proactive measures to advance the cause of low-carbon agriculture, aiming to effectively combat climate change while fostering voluntary engagement from farmers in carbon reduction activities. A primary focal point in these efforts is the enhancement of on-farm energy efficiency, which stands as one of the most widely targeted strategies for mitigating climate change. Notably, the Korean government places paramount importance on the expansion of low-carbon agricultural technologies, including energy-saving and renewable technologies, as a pivotal strategy to fulfill its emission reduction commitments stipulated by the '2050 Carbon Neutrality' goal. The pursuit of low-carbon agricultural technology dissemination primarily revolves around two distinct policy approaches: (1) facility support programs that facilitate the widespread adoption of greenhouse gas (GHG) reduction technologies; and (2) compensation programs that incentivize farmers to transition towards low-carbon agriculture. These compensation programs operate through direct compensation mechanisms and market-based incentives, collectively aimed at motivating and rewarding farmers for their active involvement in GHG reduction efforts through the adoption of low-carbon agricultural practices.

The GHG reduction facility support initiatives consist of various programs such as the 'Livestock Manure Resource Conversion Program,' the 'Forage Production Base Expansion Program,' and the 'Agricultural Energy Use Efficiency Improvement Program.' Among these programs, the 'Agricultural Energy Use Efficiency Improvement Program' stands as a prominent policy established by MAFRA. Its primary goal is to encourage farmers to voluntarily embrace GHG reduction technologies through a combination of government subsidies, loans, and personal investments. This program primarily targets sectors that demand high energy consumption, namely horticulture and livestock farming. The program extends its support to a range of energy-efficient facilities, including multi-layer insulation curtains, automated insulation covers, circulating water film cultivation systems, heat recovery ventilation devices, exhausted heat recovery units, as well as air heating and cooling installations. Additionally, the program also sponsors the adoption of new and renewable energy facilities such as geothermal heating and cooling systems, waste heat reutilization setups, and wood pallet heaters, among others.

When it comes to compensation programs, three major initiatives have been established. These include the 'Voluntary GHG Reduction Program' and the 'Low-carbon Agricultural and Livestock Product Certification System,' which have been in promotion since 2012. Additionally, since 2017, the 'External Program of the Emission Trading System (Korean ETS)' has been supervised by the Ministry of Environment (MOE) and operates as a carbon offset mechanism within the agricultural sector. Participation in these compensation programs is open to a variety of agricultural entities, such as farmers, agricultural corporations, and agricultural cooperatives. Eligibility for participation requires the adoption of carbon reduction technologies and methods that have received official government approval as a prerequisite.

Through the 'Voluntary GHG Reduction Program,' the government aims to encourage farmers to engage in voluntary carbon reduction activities. This is achieved by offering both indirect support for consulting and verification expenses, as well as direct financial incentives (KRW 10,000 per ton) for certified reductions. In the context of the 'Low-carbon Agricultural and Livestock Certification System,' the government provides comprehensive assistance throughout the certification process, covering consultation, verification costs, and distribution. As a benefit for consumers, those who purchase certified low-carbon agricultural and livestock products, though slightly pricier than non-certified counterparts, using affiliated Eco-Money cards (e.g., green cards) receive a cash reward (green point) equivalent to 15% of the purchase amount. This cash reward, supported by government subsidies, incentivizes consumers to opt for certified low-carbon products and accelerates their adoption. In the case of 'The External Program of the Korean ETS,' a market-based approach is employed. This program enables farmers to trade their carbon reductions with emission permit allocation companies within the scope of the Korean ETS. The government facilitates the initial consulting and preparation processes required for program participation. Consequently, farmers can generate additional income by participating in the carbon market within the Korea Exchange (KRX) system. In these various ways, the Korean government has dedicated significant efforts to establish diverse voluntary mechanisms for carbon reduction (Jeong *et al*., 2018).

