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Developing circular agriculture for climate change adaptation in Vietnam: Current status and challenges

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ABSTRACT
Climate change (CC) is impacting the sustainable development of every country worldwide. To adapt to CC, the Vietnamese government has promoted circular agricultural (CA) development. This study aims to provide an overview of the current status of CA development adapted to CC in Vietnam. It reviews and evaluates international experiences in developing CA, legal regulations, and practical implementation. Data sources include scientific articles, reports from researchers, agencies, and organizations. Based on this information, a SWOT analysis was conducted to identify strengths, weaknesses, opportunities, and challenges for CA development. The results indicate that Vietnam's CA models are prevalent at the micro and medium levels, while macro-level models are rarely deployed. CA models have demonstrated economic and environmental benefits, aiding farmers in adapting to CC. However, several challenges remain, including limited awareness among stakeholders, incomplete policy frameworks, the absence of a market for circular products, limited waste management capacity, small-scale production, and insufficient linkage in production processes. Despite these limitations, CA models are recognized as a strategic policy by the Vietnamese government to reduce greenhouse gas emissions and enhance resilience to climate change.

Contribution/Originality: This study provides an overview of the current status of CA development for climate change (CC) adaptation by analyzing the case of Vietnam, an agricultural country heavily impacted by climate change. The goal is to contribute to promoting and improving CA development policies in Vietnam and expanding these strategies to other countries.

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1. INTRODUCTION

Introduction: Circular agriculture (CA), as an application of the circular economy (CE) in agricultural systems, is grounded in CE concepts. CA adopts theories and principles from industrial ecology to minimize resource consumption and reduce environmental waste through closed loops of material and energy flows (Imke & Martin, 2018). CA is a relatively new concept emerging alongside the growing interest in CE. However, the development of environmentally friendly and sustainable agricultural systems has long been recognized as a priority. CA can be understood as an agricultural production model operating in a closed loop, where waste or by-products from one process serve as inputs for another (Hong, 2020). In other words, CA is a production process that minimizes waste emissions to the environment by reutilizing by-products as inputs for production. From an ecological perspective, CA is an ecological concept based on the principle of optimizing the use of all agricultural biomass to close material and resource cycles, thereby reducing both resource consumption and waste discharge into the environment (Berkum & Dengerink, 2019). CA is built on three basic principles, including: i) conserving and developing natural capital through the sustainable use of natural resources and the recreation of natural systems; ii) optimizing the benefits from natural resources by recycling as much as possible of materials and products based on technical cycles and biological platforms; iii) improving the efficiency of production systems by minimizing negative externalities, including designing out waste (Morlet, 2015).

Climate change (CC) is evolving and has negative impacts on all aspects of the global socio-economic landscape. In which agricultural sector is the most heavily affected (DCC - Department of Climate Change, 2023). The transition from a linear economy to a circular economy is chosen by many countries as a key solution to reduce the impact of climate change. Developing a circular economy in agriculture, also known as the CA, is implemented by many nations to adapt to climate change. In the European region, the circular economy not only focuses on waste management but also encompasses all economic activities, from input materials and production to consumption and waste management (European Commission, 2016). Therefore, they developed a comprehensive plan for CE implementation and ecological design across the entire European region. Member countries can utilize this plan to create their own strategies tailored to the specific conditions of each nation (European Commission, 2019). A key feature of the European Union's Circular Economy (CE) implementation plan is its lifecycle approach, which encompasses four stages: production, consumption, waste management, and waste regeneration. The European Union also identifies six priority areas for implementing the CE: plastics, food waste, critical raw materials, construction and demolition, biomass fuels, and biobased products (European Commission, 2015). Among these six priority areas, three are directly related to circular agriculture (CA): food waste, biomass, and biobased products. Prior to 2015, the concept of the circular economy (CE) was scarcely addressed within the agricultural systems of European countries (Manal et al., 2021). However, in 2015, the European Commission launched a significant initiative to promote and expand the transition to the circular economy, including the agricultural sector (European Commission, 2015). A notable success of CA in Europe lies in the production of electricity and biofuels from agricultural waste and by-products. Along with the implementation of a number of integrated supply chain models to reduce food loss and waste in agricultural production systems. In North America, the United States and Canada are prominent examples of implementing CE in general and CA in particular. Canada is notable for its "Farm Environmental Plan" (FEP), first implemented in Ontario in 1992. This program focuses on addressing environmental issues on farms, particularly by developing appropriate waste management plans, enhancing waste recycling activities within farms, and guiding farms toward ecological models with minimal environmental impact (Carruthers & Tinning, 1999). In addition, the Canadian government has issued strict regulations on environmental protection on farms. At the same time, they provide technical and financial support to FEP participants. These solutions are considered key factors contributing to the success of the program. Currently, the FEP has been implemented across most of Canada and is considered a significant approach that helps the country move toward the goals of circular agriculture and sustainable development. In contrast, the United States implements CE through a market-based approach, whereby, in addition to the government, businesses and other legal entities are free to engage in trade and provide goods and services according to the laws of supply and demand. As a result, numerous business models for environmental goods and services, resource management, climate change adaptation, and circular materials and products have emerged and developed (Nam & Hanh, 2019). In addition, the "Zero Waste" strategy has been adopted by many U.S. states, aiming to eliminate waste generation into the environment by 2030. The U.S. government also encourages circularity initiatives and the replication of good circular practices. In addition, they have issued policies to promote public-private partnerships in food waste management, collection, recycling, and disposal of agricultural waste and by-products. Finally, they have established a framework for joint donation and recycling activities on a national scale. As a result, circular agriculture in the US is widely deployed and developed (Regions of Climate Action, 2017). In Asia, CA has also become an effective solution to solve environmental pollution problems in agricultural production. It is estimated that India's agricultural production generates an average of 500 million tonnes of biomass per year. This biomass is burned by farmers right in the fields, causing air pollution, reducing soil quality, and negatively affecting human health. The Indian government has adopted circular agriculture to address the issue of environmental pollution in agriculture. They focus on developing biogas technology to treat agricultural waste and by-products. The goal of this program is to produce approximately 65 billion m^3 of biogas annually (Mittal, Ahlgren, & Shukla, 2019). However, when implementing the CA model based on biogas in practice, India encountered many difficulties. The first barrier is the lack of simple and low-cost technology to treat agricultural waste and by-products. Second, large-scale biogas development requires a large and continuous supply of waste and by-products. Meanwhile, the actual supply system of agricultural waste and by-products is very volatile and unstable. Finally, India lacks suitable business models to utilize and consume biogas generated from agricultural waste and by-products (Kapoor et al., 2020).

Unlike India, China systematically develops CA at three levels, including macro (regions and provinces), meso (symbiotic clusters), and micro (households/farms). Since 2005, the macro CA has been piloted in 10 localities, including Beijing, Shanghai, Chongqing, Guiyang, Ningbo, Hebei, Dongling, Liaoning, Shandong, and Jiangsu. Meanwhile, at the meso CA level, China focuses on developing ecological agriculture models and waste exchange markets. Finally, at the micro level, the government encourages households and farms to implement cleaner production and eco-design measures. At the same time, China has issued many laws to support CA development, such as the Circular Economy Promotion Law, Cleaner Production Law, and Environmental Protection Law (Su, Heshmati, Geng, & Yu, 2013). One prominent CA program in China is greenhouse gas emission reduction through livestock manure recycling. This program has received responses from 62.30% of livestock farms. However, the effectiveness of the program is limited. It only helps reduce 42.5% of total greenhouse gas emissions from livestock farms. The main causes of this problem include: a lack of effective waste recycling technology; a mechanism to encourage livestock manure recycling activities is not strong enough; the connection between livestock and crop production is not suitable (Ruishi, Pan, Yuan, Lu, & Zhang, 2019). In Japan, the government promulgated the Basic Law for Establishing a Recycling-Based Society in 2002. This law applies to all sectors of the socio-economy. As a result, Japan has consistently maintained the highest waste recycling rate in the world, approximately 70-80% of the total (Nam & Hanh, 2019). Thus, the foundation for Japan's CA development is based on regulations concerning waste recycling activities.

