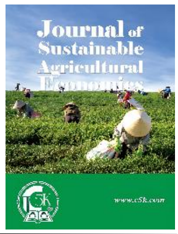
Journal of Sustainable Agricultural Economics

"Volume 1, Issue 1, Year 2024"

website: https://www.c5k.com



Research Article

Circular Economy in Agriculture: Transforming Waste into Wealth

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ARTICLE INFO

Article history:

03 Jul 2024 (Received)

16 Aug 2024 (Accepted)

23 Aug 2024 (Published Online)

Keywords:

Circular Agriculture, Waste-to-Wealth, Sustainable Farming, Resource Efficiency, Agri-Waste Management

ABSTRACT

The incorporation of a circular economy within the framework of the agriculture sector provides a way of managing wastes through the utilization of residues from crops, animal products, and other organic materials through renewal energy sources and organic manure. This paper aims to examine the possibility of applying circular economy to agricultural systems in terms of the economic and environmental impacts and limitations of circular economy application. The findings also suggest that circular strategies can create substantial value from waste, decrease input costs, enhance farmers' revenues and profits, and support ecological improvements. However, factors including high initial costs, low awareness levels, and inadequate infrastructure resist its use in many areas. This paper gives solutions to the above challenges and how the circular economy can be integrated into agriculture.

DOI: https://doi.org/10.103/xxx @ 2024 Journal of Sustainable Agricultural Economics (JSAE), C5K Research Publication

1. Introduction

1.1. Background and Importance of the Research

In the course of economic development, agriculture also plays a role in influencing global environmental issues such as waste production. Agricultural wastes in the form of crop residues, animal by-products, and other waste products total billions of tons per annum, a large proportion of which still goes unused or is poorly managed (Koul et al., 2022).

This evolution not only helps to minimize the unfavorable impacts of waste on the environment but also maximizes the efficiency of resource consumption and revenue gains to farmers. For example, instead of directly burning crop residues as is normally done, such as those that were burnt in the fields, the residues can be used to make biochar, which is good for the soil and also sequesters carbon at the same time (Patel & Panwar, 2023). Likewise, animal drops can be converted into biogas and compost—diminishing the use of chemical fertilizers and fossil fuels (Chew et al., 2019).

1.2. Principles of the Circular Economy in Agriculture

In agriculture, the circular economy is applied through several key principles:

- Waste Valorization: Agricultural waste and co-products are converted into valuable products, such as bioenergy or organic manure, thus increasing waste management and creating wealth (Xu et al., 2024)
- Nutrient Recycling: Some of the nutrients produced from organic waste, such as compost or biochar, return to the soil in a way that promotes fertility, thereby decreasing dependence on chemical fertilizers (Wang et al., 2022).
- Resource Efficiency: According to Morseletto et al. (2022), circular systems are efficient in utilizing water, energy and raw materials, hence reducing wastage.

1.3. Benefits of Circular Economy Practices in Agriculture

The adoption of circular economy principles in agriculture presents a wide range of benefits, ranging from economic, environmental, and social:

1.3..1 Economic Benefits

Recycling helps minimize the costs of inputs and, at the same time, ensures that the farmer looks for other sources of income. For instance, the application of anaerobic digesters in the process of converting crop residues to biogas can reduce the energy costs of farms by 30–50% and produce surplus energy for sale (Chew et al., 2019). It has the effect of cutting input costs, specifically the cost of chemical fertilizers, and raising the long-run yield per unit of soil (Wang et al., 2022).

1.3.2. Environmental Benefits

The reuse of implemented systems is employed in order to raise the level of utilization of resources and decrease GHG emissions. For example, the use of bioconversion in biogas production and composting of agricultural residues to produce biochar is a process of sequestration of carbon and

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Cite: Rakibul Hasan (2024). Circular Economy in Agriculture: Transforming Waste into Wealth. *Journal of Sustainable Agricultural Economics,* 1(1), pp. 12-17.

improvement of soil quality, respectively. Likewise, the amendments of the topsoil reduce methane emissions that are related to the anaerobic digestion of organic matter (Patel & Panwar, 2023).

1.3.3. Soil and Water Health

Organic amendments derived from agricultural wastes improve the physical status of the soil; this is based on nutrient status as well as water retention capacity. Biochar, through pyrolysis of crop residues, can enhance SOC, reduce nutrient leaching and is beneficial to sustainable agriculture (Chew et al., 2019).

1.4. Current Challenges in Implementing Circular Economy Practices

Nevertheless, several important limitations prevent the successful integration of circular economy concepts into agricultural settings.