CASE STUDY

Methodology

This study employs a case study methodology, a form of qualitative descriptive research, supplemented by quantitative research. The primary purpose of this study is to identify the economic, environmental, and societal consequences arising from voluntary government-initiated programs intended for reducing greenhouse gas (GHG) emissions within the Korean agricultural sector. To fulfill this purpose, the study primarily investigates the principal impacts associated with each category of GHG reduction programs and the challenges faced by participating farmers through individualized case studies. Drawing insights from the findings, the study presents implications and proposes potential policy directions to advance the adoption of low-carbon agriculture throughout Korea. The case studies are grounded in comprehensive interviews conducted with farmers and substantiated by official GHG reduction data provided by the implementing entity (Korea Agricultural Technology Promotion Agency under the Ministry of Agriculture, Food and Rural Affairs), along with energy consumption data sourced from the farmers.

The composition of the in-depth interview questionnaire employed a systematic approach of categorization and detailed content arrangement to align with the research subject and objectives. The interview guide comprises four distinct sections (refer to Table 1). The initial segment delves into the contextual background and incentives that prompted farmers to embrace new technologies. The subsequent section evaluates farmers' outcomes across economic, environmental, and social dimensions. The third part concentrates on the challenges and constraints assessed by farmers, leveraging these insights to propose feasible technological and economical avenues for carbon emissions reduction. The final section seeks their perspective on the GHG reduction programs, shedding light on their general attitudes and assessments of these initiatives. The in-depth interview survey was carried out based on the preliminary survey questionnaire (as depicted in Table 1) administered to farmers. In instances warranting further exploration, supplementary inquiries were conducted via written communication and verbal exchanges through email and telephone.

Table 1. Structure of interview guide

Section	Guiding ideas
Background and purpose	-What is the background and purpose of technology adoption and GHG reduction program participation?
Performance	-What are the economic, environmental, and social effects after adopting new technologies and participating in additional compensation programs? -What is the most significant achievement?
Difficulties and limitations	-What are the difficulties and obstacles that you have faced in the process of adopting technology and participating in the program, and which areas of the programs need further improvement and support?
Overall values	-Do you think the government’s support on technology diffusion and compensation policies such as GHG reduction programs are effective for the spread of low-carbon, low-input agricultural practices?

Selection of case study subjects

Due to limitations inherent in the case study approach, this study did not encompass all farmers participating in GHG reduction programs. Consequently, three farmers engaged in energy-intensive horticulture and floriculture within greenhouses were chosen as the subjects for the case study based on recommendations from the implementing agency. These selected farmers are actively involved in the respective GHG reduction programs and have been deemed suitable for in-depth interviews due to their heightened awareness and extensive experience with the program (refer to Table 2).

Table 2. The types of programs, applied technology, crops, and farm on the case studies

Type of program	Applied technology and method	Crops	Type of farm
Case 1: Voluntary GHG reduction program	Geothermal heat pump system	Paprika	Individual

Case 2: Low-carbon agricultural and livestock product certification system	Multi-layer insulation curtain, no-tillage, self-manufacturing liquid fertilizer, circulation agriculture (adopted 4 low-carbon methods)	Cherry Tomato	Agricultural corporation
Case 3: External program of the emission trading system	Geothermal heat pump system	Rose	Agricultural association corporation

Findings of case study: motivation, effects and limitations

Motivation

The findings of this study reveal three primary motivations that prompt farmers to participate voluntarily in programs related to energy-saving facility provision and compensation. Firstly, economic considerations emerge as the predominant incentive. These farms, specializing in energy-intensive horticulture and floriculture conducted within heated greenhouses, grapple with substantial energy expenditure, especially during winter when heating costs constitute a significant portion of their operational expenses. In pursuit of mitigating this financial strain, they actively engage with governmental support initiatives. Secondly, these farmers exhibit a marked propensity for embracing new technologies willingly. Given the need to manage both heating in winter and cooling in summer due to changing climatic conditions, they display significant enthusiasm for energy-saving technologies. As a result, they demonstrate proactive and favorable attitudes towards government-sponsored energy-saving support programs, bolstered by a solid foundation of knowledge and understanding concerning the pertinent technologies before their adoption. Thirdly, their inclination to view the incorporation of new technology as an investment rather than an expenditure is also noteworthy. They firmly believe in the potential benefits arising from these innovations. Moreover, they possess a comprehensive recognition of the social and economic costs and gains associated with technology investments. This nuanced understanding prompts them to exhibit heightened proactiveness in terms of awareness and adaptability to a rapidly changing environment.