Vietnam, an agricultural country, is being greatly affected by climate change. The Vietnamese government always focuses on reducing greenhouse gas emissions in all sectors of the economy. This was affirmed through the commitment to achieve net zero carbon emissions by 2050 by the Prime Minister of Vietnam at the COP26 conference (the 26th United Nations Climate Change Conference). Vietnam is promoting circular agriculture with the goal of reducing carbon emissions from the agricultural sector by 10% by 2030. So, how does circular agriculture actually develop? What are the drivers and barriers to circular agriculture development? And is circular agriculture the right path to sustainable agricultural development that adapts to climate change? This requires consideration and assessment of the development and effectiveness of circular agriculture models in practice. This study focuses on reviewing information and data from published articles, journals, and scientific reports by domestic and international researchers on circular agriculture. It also evaluates the effectiveness of several pilot circular agriculture models with the aims to: (i) clarify the current development status; (ii) analyze the advantages, challenges, opportunities, and threats facing; and (iii) based on these findings, propose measures to promote the development of CA in Vietnam in the near future.

2. METHODS

2.1. Research Content Framework

In this study, we review the knowledge and experiences of circular agriculture development in several countries around the world based on published scientific articles. On this basis, the scientific foundation for circular agriculture in Vietnam is further strengthened. In addition, we are synthesizing legal documents related to CE, CA, and waste management. From there, we proceed to analyze and evaluate the legal framework promoting CA in Vietnam. Finally, we selected two CA models representing the two levels of micro and meso to evaluate their actual effectiveness. The first model is a micro CA model called a circular pig farm in Yen Dung district, Bac Giang province. The second model is the meso-level CA model, implemented at Yen Cuong Agricultural Cooperative, Ninh Binh province. Data from literature review, policy analysis, and practical model assessment are used for SWOT analysis to indicate strengths, weaknesses, opportunities, and challenges for NNTH development in Vietnam (Figure 1).

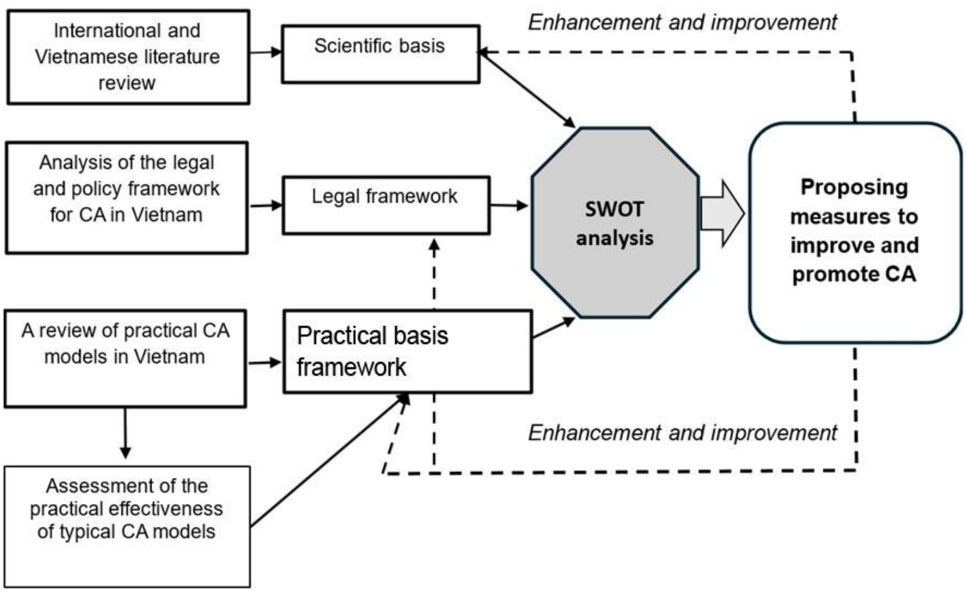

Figure 1. Research content framework.

2.2. Pilot Projects

The two selected CA models, as mentioned above, include the Circular pig-farm model a micro-level model. This model is located in Quynh Son commune, Yen Dung district, Bac Giang province. The last model, the Miso CA level, is the CA model at Yen Cuong agricultural cooperative, in Y Yen district, Nam Dinh province. Figure 2 shows two CA models on the Vietnam map.