1.4.1. High Initial Costs

Those innovations suitable for circular processes include anaerobic digesters, biochar production systems, and large plants for composting, which are capital-intensive. For example, the installation of an anaerobic digester costs between $50 000-$100; 000 most of the charges smallholder farmers can only meet the payments with subsidies (Touch et al., 2024)

1.4.2. Lack of Awareness and Expertise

There needs to be more awareness, technical knowledge, and capacity amongst many farmers, and they require further understanding of circular economy principles. Touch et al. (2024) showed that a small percentage of smallholder farmers in the developing world got information or training on circular practices; this was 24 %.

1.4.3. Infrastructure and Policy Gaps

Insufficient collection, processing and distribution systems to support waste management also create major challenges to circularity. Further, some policies have changed, and there need to be market signals for bio-based products, which is unsatisfactory for circular agriculture (Patel & Panwar, 2023).

1.4.4. Verification Challenges

Evaluating the environmental and economic impacts of circular systems is not easy and is always expensive, making it difficult to determine possible future gains on investment. For example, assessing the efficiency of biochar in carbon storage requires elaborate instrumental methods, which may take years to obtain in developing countries (Patel & Panwar, 2023)

1.5 .Case Studies of Circular Agriculture Practices

Several successful case studies highlight the potential of circular economy principles in agriculture:

1.5.1. Anaerobic Digestion in Germany

Germany has taken the lead in Europe in installing anaerobic digesters; more than 9,000 plants convert agricultural waste to biogas (Thrän et al., 2020). This practice has helped the country reduce its reliance on fossil energy sources and greatly minimized GHG emissions from agricultural waste.

1.5.2. Biochar in India

In India, rice husk is being turned into biochar to improve the fertility of the field and reduce methane emission due to open field burning of crop residues. Research has indicated that the use of biochar has raised crop yields in pilot projects by between 15 and 20 percent in regions where it has been used (Vijay et al., 2021).

1.5.3. Composting in the United States

In California, for example, commercial composting companies treat animal wastes and crop remnants organically into grade fertilizers. Such facilities provide organic matter to the vineyard and orchard, which cuts down the utilization of chemical fertilizers and enhances the ground condition.

1.6. Objectives of the Study

The purpose of this study is to evaluate the possibility of implementing the circular economy concept in agricultural systems, and, to assess the business case for converting waste to value-added products. Also, the study seeks to find out constraints and suggest practical solutions to eradicate these hurdles.

2. Materials and Methods

2.1. Study Design

This research used both quantitative and qualitative research approaches to assess the viability of implementing a circular economy in agricultural systems. The study centered on utilizing crop residues, animal by-products and other organic wastes for the production of bioenergy, biochar and organic fertilizers, among others. In the first and second research questions, both qualitative and quantitative data were collected to capture the economic and environmental benefits and costs of circular practices and the factors influencing the adoption of circular practices, respectively.

The study was designed to address three primary objectives: measure the economic advantages of circular practices, assess their effects on the environment and the difficulties farmers experience implementing circular systems. Both primary data include questionnaires administered to farmers and case studies, and secondary data from government publications, academic journals, and industry reports were used in the study to ensure a rich understanding of the topic.

2.2. Data Collection

2.2.1. Primary Data

The primary data were collected from field surveys specific to the participants, 60 farmers of the agricultural regions who are already practicing circular economy. These farmers' farms ranged from supermarket model farms, medium-sized farms, and commercial large-scale production farms. The surveys collected information on the management and disposal of waste as well as the type of circular systems used (e.g., anaerobic digestion, composting or biochar) and perceived economic/environmental benefits of using systems. Moreover, regarding obstacles to the adoption of the system, specific questions were raised about the cost, the lack of technical experience, and the lack of appropriate infrastructure. Other structured interviews were also conducted based on case studies from farms that had successfully applied circular approaches to gain a deeper understanding of implementation. For instance, a farm employing anaerobic digesters through which crop residue is biologically transformed into biogas and electricity was assessed for profitability and energy efficiency. Likewise, experiences of a composting facility of animal manure producing organic fertilizer were considered for effectiveness in cost reduction and the health benefits for the soil.

2.2.2. Secondary Data

Information obtained from agricultural waste management from government and industry reports, academic journals, and databases was collected. The data was sourced from the Food and Agriculture Organization, reports on circular economy practices by the European Commission and Agricultural uses of Biochar. These sources yielded cost information pertinent to implementing circular systems, revenue generation, including GHG avoidance, and every small increase in Soil Organic Carbon (SOC).

