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Positive impact of organic waste utilization innovation on green energy and green economy

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Abstract. Biogas not only reduces organic waste but also produces a highly valuable renewable energy product. The Energy Independence Village Program (EIVP) assists Muktisari residents in converting livestock, human, and tofu production waste into biogas. This study aimed to analyze the positive impacts of EIVP implementing innovation. The study employed a mixed-method explanatory sequential design to examine the environmental, economic, and social implications of EIVP. Positive ecological benefits showed that biogas utilization can reduce greenhouse gas (GHG) emissions by 1,085.94 tons CO_2e, and bio-slurry (a byproduct of biogas) provides a crucial environmental co-benefit by enhancing soil quality and supporting sustainable agriculture. The economic analysis revealed that biogas production significantly reduced household fuel costs and agricultural input expenses. The adoption of biogas encouraged behavioural changes in energy use, waste management, and farming practices. Findings highlight the program's contribution to circular economy practices and SDG 7 (Affordable and Clean Energy).

1 Introduction

The rapid growth of global energy demand has intensified concerns about greenhouse gas (GHG) emissions and their contribution to climate change. The energy sector remains the dominant source of anthropogenic GHGs, with agriculture and livestock activities also playing a substantial role through the release of methane (CH_4) and Nitrous Oxide (N_2O). Methane, with a global warming potential 25 times that of carbon dioxide (CO_2), is a critical contributor to agricultural emissions [1]. Consequently, managing methane from organic waste streams has become a priority in climate change mitigation efforts worldwide. Biogas technology presents an effective solution by converting organic waste into renewable energy while simultaneously reducing GHG emissions. One cubic meter of biogas can generate

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approximately 1 kWh of electricity, demonstrating its potential as a clean and decentralized energy source [3]. Biogas not only helps address waste management issues but also supports energy diversification, particularly in rural areas with abundant agricultural and livestock waste. The utilization of biogas potential is very much in line with Indonesia's energy policy, as stated in Presidential Regulation of the Republic of Indonesia No. 5 of 2006 concerning the National Primary Energy, which mandates a 17% share of new and renewable energy in the national energy mix by 2025 [3]. Globally, the adoption of biogas systems contributes to sustainable energy transition and the reduction of fossil fuel dependence.

Kampar Regency, Riau Province, Indonesia, has an economy based on agriculture, livestock, and plantations. In 2022, Kampar Regency had 21,000 cattle producing [4]. One adult beef cattle produces an average of 21 kg of manure per day [5], so there are 441 tons of beef cattle manure every day. Without proper management, this waste caused pollution and social problems. In addition to cow dung waste, the people of Muktisari Village, Tapung District, Kampar Regency, also face the problem of tofu household industrial waste, which often causes conflict due to resulting water pollution.Tofu industry waste has a high protein content and is easily decomposed, so without further processing, it can lead to river pollution and foul odors. Tofu wastewater contains more than 50% methane (CH_4), with great potential as a biogas fuel [6].

Another waste with potential as a biogas feedstock is human waste. Human waste has the same potential for biogas generation as cow waste. Human waste can contain up to 70% methane in biogas, and its pH is around 7.3, the optimum pH range for biogas production. The application of human waste to produce biogas has been quite practical at the Bina Umat Islamic Boarding School in Yogyakarta, which has 870 students. One kilogram of human waste can produce approximately 0.35–0.5 m^3 of biogas [7]. A large portion of livestock manure, tofu industrial waste, and human excreta are still unmanaged, contributing to water pollution, unpleasant odors, and methane emissions. These challenges highlight the need for innovative, community-based, and financially sustainable approaches to waste-to-energy utilization.

Corporate social responsibility (CSR) programs have emerged as promising vehicles for promoting environmental innovation and circular economy practices in developing countries. By combining business resources with local participation, CSR-driven initiatives can accelerate the diffusion of green technology, empower communities, and generate multiple co-benefits. This study analyzes the Energy Independent Village Program (EIVP), a CSR initiative implemented by PT Pertamina Hulu Rokan (PHR). The program transforms livestock, human, and tofu production waste into biogas for domestic and institutional use, while also producing biofertilizer (bio-slurry) to support sustainable agriculture. The company's role (PT PHR) is to support investment activities by providing biogas infrastructure, training, and mentoring. Accordingly, the objectives of this study are:

1. To analyze the innovation process of utilizing organic waste as a renewable energy source.
2. To evaluate the environmental, economic, and social benefits derived from waste-to-energy conversion.

By addressing these objectives, the study contributes to the growing body of literature on CSR-driven environmental innovation. It provides policy-relevant insights for scaling up biogas utilization as part of the green energy and circular economy transition in developing countries.