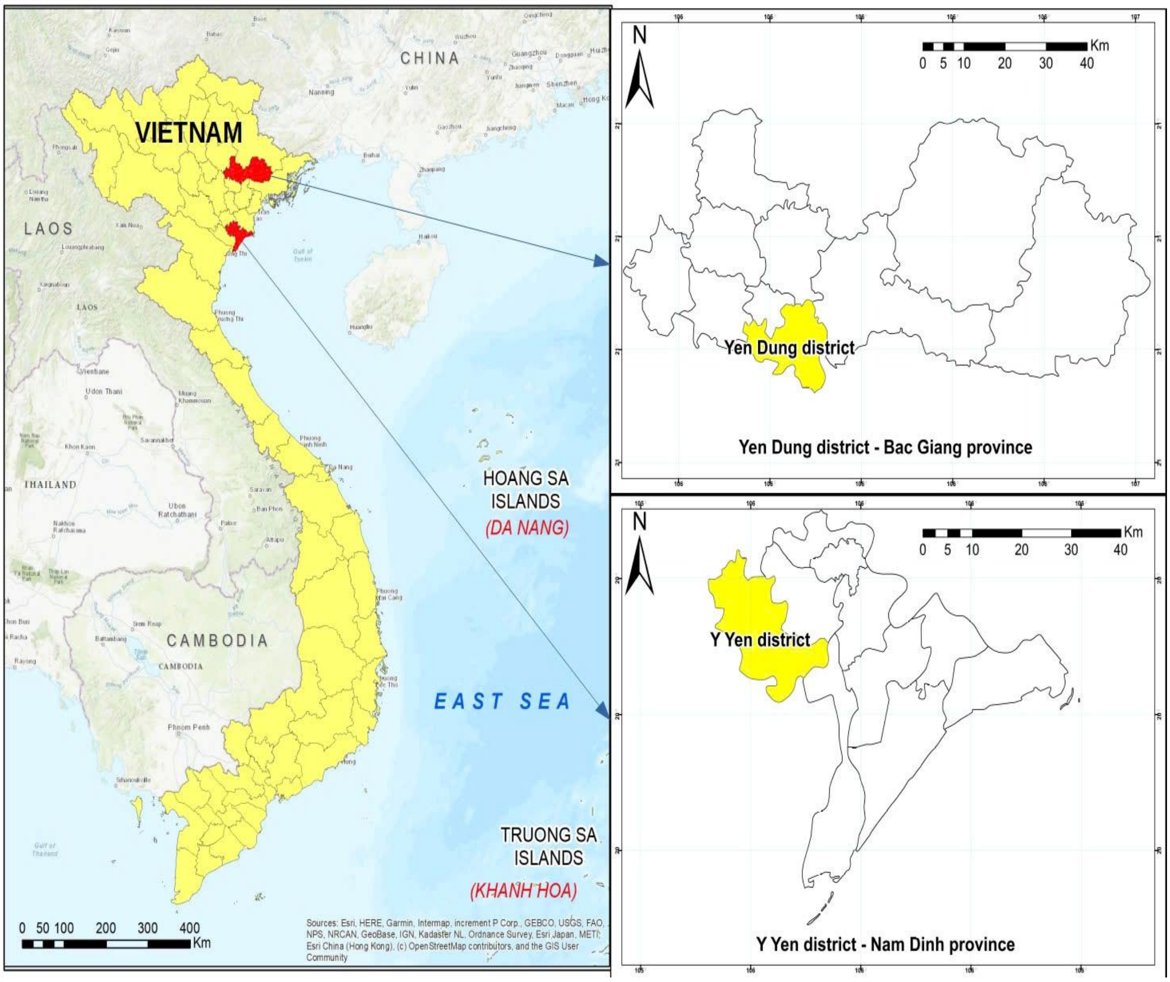

Figure 2. Locations of the two pilot circular agriculture models.

Circular Pig Farming Model (Micro-Level Model): The selected farm is a fattening pig farm with an annual capacity of 2,500 pigs, located in Tan An commune, Yen Dung district, Bac Giang Province. The total area of the farm is 10,000 m². Within the farm, all waste generated from pig farming activities is designed to be recycled and reused through three waste circularity chains: (i) the solid waste circularity chain, (ii) the liquid waste circularity chain, and (iii) the gaseous emissions circularity chain (Figure 3).

Chain 1 – Solid Waste Circularity: In this chain, a manure press is used to separate and collect solid waste. The solid manure is then used to cultivate earthworms. The resulting vermicompost is applied to crops within the farm or sold to local farmers for soil and crop fertilization.

Chain 2 – Liquid Waste Circularity: In this chain, livestock wastewater, after passing through the biogas digester, is directed into a subsurface flow constructed wetland for treatment (with a hydraulic retention time of 1–2 weeks). Subsequently, the treated wastewater is transferred to a biological pond and stored for approximately 2 weeks to reduce pollutants and harmful microorganisms (E. coli and coliforms) through biochemical transformations and the disinfecting effect of sunlight. The water from the biological pond is then used to irrigate the acacia plantation and green areas within the farm on a biweekly basis. Consequently, all wastewater is reused without being discharged into the environment.

Chain 3 – Gas Emissions Circularity: A biogas system is used to treat wastewater after manure pressing. Gas produced from the biogas system is used for electricity generation and combustion. As a result, the entire amount of gas generated from the biogas system is thoroughly utilized, rather than being released into the environment.

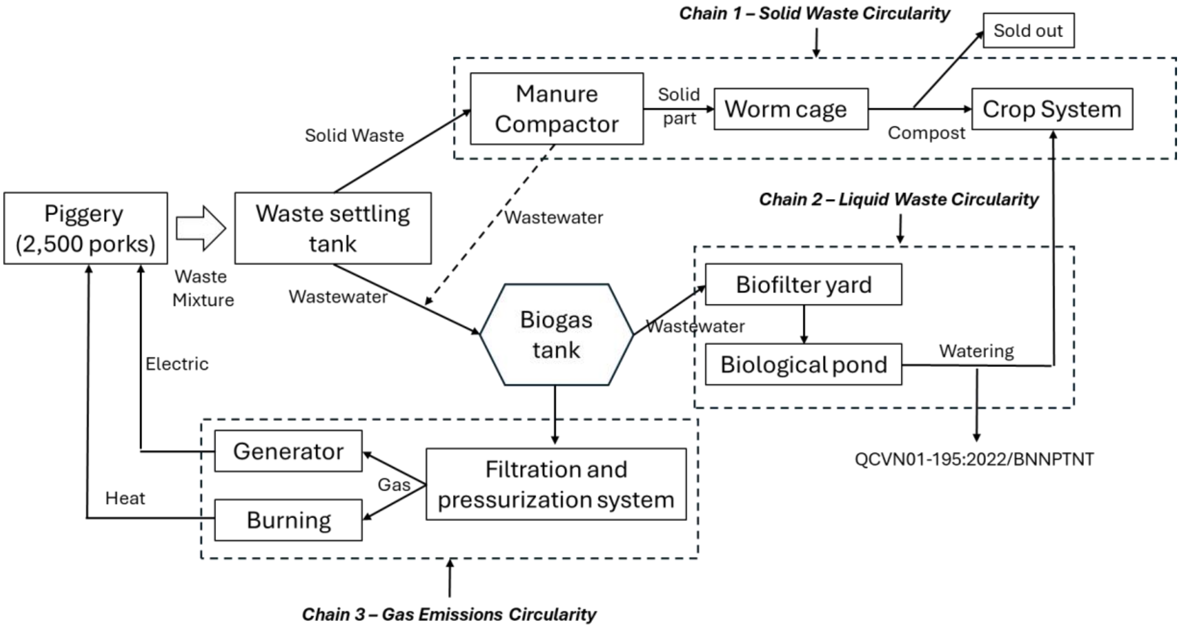

Figure 3. Waste Circularity flows in the Circular pig farm.

CA Model at Yen Cuong Agricultural Cooperative (Miso – Level): This model is implemented in four villages of Tam Binh, Thang Loi, Phuc Xa, and Duyen My in Yen Cuong commune. There is a close link between the activities of household waste management, livestock, and crop cultivation of households that are members of the cooperative. As a result, all organic matter from household waste, livestock waste, and agricultural by-products is fully utilized, contributing to reducing waste discharge to the environment. At the same time, it helps the cooperative save input costs (chemical fertilizers) and improves the quality of agricultural products. The chains of links for waste recycling in the model are depicted in Figure 4.

Chain 1 – Crop by-product Circularity: By-products generally from crops such as straw, corn stalks, and peanut stems are collected to feed buffalo, cattle, and pigs. Residues that are not suitable as animal feed are used as composting material to return nutrients to the soil or as bedding material in buffalo, cattle, pig, and chicken pens.

Chain 2 – Livestock Waste Circularity: All cooperative members raising buffalo, cattle, pigs, and chickens use bedding material in their pens. As a result, all waste (manure and urine) is mixed with the bedding. After each production cycle (3–6 months), the used bedding is collected and utilized as composting material to fertilize crop cultivation areas.

Chain 3 – Household Solid Waste Circularity: Household solid waste in Yen Cuong Agricultural Cooperative is sorted at the source. All organic solid waste is used as composting material to provide fertilizer for crop production. Recyclable waste, including plastic, metal, paper, glass, etc., is sold to local scrap collection facilities. The remaining waste (except recyclable waste and organic waste) will be collected and processed by the commune's domestic waste management system.

Chain 4 – Composting for Crops: All the organic fertilizer produced from composting is returned to the cooperative's fields. This reduces the amount of chemical fertilizers used. The result is savings in production costs and improved soil and crop quality.