Major Effects

- **Case 1: Paprika farm**

In terms of the economic effect, the study found a significant reduction in energy expenditures for winter heating, with the farmer managing to cut costs by 50% during the four-month winter season (from November to February) following their transition from fossil fuel-based energy to geothermal energy in 2018. In contrast to the case of diesel boilers, where significant temperature fluctuations occurred between day and night, the adoption of a geothermal heat pump system facilitated more precise temperature control within the greenhouse. This enhanced control led to diminished temperature deviations and subsequently reduced stress on crops, thereby enhancing both the yield and quality of paprika produce. Furthermore, the implementation of an automatic adjustment cooling system resulted in fewer instances of opening and closing of the greenhouse roof, thereby curbing the loss of essential carbon dioxide required for photosynthesis during paprika growth. Therefore, there was a reduction of around 15% in the associated carbon dioxide injection costs for photosynthesis.

As a consequence of enhanced crop growing conditions, the crop harvesting period extended from 6 months to 9 months, leading to a growth of approximately 10% in production and sales. Additionally, by engaging in the voluntary GHG reduction program, the farmer received a compensation of KRW10,000 (approx.. USD 7.4 as of October 31, 2023) per ton of carbon reduction, resulting in a cumulative non-farm income of KRW10.02 million over the program's three-year duration (from 2018 to 2020). In terms of environmental effect, the farmer transitioned from using fossil fuels like bunker fuel and diesel for heating to adopting a geothermal heat pump system. This shift contributed to a total reduction of 1,002 tons CO_2eq. in greenhouse gas emissions over the course of three years.

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Fig.1. (Above) A view of the farm's geothermal facility, (Below) Heat storage tank and geothermal heat pump facility of the farm

- **Case 2: Cherry tomato farm**

In terms of the economic effect, the farmer significantly reduced winter heating costs by 78% during the four-month winter season (from December to March) by adopting multi-layer insulation curtains and switching from an oil boiler to an electric boiler. Additionally, these curtains served as light shields during the summer, reducing crop stress and enhancing growth and quality. The farmer also achieved considerable agricultural savings through self-made materials and no-tillage practices, leading to lower energy, labor, chemical, and forage expenses. Participation in the low-carbon agriculture and livestock product certification system resulted in certification and price premiums for certified products. For example, the farm's low-carbon certified cherry tomatoes fetched prices 2-3 times higher than wholesale uncertified cherry tomatoes, driven by increased demand from schools and public institutions offering eco-friendly meals.

Regarding the environmental effect, the study confirms that the farm's carbon emission level stood at a mere 15.9, reflecting an impressive 84% reduction compared to the standard emission level of 100 for certified agricultural products. Furthermore, the adoption of the no-till farming method plays a pivotal role in curbing carbon emissions. This approach promotes soil carbon storage and organic matter decomposition, achieved by burying crop residues in the soil, effectively storing carbon. Additionally, the method contributes to emission reduction by diminishing the energy input required for producing commercial chemical fertilizers. Instead, self-made agricultural materials replace chemical fertilizers. On the social front, the farmer's interactions with consumers, including farm visits and direct transactions, have expanded. This has led to a reduced social distance between producers and consumers, fostering a virtuous cycle that intertwines eco-friendly production with ethical consumption.