2.3. Analytical Framework

2.3.1. Economic Analysis

A review of the economic benefits of circular practices was made on the strategies of cost-benefit analysis based on the initial cost of investments and circular equipment, operating cost, and potential revenues from the circular strategy. For example, the case specifically compared the cost of an anaerobic digester against the cost of the energy that would be saved and the cost of the power generated from the sales of biogas. Economic return of biochar production was compared to the advantages of enhanced yield and reduced cost of fertilizers.

2.3.2. Environmental Impact Assessment

For environmental impact, the extent of change in GHG emission and soil quality were used to assess the benefits. This is a quantitative study in which potential carbon sequestration of biochar, methane reduction from anaerobic digestion, and nutrient improvement of soil through compost application was estimated using data obtained from case studies and secondary sources. These metrics gave a comprehensive image of the environmental benefits of circular activities.

2.3.3. Data Visualization

To enhance access to the findings of this study, the results were displayed by making use of statistical software and generate graphs and charts. These visualizations included:

- Bar Chart: Analyzing the cost benefits and the revenues of various circular economy systems.
- Pie Chart: Highlighting the utilization rates of agricultural waste (e.g., the proportion used for bioenergy vs. composting).

2.4. Data Analysis

Data analysis was done in two stages. In the first phase, the economic data were analyzed with the help of the SPSS tool to detect such trends and relationships. For instance, those farms that invested more in circular practices at the beginning of the study received higher circular benefits and higher returns on investment. In the second phase, environmental data were utilized to determine the carbon dioxide reduction levels and the enhancement of the soil's organic carbon stocks. This phase involved the determination of average emission reductions per ton of waste processed and a comparison of carbon sequestration of biochar against conventional waste disposal.

2.5. Limitations of the Study

Although the study was able to offer a wealth of understanding about the viability of circular practices, the following limitations were encountered. First, the sample size of surveyed farmers was relatively small and second, the survey covered only one district of the state. Second, for some of the environmental data, the study relied on secondary data sources and thus may have yet to capture the true regional rates of carbon sequestration. Lastly, there was no consideration of the dynamics of the market price of bio-based products, including biochar and compost, which are used in circular practices.

2.6. Ethical Considerations

The research followed the ethical standards when collecting and analyzing the data. The farmers who participated in the study provided their consent, and anonymity was observed throughout the study. Secondary data collected were used in accordance with copyright and data-sharing requirements.

3. Results and Discussion

3.1. Economic Impact of Circular Practices

The real option valuation showed that farmers in the circular economy of agriculture stand to gain significantly in terms of tangible financial value. For the participating farms, anaerobic digesters – which turn crop residues and animal manure into biogas and bio-fertilizers – showed energy cost savings of 30 to 50 percent. Furthermore, farms that sell excess biogas said that their yearly income ranged from $10,000-$15,000 based on the size of the farm. Composting cut fertilizer costs by 25–40%, while biochar production added 10–15% to yield, thus improving farm revenues, as presented in Table 1.

Table 1. Economic Impact of Circular Economy Practices

Practice	Initial Investment (USD)	Cost Savings (%)	Annual Revenue (USD)	Yield Increase (%)
Anaerobic Digestion	\$50,000–\$100,000	30–50	\$10,000–\$15,000	N/A
Composting	\$10,000–\$25,000	25–40	N/A	10–15
Biochar Production	\$15,000–\$30,000	20–30	\$5,000–\$8,000	10–15

The economic feasibility of circular practices depends on the scale of operations and initial investment. Large-scale farms experienced quicker payback periods due to higher energy generation and cost savings, while smallholder farmers faced longer payback times due to limited capacity. Fig. 1 shows the Cost Savings Across Circular Economy Practices. And Fig. 2 describes the Yield Increase.