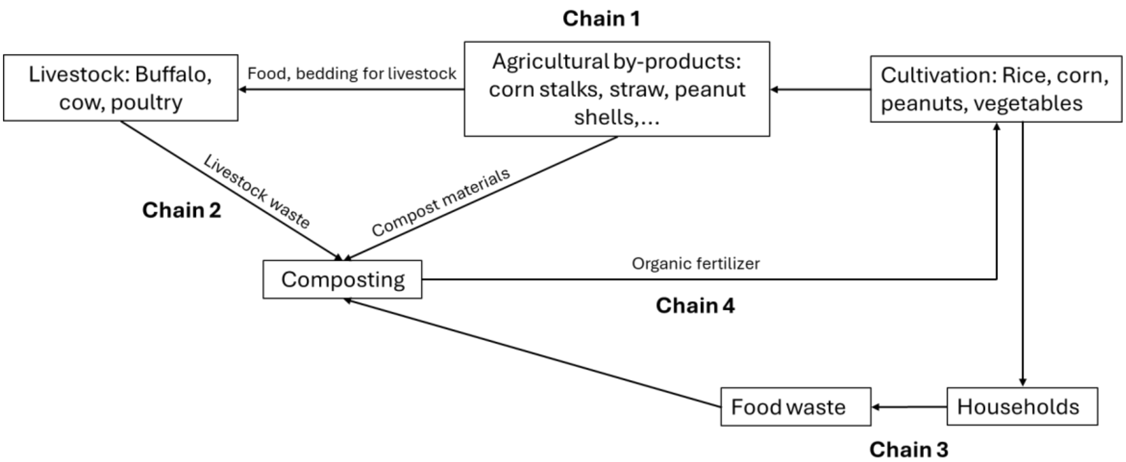

Figure 4. Circularity chains in the CA model at Yen Cuong agricultural cooperative.

2.3. Primary Data Collection Methods

* *Data collection:* Information on costs, income, profits, and operational data of the two CA models was collected over a period of 6 months to assess economic and technical efficiency.

* *Manure and wastewater sampling*

Manure sampling: Collect three manure samples, including one sample after the manure press, one sample after the earthworm farming process at the Circulating pig farm model, and one sample after the composting process in the CA model at Yen Cuong Agricultural Cooperative.

Manure samples were replicated three times to ensure representativeness. Analytical parameters for the manure samples included pH, total nitrogen (T-N), total phosphorus (T-P), and total organic carbon (TOC).

Wastewater sampling: 01 wastewater sample after the waste treatment system was taken at the recirculating pig farm (repeated 3 times) to analyze the quality indicators, including pH, Lead (Pb), Cadmium (Cd), Arsenic (As), Chromium (Cr), Mercury (Hg), Chlorine (Cl^-), and E. coli.

* *Analytical Methods*

The collected feces and wastewater samples were preserved and brought back for analysis at the ISO-standard laboratory of the Vietnam National University of Agriculture. Specific analysis methods for each parameter are shown in Table 1.

Table 1. Methods for analyzing parameters in manure and wastewater.

No	Parameter	Unit	ISO for Method Analyze
I	***Manure samples***		
1	pH	-	ISO 10390:2005
2	Total Nitrogen (T-N)	%	ISO 13878:1998
3	Total Phosphorus (T-P)	%	ISO 11263:1994
4	Total Organic Carbon (TOC)	%	ISO 14235: 1998
5	Total Potassium (T-K)	%	ISO 5310:1986
II	***Wastewater samples***		
1	pH	-	ISO 10523-2008
2	Lead (Pb)	mg/L	ISO 8288-1986
3	Cadmium (Cd)	mg/L	ISO 5961-1994
4	Arsenic (As)	mg/L	ISO 11969:1996
5	Chromium (Cr)	mg/L	ISO 9174-1998
6	Mercury (Hg)	mg/L	ISO 17852:2006
7	Chlorine (Cl^-)	mg/L	ISO 9297-1989
8	E.coli	MPN/100ml	ISO 9308-2:2012

2.4. Data Processing

SWOT Analysis: SWOT analysis is conducted to assess the strengths, weaknesses, opportunities, and challenges of CA development in Vietnam.

Comparison with Environmental Regulation: The results of the analysis of quality indicators in compost of the CA models were compared with QCVN01-189:2019/BNNPTNT - National Technical Regulation on Fertilizer Quality (Ministry of Agriculture and Rural Development of Vietnam (MARD), 2019b).

Meanwhile, wastewater quality indicators are compared with QCVN01-195:2022/BNNPTNT - National Technical Regulation on Using Livestock Wastewater to Irrigate Crops (Ministry of Agriculture and Rural Development of Vietnam (MARD), 2022).

Data analysis: We use Excel software to synthesize data, design data tables, and draw charts.

3. RESULTS

3.1. Current Status of Circular Agriculture Development in Vietnam

*3.1.1. *Assessment of Potential*

According to the General Statistics Office of Vietnam (2024), Vietnam currently has a total of 14.46 million hectares of cultivated land, 621.6 million main livestock (buffalo, cow, pig, poultry, and goat), 14.87 million hectares of forest, and more than 1.12 million hectares of aquatic exploitation (Table 2). With significant potential, Vietnam's agricultural production consistently plays a vital role in the national economy, contributing substantially to both domestic and global food security.

Table 2. Summary of the agricultural, forestry, and fishery production situation in Vietnam.

No	Plant	Unit	Value
I	Crop area	Thous.ha	14,462.4
1.1	Annual crops		10,658.7
-	*Cereals*		*7,998.8*
-	*Annual industrial crops*		*420.1*
1.2	Perennial current crops		3,803.7
-	*Perennial industrial crops*		*2,168.8*
-	*Fruit crops*		*1,297.7*
II	Number of Livestock	Mill.heads	621.6
2.1	Pig		26.5
2.2	Buffalo		2.0
2.3	Cattle		6.2
2.4	Poultry		584.1
2.5	Goat		2.8
III	Area of forest	Thous.ha	14,874.3
3.1	Natural forest		10,133.9
3.2	Planted forest		4,740.4
IV	Harvested area of water surface for aquaculture	Thous.ha	1,124.1
4.1	Harvested area of marine aquaculture		42.7
4.2	Harvested area of inland aquaculture		1,081.4

Besides its positive economic and social contributions, Vietnam's agricultural sector also causes major environmental problems. Specifically, greenhouse gas emissions from the agricultural sector account for 14.8% of Vietnam's total GHG emissions (MARD, 2024). At the same time, this sector generates a large amount of agricultural by-products, about 156 to 160 million tons per year. Of these, the two sectors generating the most are crop cultivation and livestock farming, with 80-90 million tons per year (accounting for 53%) and 61-81.8 million tons per year (accounting for 43%), respectively. Following that, the forestry sector has an average emission volume of 5 million tons per year, accounting for 3%. The lowest emission sector is aquaculture, with an emission level of 1 million tons per year, accounting for only 1% (Figure 5). The worrying issue is that the current recycling rate of agricultural waste and by-products in Vietnam is quite low, only about 35%. The remaining 65% is not properly managed, leading to the risk of environmental pollution and increased greenhouse gas emissions (Ministry of Agriculture and Rural Development of Vietnam (MARD), 2024).