Fig.2. Energy-saving and low-carbon agricultural methods adopted by the farm. (Above) Multi-layer insulation curtains (Left), self-manufactured animal waste compost (Right), (Below) self-manufactured liquid fertilizers (Left), no tillage (Right)

- **Case 3: Rose farm**

In terms of economic impact, upon transitioning the heating system from an electric hot water boiler to a geothermal heat pump system inside the glass greenhouse, the farm achieved a winter heating cost reduction of approximately 41% during the three-month winter season (from December to February). Furthermore, despite running both heating and cooling systems, the annual total energy expenses for the farm dropped by more than KRW100 million(approx. USD 74,013) following the adoption of the geothermal heat pump system in 2016. Notably, the implementation of a sophisticated environmental control system within the greenhouse maintained optimal conditions for rose cultivation. This led to the stabilization of growth conditions and substantial improvements in rose growth, production, and quality, consequently augmenting farm income. The study also identified reduced carbon emissions during the program period (2016 to 2020). If the farm's certified reductions are traded within the carbon market, an estimated total profit of about KRW75 million(approx. USD 55,502) in non-farm income could be generated. Post-implementation of the geothermal heat pump system, carbon emissions on the farm were verified to have decreased by a total of 2,139 tons CO_2eq. (equivalent to 535 tons CO_2eq. per year), resulting in a 30% decline in GHG emissions over the program's four-year duration.

Fig.3. Geothermal heat pump facility of the farm and complex temperature control system

Table 3. Key effects

	Economic	Environmental	Social
Case 1	-Heating costs 50% decrease -Production and sales 10% increase -Carbon injection costs 15% decrease -Carbon reduction incentive increase	GHG emissions reduction (334 tons CO_2eq per year / total 1,002 tons CO_2eq From 2018.1~2020.12)	-Energy risk management improvement -Environmental and climate awareness improvement
Case 2	-Heating costs 78% decrease -Production and quality increase -Energy and labor costs decrease -Agricultural material costs decrease	GHG emissions (84% reduction)	-Energy risk management
Case 3	-Heating costs 41% decrease -Production and quality increase -Carbon trading incomes increase	GHG emissions (535 tons CO_2eq per year / total 2,139 tons CO_2eq. reduction From 2016.1~2020.1)	-Spread of ethical production and consumption culture

In summarizing the principal achievements stemming from the case studies conducted with farmers regarding GHG reduction support and compensation programs, several noteworthy outcomes come to the forefront. Firstly, the transition from fossil fuels to renewable energy stands out as a key mechanism by which farmers were able to mitigate the uncertainties and risks associated with energy sources. Secondly, the programs instituted by the government play a critical role as a safety net for agricultural management, exerting a positive influence by reducing production costs and generating supplementary non-farm profits. Particularly noteworthy is their capacity to lower the barriers to the adoption of new energy-efficient technologies within the agricultural sector, effectively relieving farmers of the financial burdens connected to the incorporation of high-cost renewable energy facilities. Furthermore, these programs contribute to heightening market competitiveness through the substantial reduction of heating costs, which ranged from around 40% to 70% during the winter season. This reduction not only enhances product quality but also leads to a marked decrease in production expenses. Thirdly, from a long-term perspective, these initiatives possess the potential to mitigate the social costs associated with attaining carbon neutrality. This is realized through the conservation of both costs and time that would otherwise be expended in responding to climate change challenges, spanning from the individual farm level to broader regional and national levels. In essence, farmers are accumulating valuable on-field knowledge and experiential insights pertaining to the genesis and amelioration of GHG emissions within the agricultural production realm. This result highlights the substantial latent potential embedded in government-led programs to heighten farmers' environmental awareness and galvanize the adoption of eco-friendly agricultural practices.

Limitations

While the government programs exhibit the positive outcomes, the case study has also unveiled certain limitations inherent to these programs, warranting enhancement. A major focus should be on enhancing the economic viability of high-cost, low-carbon agricultural technologies. This involves facilitating the adoption of appropriate low-carbon facilities for different farm contexts. The primary concerns include substantial initial investment costs linked to new technology adoption, along with challenges related to facility maintenance, renovations, aging equipment replacement, and accessing post-implementation warranty services—barriers prominently raised by farmers. Secondly, program participation entails intricate procedures that demand both physical and time-related costs, encompassing intricate steps such as data preparation, review, emissions monitoring, and certification. These intricacies serve as significant challenges, deterring farmer engagement. Thirdly, the current incentives for expanding target farmhouses are inadequate, necessitating a diverse incentive framework. For instance, within the 'Low-Carbon Agricultural and Livestock Certification System,' complex certification standards, procedures, and perceived insufficient economic compensation are issues. The 'Voluntary GHG Reduction Program' offers limited participation over three years, hindering investment recovery. Similarly, the 'External Program of the Emission Trading System' burdens farmers with full certification costs. The inconvenience of trading certified reductions through the Korean ETS's markets compounds farmers' challenges.