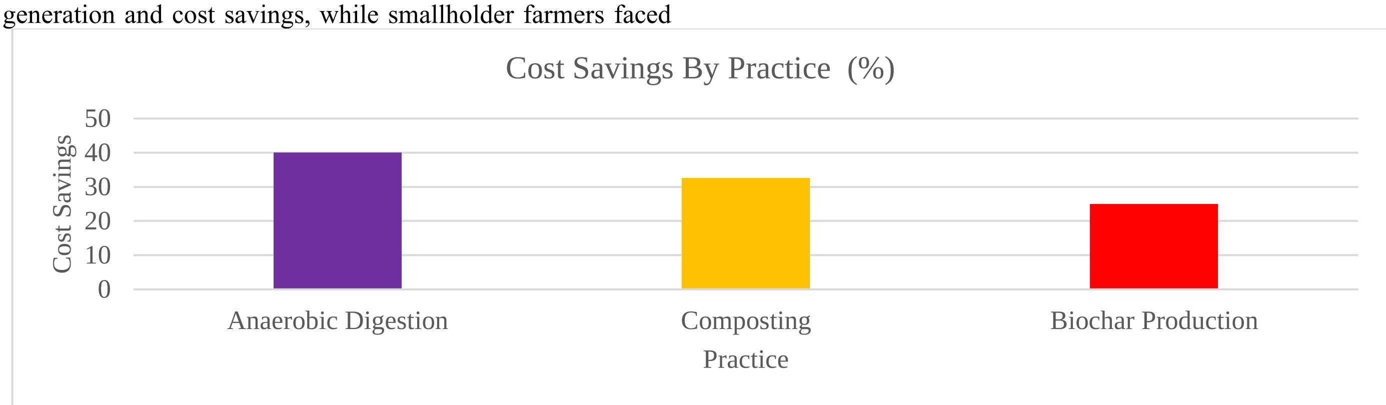

Fig. 1. Cost Savings Across Circular Economy Practices

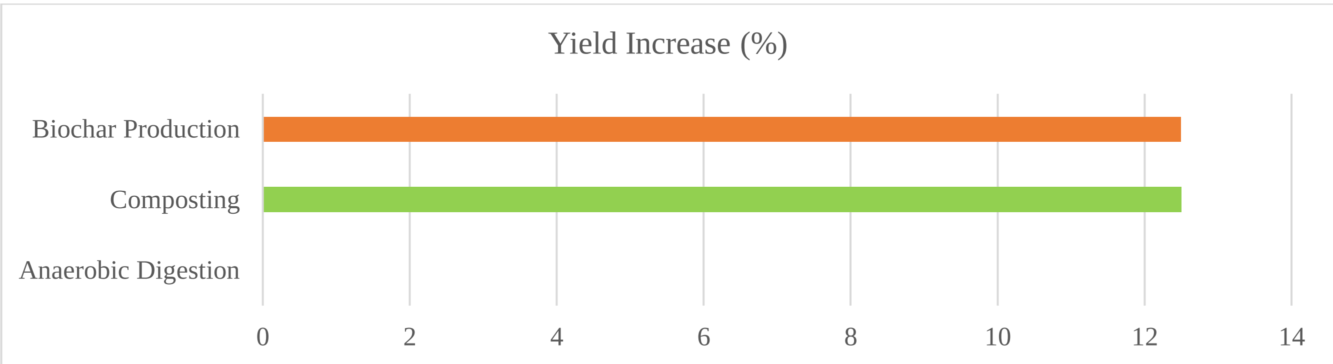

Fig. 2. Yield Increase

3.2. Environmental Benefits of Circular Practices

Circular practices were shown to have positive material environmental impacts by lowering GHG emissions and enhancing soil quality (Fig. 3). Anaerobic digestion cuts down methane from decomposing organic waste by 60–70%, while composting eliminates synthetic fertilizers, hence reducing nitrogen oxide emissions. Thus, biochar production preserved an average of 1.8 tons of CO_2 per hectare per year for long-term storage and climate change (Table 2).

Table 2. Environmental Benefits of Circular Practices

Practice	GHG Reduction (%)	Carbon Sequestration (tons CO_2/acre/year)	Soil Health Improvement
Anaerobic Digestion	60–70	N/A	Increased organic matter
Composting	30–40	N/A	Improved nutrient levels
Biochar Production	25–30	1.8	Enhanced water retention

Composting and biochar also enhanced soil quality by increasing organic matter and nutrient content, which enhanced long-term agricultural production. These results show how circular economy activities have economic and environmental value.