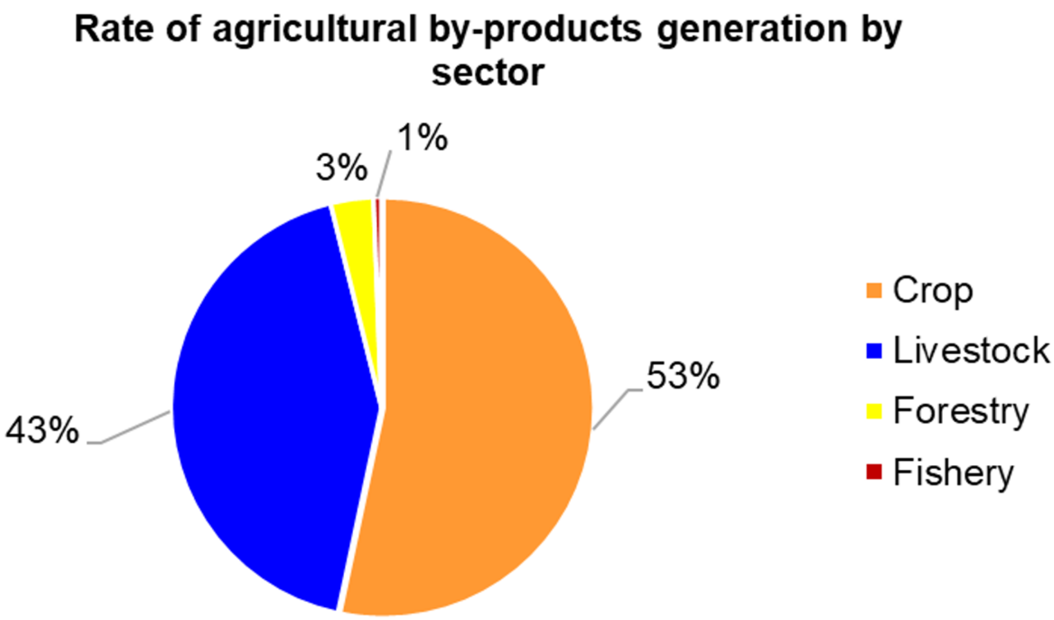

Figure 5. Rate of agricultural by-products generation in agricultural sector of Vietnam.

In fact, Vietnam has had many technical solutions to utilize livestock waste and agricultural by-products for different purposes. For example, research on using agricultural by-products to create compost for plants (Tuan, Vu Thi, & Nguyen, 2016). Another technique is to utilize straw, rice husks and biological products as biological bedding in household-scale buffalo, cow and pig farming to reduce waste generation in livestock farming (Vien, 2017). In addition, agricultural by-products are also used as feed for buffaloes and cows (Dinh, 2017) or used as a growing medium for mushrooms and vegetables (Minh, Nham, Mo, Viet, & Ha, 2021). In the livestock sector, animal manure and urine are treated with biogas systems to produce gas for cooking or electricity generation (Giang et al., 2012). In addition, livestock manure is also used to raise earthworms (Van, Huong, Trang, & Yabe, 2025), fish and black soldier flies (Linh & Nhien, 2022). These solutions have contributed to promoting the development of CA in Vietnam. However, most of these measures are only implemented on a small scale (micro level) and have not been deployed synchronously on a large scale. That is why the current recycling rate of agricultural waste and by-products in Vietnam is only about 35%.

*3.1.2. *Development Policies for Circular Agriculture*

The term Circular Economy, in general, and Circular Agriculture, in particular, have only been used in Vietnam in recent years. However, issues related to Circular Agriculture have already been mentioned and integrated into many guidelines and policies of the Vietnamese Government. The policies promoting Circular Agriculture in Vietnam are summarized in Table 3.

Table 3. Summary of Policies Promoting Circular Agriculture in Vietnam.

No.	Policy	Content
1	Law on Environmental Protection of Vietnam 2020 (Vietnam National Assembly, 2020)	Provisions related to Circular Economy are detailed in Article 142, Section 1, Chapter XI, which addresses "Economic instruments, policies, and resources for environmental protection".
2	Livestock Development Strategy (Government of Vietnam, 2020)	It includes the content: *"Promoting livestock extension programs based on closed-loop chains and circular economy… Developing technologies for livestock waste treatment associated with organic fertilizer production and the processing of products for aquaculture farming... contributing to fostering the circular economy in livestock production."*
3	Circular No. 12/2021/TT-BNNPTNT provides guidelines on the collection and treatment of livestock waste and agricultural by-products for reuse in other purposes (Ministry of Agriculture and Rural Development of Vietnam (MARD), 2021).	It promotes circular practices and the reuse of agricultural waste and by-products in livestock and crop production for purposes such as compost production, biofuel generation, and growing media, aiming to minimize waste generation and optimize resource efficiency.
4	Green Growth Strategy for the 2021–2030 Period (Government of Vietnam, 2021)	The strategy specifies solutions for achieving green growth across key economic sectors, with particular emphasis on agriculture.
5	Scheme on Developing Circular Economy in Vietnam (Government of Vietnam, 2022b)	In this scheme, the Vietnamese Government affirms the important role of the CA in national socio-economic development. At the same time, it has assigned the Ministry of Agriculture and Rural Development (MARD) to build a legal basis to promote the development of CA models. In addition, MARD must focus on researching solutions to improve the capacity to reuse and recycle agricultural waste and by-products.
6	National Climate Change Strategy to 2050 (Government of Vietnam, 2022a)	The strategy clearly identifies solutions to reduce emissions and adapt to CC in the agricultural sector. New technologies should be applied in agricultural production to treat waste and by-products into organic fertilizer and biogas. Second, it encourages farmers to adopt improved agricultural practices to reduce greenhouse gas emissions. Finally, the government will focus on improving agricultural logistics and developing appropriate cold supply chains to reduce greenhouse gas emissions during the harvesting and storage of agricultural products.
7	Strategy for Science, Technology, and Innovation Development in Agriculture and Rural Development to 2030, with a Vision to 2050 (Ministry of Agriculture and Rural Development of Vietnam (MARD), 2023)	In this strategy, MARD focuses on building policy mechanisms to support agricultural production models according to value chains, CA, organic agriculture, and green agriculture.
8	Methane Emission Reduction Action Plan to 2030 (Government of Vietnam, 2022b)	This plan points out specific solutions to reduce methane emissions in agriculture (crop and livestock), a sector that accounts for 50% of Vietnam's methane emissions. The key solution is to increase the reuse and recycling of waste and agricultural by-products through CA models.

In general, Vietnam has built a policy based on CE, including CA. However, the policy for CA development is incomplete and dispersed in some other aspects. As a result, CA in Vietnam has not developed to its full potential. In the coming time, the Vietnamese Government should refer to international lessons to complete the policy mechanism for CA. In particular, it is necessary to pay special attention to the experiences of China and Japan, countries with synchronous policy systems for CA development and cultural characteristics similar to Vietnam.

*3.1.3. * CA Models in the Real*

In Vietnam, CA development is quite similar to the case of China when it is implemented at many different levels (Su et al., 2013). There are two common levels of CA in Vietnam, including micro-level and meso–level (or community level). The micro level is widely implemented in agricultural production facilities such as livestock farms, crop farms, and aquaculture farms. At this level, the main solutions applied are cleaner production, application of automation technology, and use of biotechnology to reuse and recycle waste. These solutions help the farms reduce waste, minimize greenhouse gas emissions, save input costs, and improve economic efficiency. However, this model develops spontaneously on a small scale and lacks cohesion. Therefore, its efficiency and sustainability are not really high. At the micro-level, circular agriculture has demonstrated its role in utilizing waste, reducing environmental pollution, and improving farmers' economic efficiency. However, its limitation lies in being confined within an individual farm or facility, lacking connectivity with external elements and facilities, thus remaining small-scale and unable to form integrated production chains. Meanwhile, at the meso-level (linkage/symbiosis), several models have been implemented in Vietnam, forming short-chain linkages such as livestock–crop production–waste management; livestock–crop production–aquaculture–waste management; and agriculture–tourism–catering services–waste management. At this level, there is integration between agricultural production and other sectors such as waste management, tourism, and food services. However, these models have so far been implemented only on a small scale, emerging spontaneously without specific planning or strategies, making them suitable only for small and medium-scale production, without the potential to expand to regional or interregional scales. Some representative circular agriculture models in Vietnam are summarized and described in Table 4.