2 Method

2.1 Study Area

The study was conducted in two locations: Muktisari Village, Tapung District, Kampar Regency, and Maharani Village, Rumbai Barat District, Pekanbaru City. Both sites are characterized by mixed rural-urban livelihoods that rely on livestock farming and small-scale agriculture. Before the program's implementation, these villages faced recurring issues related to livestock and industrial waste management, including water pollution, odor, and community health concerns. The program was initiated by PT Pertamina Hulu Rokan (PHR) through its CSR initiative.

2.2 Research design

This study adopts a systems thinking perspective to interpret the interconnections among the Energy Independent Village Program (EIVP) impact. From a system perspective, the program contains three major interconnected domains :

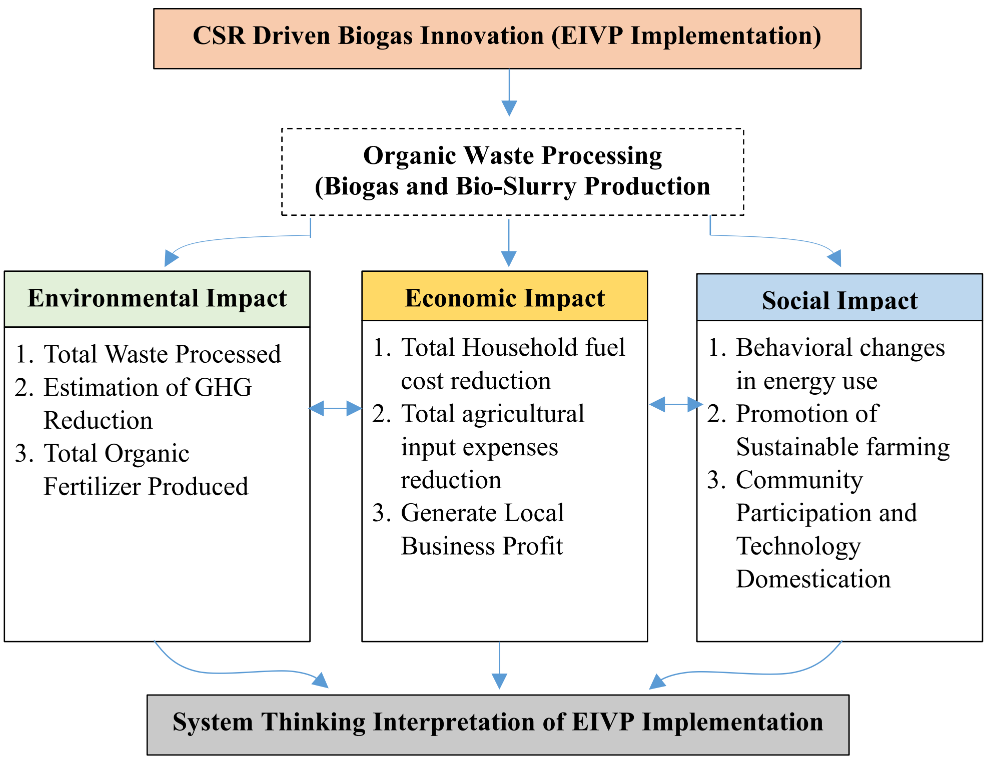

Fig. 1. Conceptual framework for assessing the impact of EIVP implementation

This study employed a mixed-method approach using an explanatory sequential design. The use of mixed methods is intended to explain the results of quantitative analysis obtained through interviews and FGDs with relevant stakeholders. The quantitative phase focused on measuring the environmental and economic outcomes of the biogas innovation, while the qualitative phase provided contextual explanations through stakeholder perspectives. The mixed-method strategy was chosen to capture both measurable impacts and social dynamics surrounding technology adoption.

2.3 Data collection

The study was conducted from June to August 2024 (3 months) through a combination of structured interviews, field observations, and focus group discussions (FGDs).

- Respondent 30 participants that were involved directly in the program, including PHR CSR staff, local group leaders, biogas users, program facilitators, government officials, and group members of Bina Muktisari and Biotama Agung Lestari.
- Sampling technique: purposive sampling focusing on key participants.
- Quantitative data: covered waste volume, biogas production, greenhouse gas (GHG) reduction, and household cost savings.
- Qualitative data: explores changes in community behavior, gender roles, and collaboration networks resulting from the program.

2.4 Data analysis

Quantitative data were analyzed using descriptive statistics to estimate waste utilization rates, energy substitution, and economic savings. Qualitative data from interviews and FGDs were transcribed, coded, and categorized thematically to identify key social impacts and community perceptions related to the EIVP. Quantitative and qualitative findings were integrated during the interpretation phase to provide a holistic understanding of program outcomes.