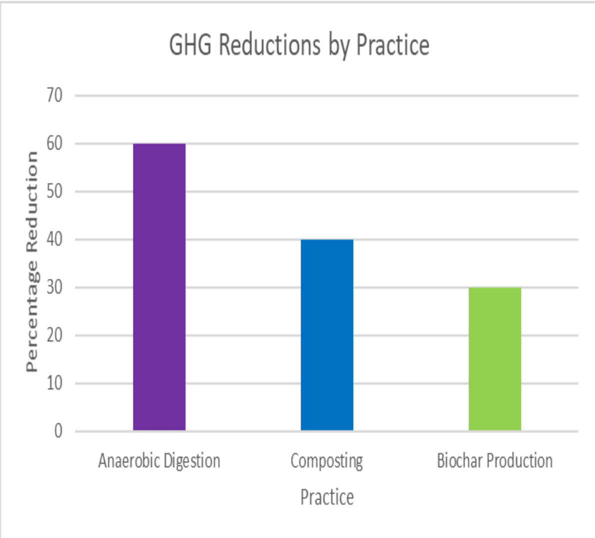

Fig. 3. GHG Reductions by Practice

3.3. Barriers to Adoption

From the analysis, presented in Fig. 4, it was evident that high initial investment costs are the toughest entry barriers to access credit for small-scale farmers. For instance, anaerobic digesters range from $ 50,000 to $ 100,000, and they can only be financed with support or subsidies. Similarly, the cost of constructing it was also high. The cost of producing biochar in biochar production units and composting facilities is high, discouraging its use. The inability to seek technical assistance also continues to be an implementation issue because there is little known as to where to seek it. It is likely that only a few farmers are familiar with the concept of circular economy or should be made aware of any training they could embark on to practice circular agriculture. In addition, there are infrastructural voids, including a need for more structures to support waste collection and handling in circular systems.

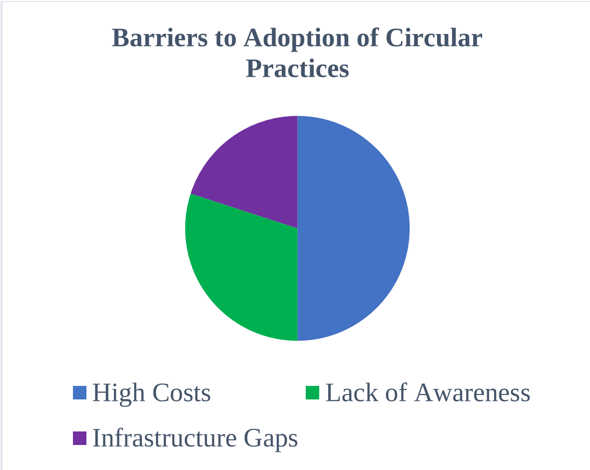

Fig. 4. Barriers to Adoption of Circular Practices

3.4. Policy and Market Implications

To manage these barriers, policymakers need specific remedies. To offset the implementation cost of circulars, it is suggested that the organization should subsidize and offer low-interest loans to the organization. Governments should also utilize training and extension services to educate farmers on the principles of circular economy systems. Market development is still another important consideration. Since its inception, the company has been steadily expanding its markets.Biochar and organic fertilizers are good examples of circular products that farmers will be encouraged to buy once their markets are expanded. The government can also introduce other forms of support formations for these products with the intention of making them popular as well as profitable.

4. Conclusion

The application of circular economy concepts in farming provides a breakthrough approach to addressing waste management challenges and, at the same time, creating value for farmers. Bioenergy, biochar, and compost are examples of value-added agricultural residues and animal by-products that circular practices minimize waste, maximize resource use, and improve soil quality. Practices such as anaerobic digestion and composting, as well as biochar production, were shown in this study to produce economic returns and savings of between 25 and 50 percent while also boosting crop yields by between 10 and 15 percent. Further, these practices also have other benefits, such as the reduction of greenhouse gas emissions and enhanced soil organic matter. However, as the benefits are quite clear, challenges like high costs of entry, shortage of skilled labor, and poor infrastructure prevent the general adoption of the technology. As it is, smallholder farmers, for instance, need help accessing the necessary inputs and knowledge to put circular systems into practice. These barriers can only be overcome with a policy incentive approach that promises subsidies, low-interest loans, and capacity-building programs. The continuing growth of the bio-products markets and the global harmonization of waste management systems will only improve the circumstances for the scale-up of circular processes. The findings underscore the potential of circular agriculture to achieve a dual impact: minimizing impacts on the environment while at the same time increasing the profitability of farming. From the analysis, it was clear that high initial investment costs are the most stringent entry barriers to credit access for smallholder farmers. For instance, anaerobic digesters cost from \$ 50,000 to \$ 100,000 and can only be financed by support or subsidies. Mall-scale farmers. For instance, anaerobic digesters range from \$ 50,000 to \$ 100,000, and they can only be financed with support or subsidies. Likewise, the cost of construction of the same was also high. Production of biochar in biochar production units and composting facilities is expensive and deters use. The other implementation problem that remains is the inability to seek technical assistance because it is still being determined where to turn for it. Only a handful of farmers have an understanding of the circular economy or should be informed of any training they can engage in to practice circular farming. Moreover, there are infrastructural gaps that exist; for instance, there needs to be more structures specifically to manage the collection and handling of waste in a circular system.

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