Table 4. Representative Circular Agriculture Models Currently Implemented in Vietnam.

No.	Name of the Model	Techniques Applied	Efficiency
1	Circular Economy Model at Vinamilk Dairy Farm (Cu & Mai, 2024)	- All livestock waste from dairy cattle is separated into solid and liquid phases. The solid portion undergoes Japanese microbial composting technology to produce organic compost, which is then used for the farm's forage fields. This practice replaces chemical fertilizers, improves soil fertility, and reduces greenhouse gas emissions. - The liquid waste is directed into large-capacity biogas tanks to generate biogas, which provides energy for various operations such as milk pasteurization for calves, heating water for daily use, drying towels and clothes, and drying hay.	Vinamilk has been recognized as one of the five enterprises effectively implementing the circular agriculture model. The company is also listed among the top 10 sustainable businesses in Vietnam in 2022, according to the Corporate Sustainability Index (CSI).
2	The One-Million-Hectare Circular Rice Cultivation Program in the Mekong Delta	Applying new rice cultivation techniques such as: implementing synchronized mechanization from soil preparation, seeding, irrigation, spraying, weeding, harvesting, and storage; adopting integrated pest management based on biological approaches (biological control, plant protection products of biological origin); managing rice straw and agricultural by-products in a circular manner (composting straw to return nutrients to the soil; using straw balers to collect straw for livestock feed); applying fertilizers according to crop needs and increasing the use of organic fertilizers from livestock; managing water resources efficiently (maintaining moderate soil moisture,	Rice yield increases by 100–200 kg/ha compared to traditional farming. At the same time, greenhouse gas emissions are significantly reduced from 10 tons CO_2-eq/ha (traditional farming) to 4.47–5.94 tons CO_2-eq/ha (improved farming).

No.	Name of the Model	Techniques Applied	Efficiency
		shortening the flooding period on paddy fields).	
3	Biosecure Pig Farming Model 4F (Farm-Food-Feed-Fertilizer) by Que Lam Group in Thua Thien Hue	- The model is established on a 15-hectare area in Thua Thien Hue, consisting of a complex that includes: a bio-product manufacturing plant with a capacity of 50,000 tons/year; an organic animal feed factory with a capacity of 100,000 tons/year; an organic pig farm with a scale of 8,000–10,000 pigs for meat per year; and more than 10 hectares of cultivated crops. - The goal is to create a closed-loop agricultural ecosystem in which all waste and agricultural by-products are treated and processed into organic fertilizer to be recycled back to the farm, contributing to reducing environmental pollution, utilizing resources, and lowering greenhouse gas emissions.	Ensure biosecurity for the pig herd; treat 100% of livestock waste generated; contribute to improving soil fertility through organic farming practices. This has become a prominent circular agriculture model in Vietnam, encouraged for implementation by the Ministry of Agriculture and Rural Development.
4	Waste-based Circular Agriculture Farm Models	Developed based on Vietnam's traditional agricultural models such as: - VAC Model: Garden – Pond – Livestock (common in delta regions) - RVAC Model: Forest – Garden – Pond – Livestock (Common in midland and mountainous areas) - VAC-B and RVAC-B Models: Variations of the VAC and RVAC models with the addition of a biogas system to treat waste, generate biogas, and supply energy for the system.	These models are derived from traditional farming systems, making them highly adaptable and sustainable. They feature a strong integration between crop production, livestock farming, aquaculture, and waste management; high biodiversity within the system; strong waste recycling capability; and high adaptability to climate change. Limitations: Low level of specialization, primarily applied on small household scales, making it difficult to produce commercial-scale products.
5	Rice–Shrimp/Fish Farming Model	This is a model that combines rice cultivation with shrimp or fish farming in the same paddy field. It is widely and effectively applied in areas where rice-growing land is often waterlogged. The activity of shrimp and fish helps stimulate the development of rice root systems. Leftover feed for shrimp or fish serves as an additional nutrient source for the rice. Moreover, their presence in the field enhances biodiversity within the rice ecosystem, which helps reduce pest and disease outbreaks on rice crops.	The model helps enhance climate change adaptation in waterlogged and low-lying areas; reduce production costs; and generate clean agricultural products by minimizing the use of chemical fertilizers and pesticides.

3.2. Results of the Pilot Model Assessment on Circular Agriculture

*3.2.1. * Circular Waste Management Pig Farming Model*

The monitoring results of the circular waste management pig farming model over a 6-month period showed that the waste recycling chains have brought significant economic and environmental benefits to the farm. Specifically:

Solid waste recycling chain: According to the emission coefficient issued by the Ministry of Agriculture and Rural Development, on average, a fattening pig generates 1.4 kg of manure per day. With a scale of 2,500 pigs per production cycle (each cycle lasting 4.5 months, approximately 135 days), the total amount of manure generated by the farm is 472.5 tons per cycle. After passing through the manure press, the solid fraction accounts for 40%, equivalent to 189 tons per cycle (while the remaining 60% in liquid form is directed into the biogas digester together with wastewater from barn cleaning for treatment). The entire amount of solid waste after pressing is used by the farm to cultivate earthworms. The vermicompost yield (including both compost and worms) is equal to the input solid waste mass, with a vermicompost-to-worm biomass ratio of 9:1. Accordingly, the quantities obtained are 170.1 tons of vermicompost and 18.9 tons of worm biomass per production cycle (see Table 5).

Table 5. Selected information on solid waste management of the farm.

Parameter	Unit	Quantity
Total number of pigs	Head / Production cycle	2,500
Average solid waste generated	Tons / Production cycle	472.5
Solid waste obtained after manure pressing.	Tons / Production cycle	189.0
Vermicompost obtained (after using solid waste to raise earthworms)	Tons / Production cycle	170.1
Earthworm biomass obtained	Tons / Production cycle	18.9

Based on the monitoring data above, we calculated the environmental and economic effectiveness of the solid waste recycling chain as follows:

Environmental effectiveness: The solid waste recycling chain helps the farm reduce 40% of manure generation, equivalent to a reduction of 1.4 tons of manure per month (189 tons of solid waste in 4.5 months). Importantly, the solid waste recycling chain helps farms avoid discharging waste into the environment. This not only contributes to environmental protection but also helps farms reduce environmental treatment costs. On the other hand, using earthworms to treat pig manure contributes to increasing the nutrient content in compost. The results of Table 6 show that the quality indicators of the manure after raising earthworms increased significantly compared to before. Specifically, the pH value increased by 0.26% from 6.56 to 6.82. Meanwhile, the content of total nitrogen (TN), total potassium (TK), and total phosphorus (TP) increased by 0.75%, 0.38%, and 0.73%, respectively. Using compost to fertilize plants helps limit the use of chemical fertilizers, thereby reducing greenhouse gas emissions and improving soil quality.