CONCLUSION AND POLICY IMPLICATIONS

The Korean government has placed a significant emphasis on the pivotal role of the agricultural sector in attaining GHG emission reduction objectives enroute to achieving carbon neutrality. Within this context, the Korean agricultural sector is obligated to embrace more ambitious and formidable reduction targets. Particularly, the agricultural sector in Korea is confronted with various energy challenges, including an increase in energy consumption due to expanded agricultural machinery distribution and horticultural facilities, as well as high dependence on fossil fuel energy within the agricultural domain. Thus, to attain these reduction targets, there is an urgent need for policy initiatives that foster a robust shift towards low-carbon agriculture, which is based on the transition from fossil fuel to renewable energy sources. For these reasons, this study aimed to analyze the effects of government-led greenhouse gas reduction programs within the agricultural sector in relation to energy transition. Through a case analysis of farms, the study showed the positive effects of renewable energy and energy-saving facilities, highlighting aspects such as greenhouse gas reduction, cost savings, increased productivity, and the social cost reduction associated with carbon neutrality. Despite these positive effects, the widespread dissemination of renewable energy and energy-saving facilities among farmers has been impeded by factors such as inadequate awareness of energy benefits, the burden of initial investment costs, and uncertainties regarding construction techniques and outcomes. Particularly, the issue of high initial investment costs has consistently been highlighted as a barrier to the expansion of renewable energy and energy-saving facilities. Therefore, there is a compelling need for intensified policy support to address this challenge.

Therefore, this study proposes several policy implications to expedite widespread adoption of low-carbon agriculture. To expedite the widespread adoption of low-carbon agriculture, several pivotal measures must be taken. Firstly, the government should enhance environmental and energy education to shift public perception and build environmental awareness. This awareness forms a foundation for implementing national carbon neutrality goals. Secondly, Greenhouse Gas (GHG) reduction programs play a key role in the transition to low-carbon practices. Recognizing diverse farmer conditions, customized programs aligned with farm characteristics are crucial (Jeong *et al*., 2022; Jeong *et al*., 2021a). Incentives for farmers and institutional rewards should be expanded. Thirdly, policies should reduce barriers to adopting carbon reduction technologies. Farmers recognize climate change's seriousness, but practical implementation lags due to barriers such as costs and technology skepticism (Chung and Park, 2022; Jeong *et al*., 2021b). Increasing awareness, improving technology accessibility, and investing in R&D are essential. Fourthly, tailored incentives for stakeholders are vital for GHG emission reduction. Producers, distributors, and consumers should comprehend low-carbon technologies' purpose. Fifth, sharing best practices among farmers is critical for sharing experiences and values. Comprehensive evaluations in various perspectives and field trips enhance understanding low-carbon technologies and practices. Sixth, precise GHG measurement and improved statistics are crucial. Lastly, the transition to low-carbon agriculture enhances agriculture's foundation and public values. Policymaking should balance existing systems to ensure food security while reducing GHG emissions, adapting to climate change-induced output variations.

This study, rather than being purely an academic paper, aims to provide insights for policy development for energy transition of the agricultural sector. It demonstrates that renewable energy and energy-saving facilities can serve as one of the means to alleviate energy-related issues in the agricultural sector, underscoring the significance of government policy support in this context. It is envisaged that future policy support, utilizing the findings of this study, coupled with technological and economic benefits, will lead to the effective expansion of renewable energy and energy-saving facilities, amplifying their positive effects. In future research, there are plans to further enhance the validity and reliability of relevant analyses by acquiring more cases of farmers participating in government programs related to energy transition.

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COMPETING INTERESTS

The author declares no conflict of interest.