The greenhouse gas (GHG) emission reductions from biogas utilization are calculated by the standard approach adopted by the Intergovernmental Panel on Climate Change (IPCC). The calculation method used to estimate GHG emissions from organic waste management (livestock, human, and tofu waste) follows IPCC guidelines and other relevant research. Based on the IPCC 2006 Guidelines for National Greenhouse Gas Inventories [8], methane emissions from anaerobic degradation of organic waste can be calculated using the formula:

$$E = Mi \times EFi \times GWP$$

- **E :** Emission CH_4 (kgCH4/year)
- **Mi**: Total waste processed (kg/year)
- **EFi**: Methane emission factors for each type of waste (kg CH_4/kg waste)
- **GWP (*Global Warming Potential*)**: 1 ton CH_4 = 28 ton CO_2e (CO_2 equivalent).

To complement the mixed-method explanatory approach, this study employs a causal loop diagram (CLD) as an analytical tool to interpret the systemic relationship among environmental, economic, and social outcomes of EIVP. The CLD approach is rooted in systems thinking theory, which emphasizes feedback structure, circular causality, and interdependence among system components. The CDL in this research functions as a conceptual mapping instrument to synthesize empirical findings and visualize the feedback mechanism emerging from the implementation of community-based biogas innovation.

3 Results and discussion

3.1 The Energy Independent Village Program (EIVP)

The EIVP is designed to increase community capacity to utilize biogas from several organic waste sources (livestock, human waste, and tofu waste). There are several biogas sources: from wastes and residues of agriculture and related industries, municipal solid waste, municipal wastewater, animal excrement, and Industrial solid and liquid wastes (industrial sludge) [2]. The EIVP is implemented in two stages: the first (2022), focused on cow manure as the initial feedstock, and the second (2023), focused on program innovation using goat manure, tofu production, and human waste.

The EIVP is implemented by the Bina Muktisari Farmers Group, supported by PT Pertamina Hulu Rokan (PHR). The program is located in Muktisari Village, Kampar Regency, and Maharani Village, Rumbai Barat District, Pekanbaru City. They used a biogas fixed dome-type (SNI 7826:2012). A total of 20 digesters have been built in these two stages. In addition to producing biogas, EIVP also produces bio-slurry. Bio-slurry is cow manure that has had its methane removed and flows out of the biogas reactor through the outlet and overflow as sludge. Laboratory analysis shows that fermenting 1 kilogram of fresh manure mixed with 1 liter of water produces 1,840 grams of bio-slurry [9]. There are two products from the biogas production process: solid organic fertilizers (SOF) and liquid organic fertilizers (LOF), also called bio-slurry. The Biotama Agung Group manages the two products. The LOF branding is by "Prima Bio-slurry: Liquid Biological Agent," while the SOF is called "Prima Solid Bio-slurry," and is currently produced on a limited scale. Bina Muktisari Group members have used the LOF to fertilize their oil palm and vegetable crops. It has also been sold to several farmers in Muktisari Village and consigned to the BUMDES Berkah Amanah (Village-Owned Enterprise) and the Tri Manunggal Village Cooperative.

3.2 Environmental impact : waste utilization, GHG reduction, and soil improvement

The EIVP has demonstrated significant environmental benefits by converting organic waste into biogas. Between 2022 and 2024, the program utilized approximately 220,79 tons of organic waste per year, including livestock manure, tofu production residues, and human waste. This utilization represents about 8.08% of total manure, tofu, and waste generated in Muktisari Village, with nearly 100% of tofu production waste successfully converted into biogas.

The use of waste for biogas production directly contributed to reducing methane emissions. The estimated GHG reduction in 2024 reached 563.29 tons of CO_2e, primarily from cattle manure, followed by tofu waste, goat manure, and human excreta. Cumulatively, the program achieved a total reduction of 1,085.94 tons of CO_2e in methane emissions between 2022 and 2024.

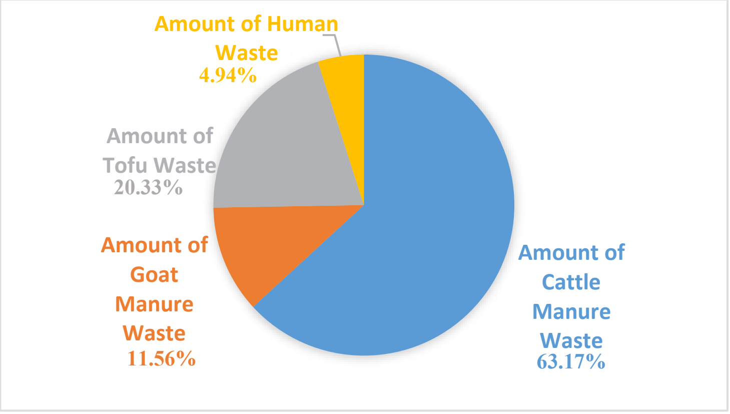

Fig. 2. Contribution of organic waste types to total GHG emission reduction
Source : Processed from primary data collected by CARE IPB (2024)

Figure 2 illustrates the relative contribution of different organic waste streams to total GHG emission reduction. Cattle manure accounts for the largest share, highlighting its strategic role in methane mitigation at the village scale. These results confirm that community-based waste-to-energy systems can substantially contribute to local climate mitigation targets, aligning with the IPCC (2006) guidelines for the methane recovery from organic waste.