Table 6. Analysis of selected nutritional indicators of pig manure before and after vermiculture

No.	Parameter	Unit	Pig manure after pressing	Vermicompost	Increased rate (%)
1	pH	-	6.56	6.82	0.26
2	Total Nitrogen (TN)	%	0.44	1.19	0.75
3	Total Potassium (TK)	%	4.57	4.95	0.38
4	Total Phosphorus (TP)	%	0.79	1.52	0.73

Economic effectiveness: Each pig production cycle of the farm lasts 4.5 months. This is also the time to harvest worm manure from the worm farms. After each earthworm cycle, the farm obtains 170.1 tons of vermicompost × 1.5 million VND/ton = 255.15 million VND, and 18.9 tons of earthworm biomass × 30 million VND/ton = 567 million VND. The total benefit obtained from one earthworm cycle is 822.15 million VND (equivalent to 182.67 million VND/month).

Wastewater recycling chain: With a farm scale of 2,500 fattening pigs, the average wastewater generated is 150 m^3/day, including barn cleaning water, urine, and liquid fraction after manure pressing. All of this wastewater is utilized to irrigate the farm's acacia plantation after being treated to meet QCVN 01-195:2022/BNNPTNT standards (see Table 7). This practice prevents any impact on surrounding water bodies. In addition, the wastewater recycling chain contributes to saving water resources, recycling nutrients for crops, and reducing the cost of discharging wastewater into the environment.

Table 7. Quality of treated wastewater used for irrigating acacia trees on the farm.

No.	Parameter	Unit	Value	QCVN 01-195:2022/BNNPTNT Standard
1	pH	-	7.28	5.5 – 9.0
2	Pb	mg/L	0.0038	≤0.05
3	Cd	mg/L	0.007	≤0.01
4	As	mg/L	0.002	≤0.1
5	Cr	mg/L	NA	≤0.5
6	Hg	mg/L	NA	≤0.002
7	Cl^-	mg/L	37	≤600
8	E.coli	CFU/100ml	4,500	>1,000 – 5,000 (Used for forestry trees and perennial trees)

Note: NA = Not available

Air emission recycling chain: The methane (CH_4) generated from the biogas digester is currently used by the farm to operate a generator for on-farm electricity needs. This circular chain provides 20% of the farm's monthly electricity consumption (50 kWh/day or 1,500 kWh/month), equivalent to a savings of 150,000 VND/day or 4.5 million VND/month on the electricity bill. In addition, by utilizing all the gas from the biogas system, the farm does not have to burn or discharge excess gas into the environment.

*3.2.2. * CA Model at Phu Cuong Agricultural Cooperative*

Table 8 shows the sources of agricultural waste and by-products in Phu Cuong Agricultural Cooperative. Accordingly, the total amount of organic matter from sources is on average 20 tons per day (nearly 5.3 thousand tons in 6 months). All of this organic matter is used as animal feed, compost, or animal bedding.

Table 8. Generation rate of waste and by-products in Phu Cuong Agricultural Cooperative.

No.	Source of Waste and by-product	Scale		Generation Rate	
		Unit	Quantity	(Tons/Day)	Tons/6 months
1	Pig farming	Head	2,500	3.5	630
2	Buffalo and cattle farming	Head	650	13	2,340
3	Poultry farming	Head	25,000	3	540
4	Household activities	Household	1,000	0.65	117
5	Crop residues	Ha	445	3.75*	1,669
	Total		**28.15**	**20**	5,296

Note: (*) By-product generation for crops of Phu Cuong Agricultural Cooperative is 7.5 tons/ha/year, equivalent to 3.75 tons/ha/6months.

Environmental effectiveness: Based on the linkage chains in the model (Figure 4), all livestock waste (buffalo, cow, pig, chicken), food waste and crop by-products in the cooperative's fields are fully utilized to produce compost. The composting process produces 3,700 tons of good-quality compost/crop (Table 8) for crop production, meeting 70% of the cooperative's organic fertilizer needs. Table 9 presents the compost quality in the model. It can be seen that the pH is neutral, ranging from 6.8 to 7.8; the organic carbon content (TOC) reaches an average of 22.38% (ranging from 19.23 to 24.18%); the total nitrogen content (T-N) and total phosphorus content (T-P) reach 0.51% and 0.066%, respectively. Meanwhile, the Carbon/Nitrogen ratio reaches 41 - 44. All of these values meet the fertilizer quality standards of Vietnam. This not only limits waste generation into the environment but also contributes to reducing greenhouse gas emissions during the cultivation process. In addition, increased use of compost also contributes to improving soil quality and crop productivity.

Economic effectiveness: In six months, this model reduced the total of 117 tons of waste and by-product generation that must be collected and treated. With the price of waste collection and treatment at this time as 400,000 VND/ton, the total money saved by this model is 46.8 million VND in 6 months (or 7.8 million VND/month). In addition, during the 6 months, the model produced 3,700 tons of compost, which, at an average selling price of 20,000 VND/kg (2 million VND/ton), generated 7.4 billion VND per 6 months (or 1.24 billion VND/month). This represents a substantial source of revenue for the cooperative.

Table 9. Quality Parameters of Compost in the Model.

Value	Parameter				
	pH	TOC (%)	T-P (%)	T-N (%)	Proportion Carbon/Nito
Min	6.8	19.23	0.046	0.47	41
Max	7.6	24.18	0.106	0.58	44
Mean	7.1	22.38	0.066	0.51	42
SD	*0.30*	*2.10*	*0.02*	*0.04*	-

Thus, based on the monitoring and evaluation of the two pilot circular agriculture models, it can be seen that both models play a significant role in reducing waste generation and protecting the environment. In addition, the models create additional value by saving input costs and selling by-products. This demonstrates that the development of circular agriculture models provides a dual benefit, both economically and environmentally, for farmers.

4. DISCUSSION

4.1. Analysis of Challenges and Difficulties for Circular Agriculture in Vietnam

CA has emerged and is gradually becoming a new trend in agricultural development in Vietnam. However, its practical implementation still faces numerous difficulties and challenges due to several barriers, as outlined below.

Insufficient understanding of circular agriculture: The term 'circular agriculture' has only been mentioned in Vietnam's theoretical framework in recent years, although some of the core concepts of the circular economy have long existed in the country's agriculture. Moreover, in Vietnam, there are many related terms for agricultural development, such as: ecological agriculture, organic agriculture, sustainable agriculture, climate-smart agriculture, green agriculture, and circular agriculture. This diversity of terminology has inadvertently caused confusion and a lack of clear understanding regarding the content, role, and practical significance of circular agriculture for both policymakers and farmers. This is also a fairly common situation in agricultural development in some countries in the Asian region. Therefore, it is necessary to have propaganda programs to improve farmers' knowledge about CA in the coming time (Nam & Hanh, 2019).

Incomplete policy and institutional framework for circular agriculture: Currently, Vietnam has not yet established a comprehensive legal framework for implementing the circular economy in general, and circular agriculture in particular, unlike countries such as Japan, China, and India (Ruishi et al., 2019). Relevant aspects of the circular economy have only been mentioned in a scattered manner across several legal documents, such as the 2020

Environmental Protection Law, the Green Growth Strategy, and the Waste Management Strategy. This makes it difficult for ministries, agencies, and local authorities to systematically implement circular economy measures. Furthermore, specific standards for evaluating the implementation of the circular economy and circular agriculture have not yet been researched or issued by state management agencies. For example, the Ministry of Agriculture and Rural Development has issued Circular No. 19/2019/TT-BNNPTNT (Ministry of Agriculture and Rural Development of Vietnam (MARD), 2019a) on the collection, treatment, and utilization of crop residues and Circular No. 12/2021/TT-BNNPTNT (Ministry of Agriculture and Rural Development of Vietnam (MARD), 2021) guiding the collection, treatment, and reuse of livestock waste and agricultural by-products for other purposes aim to promote waste and by-product recycling. However, the Ministry has not yet issued specific quality standards for each type of agricultural waste and by-product after treatment to permit legal reuse. Consequently, farmers and agricultural production facilities are unable to legally implement the reuse of agricultural waste and by-products in practice. Lessons learned from China and Japan suggest the need for separate policy support for waste circularity activities and the consumption of recycled reusable products at the regional and national levels (Ruishi et al., 2019).

Limited capacity in recycling and reusing agricultural waste and by-products: The annual volume and composition of agricultural waste and by-products in Vietnam are currently very large and diverse. However, recycling and reuse technologies remain very limited, focusing mainly on basic types of agricultural waste and by-products, such as field biomass and livestock waste, while many other types of waste and by-products have not received sufficient attention. Consequently, currently only about 10% of crop residues are used as on-site fuel, 5% as industrial raw material, and 3% as livestock feed; over 80% remain unused and are either discharged directly into the environment or burned, causing environmental pollution. To develop circular agriculture, it is necessary to focus on investing in developing new modern technologies in the field of waste circulation and reuse, especially the foundation of biotechnology (Mittal et al., 2019). The case of India's biogas-based CA development is a typical example of focusing on developing core technologies that Vietnam can learn from to improve its capacity to utilize agricultural waste and by-products.

Lack of stable markets for circular agriculture materials and products: Market factors have a significant impact on the implementation of circular agriculture. These include the shortage of financing and investment funds for developing circular production and business models, and the fact that traditional agricultural inputs (such as fertilizers and pesticides) are supplied more stably and abundantly than inputs produced from recycled waste (e.g., compost, biofertilizers). As a result, the adoption of circular inputs as substitutes for conventional materials remains limited. Japan has been very successful in the process of legalizing waste circulation and recycling activities, forcing production and business units to redesign their production and business models in a way that is favorable for the circular economy (Ruishi et al., 2019).

Weak integration among essential components of the circular agriculture system: Currently, the arrangement of crop and livestock structures, as well as the organization of agricultural production space in Vietnam, is not yet rational and lacks sufficient integration. This makes it very difficult to implement large-scale recycling of agricultural waste and by-products. Moreover, the essential components needed to promote circular agriculture such as agricultural processing enterprises, facilities for recycling and reusing agricultural waste and by-products, agricultural input supply services, and agricultural cooperatives still have limited capacity and uneven development in Vietnam. As a result, they fail to establish strong linkages necessary for the effective implementation of circular economy practices in agriculture.

Small-scale production, weak linkages, and asynchronous technology application: A core weakness of Vietnamese agriculture is its small-scale production, with over 8 million farming households cultivating less than 5 ha each. Additionally, the linkage between components in the agricultural model, such as livestock, crop cultivation, and aquaculture, is not yet tight. Coordination between farmers, traders, processors, and agricultural producers is still loose. This prevents the formation of integrated agricultural production chains, creating difficulties for recycling and material circulation in circular agriculture. Furthermore, due to the small-scale nature of production, investments in mechanization and the application of science and technology by individual households are limited and inconsistent. Consequently, the capacity of Vietnamese farmers to manage agricultural waste and by-products is very low.

4.2. Proposed Solutions for Improvement

To overcome the barriers and address the above challenges, the Vietnamese government should implement the following specific measures:

Improve the legal framework for implementing the circular economy in general and circular agriculture in particular: A dedicated national strategy or plan for circular economy implementation should be issued, enabling ministries, agencies, and local authorities to develop and implement sector- and locality-specific circular economy plans. Special attention should be given to policies regulating the management and reuse of agricultural waste and by-products. Vietnam can learn from China in building CA at three levels: micro (grassroots), community, and regional/national levels (Su et al., 2013). Currently, Vietnam's micro and community-level models have been formed and developed. The promulgation of specific development policies will soon promote the implementation of the regional and national levels of the CA model in practice.

Develop standards, guidelines, and manuals: Proactively establish standards and evaluation criteria for circular agriculture, and compile guidance documents and manuals to direct extension officers and farmers in implementing specific circular agriculture practices. This solution will contribute to overcoming the limitations in farmers' awareness of agricultural production. This problem is very common in Vietnam as well as other agricultural countries in the Asia region (Nam & Hanh, 2019).

Establish incentive mechanisms to promote circular agriculture: Focus on building markets for circular agriculture materials and products, and creating financial funds to support farmers and enterprises participating in circular agriculture.

Effectively implement agricultural restructuring towards circularity: Circular production requires the reorganization and redesign of agricultural systems. Components such as crop production, livestock farming, processing enterprises, recycling facilities for agricultural waste and by-products, agricultural service systems, and cooperatives should be appropriately designed and arranged to create a complete agricultural ecosystem that facilitates energy and material circulation.

Promote scientific and technological applications in agricultural production: To CA development, Vietnam government should focus on researching solutions for transferring waste and by-products from agriculture to become the input of other products. For example, treatment of animal waste into composting; using by-products from cultivation as food for animals; producing biofuel from livestock waste, and so on. In addition, it is necessary to incentivize application of technical and technological innovations to expand the scope of CA models, especially such as automatic technologies, AI, Blockchain, and IoT.

Strengthen training for agricultural officials and farmers: CA wants to develop; it needs agricultural officials and farmers who fully understand it. Therefore, the government should focus on strengthening training and dissemination of basic knowledge and skills on CA for officials and farmers. Only when farmers clearly understand the role and benefits of CA will they be motivated to transform from traditional production to circular production.

Scaling up and increasing connectivity in CA models: CA in Vietnam is currently developed only at two levels: grassroots and community, with small scale. As a result, production efficiency is not high and does not produce products that are competitive enough in the market. To expand the scale of CA, it is necessary to develop production according to the value chain. At the same time, it is important to increase connectivity between agricultural production and other sectors such as industry, transportation, trade, services, and waste management.

5. CONCLUSIONS

CA is developing rapidly around the world, becoming a key solution for adaptation to CC situations in the agriculture sector. This study contributes to understanding the practical development of CA in Vietnam and provides a foundation for national policy formulation. Specifically, in Vietnam, with its rapidly developing agricultural sector, a large volume of agricultural waste and by-products is generated, causing environmental pollution and wasting natural resources. Implementing circular agriculture is an appropriate solution for Vietnam to reduce environmental pollution, lower greenhouse gas emissions from agricultural production, contribute to the commitment to achieve net-zero greenhouse gas emissions by 2050 as pledged at COP26, and build an eco-friendly, economically efficient agricultural system that can adapt to irregular climate variations. However, to effectively implement circular agriculture and achieve the desired goals, the Vietnamese government needs to undertake coordinated measures to remove key barriers, including: insufficient understanding of circular agriculture; an incomplete policy and institutional framework; limited capacity for recycling and reusing agricultural waste and by-products; lack of stable markets for circular agriculture; and weak integration among components of the circular agriculture system. This study represents an initial assessment of the development status of circular agriculture in Vietnam. Therefore, the results only provide an overall picture and do not yet deeply analyze specific aspects related to circular agriculture. In the future, more in-depth studies are required to promote and accelerate the development of circular agriculture in Vietnam.

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