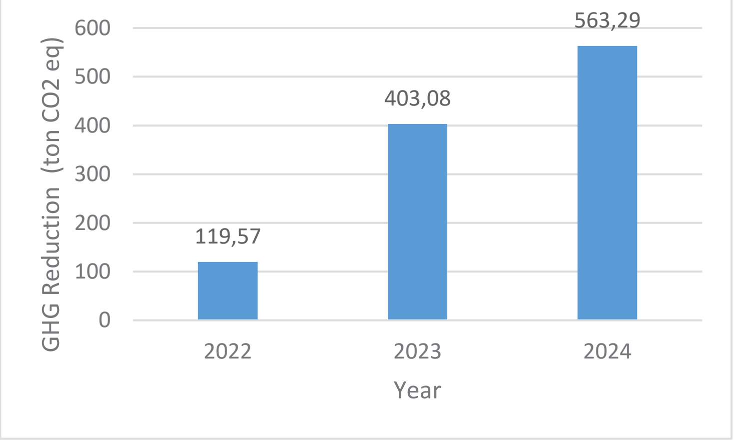

Fig. 3. Cumulative GHG reduction (2022-2024)
Source: Processed from primary data collected by CARE IPB (2024)

Figure 3 shows the estimated GHG reduction reached 563,29 tons CO_2eq in 2024. The results are consistent with previous studies showing that integrating livestock and agro-industrial waste management into biogas systems can reduce methane emissions by up to 70% compared to unmanaged conditions [2, 10]. Moreover, the EIVP produced bio-slurry, a byproduct rich in organic nutrients that contributes to soil health and nutrient cycling, further strengthening the program's circular environmental benefits.

Beyond methane mitigation, the bio-slurry byproduct provides a crucial environmental co-benefit by promoting soil regeneration and supporting sustainable agriculture practices. Laboratory analyses revealed that the liquid organic fertilizer (LOF) contains 2.12% organic carbon, 0.16% total nitrogen, 0.06% phosphorus (P_2O_5), and 0.51% potassium (K_2O), complemented by essential micronutrients such as calcium, magnesium, and iron. The presence of beneficial microorganisms, *Azotobacter sp.* and *Lactobacillus sp,* enhances biological nitrogen fixation and phosphate solubilization, thereby improving nutrient bioavailability in agricultural soils.

Meanwhile, the solid organic fertilizer (SOF) exhibits substantially higher nutrient concentrations, including 23.55% organic carbon, 10.90% total nitrogen, 2.30% P_2O_5, and 3.54% K_2O. Both LOF and SOF also contain humic acid (4–5%), which increases the soil's cation exchange capacity, enhances nutrient retention, and improves soil water-holding capacity. These characteristics make bio-slurry a valuable biofertilizer that can restore soil structure and fertility degraded by prolonged reliance on chemical fertilizers.

Consistent with a previous study [11], the application of bio-slurry significantly improves soil physical and chemical properties within integrated farming systems. Similarly, Dani *et al.* [12] highlighted that biogas digestate also contributes to soil carbon sequestration and enhanced microbial diversity. Collectively, these processes establish a closed-loop nutrient system in which organic waste is recycled into productive agricultural input, strengthening agroecosystem resilience.

Therefore, the EIVP not only reduces waste and emissions but also regenerates the ecological capacity of local agroecosystems, reinforcing its role in circular environmental management. The environmental benefits of the EIVP are driven by two mechanisms: methane capture through aerobic digestion and nutrient recycling via bio-slurry application. While methane capture directly reduces climate forcing, nutrient recycling indirectly mitigates emissions by lowering synthetic fertilizer demand, which is energy-intensive and carbon-heavy.

3.3 Economic impact : circular economy and cost efficiency

The economic analysis revealed that biogas production significantly reduced household fuel costs and agricultural input expenses. A total of 18 households and two Islamic boarding schools participated as biogas users. Before the program, each household consumed between 1 and 5 LPG cylinders per month at an average price of IDR 20,000 per cylinder. After adopting biogas, households saved IDR 240,000–1,200,000 per month, while Islamic boarding schools saved approximately IDR 2.4 million per month. There are several studies about the benefits of biogas production as a substitute for LPG. The average biogas production per dairy farmer household is about 1 m3/year, equivalent to 2,17 kg LPG [18]. On a broader scale, the use of biogas can reduce people's dependence on LPG, as has already happened.

In addition to fuel savings, using bio-slurry as an organic fertilizer reduced reliance on chemical fertilizers. Farmers reported an average saving of IDR 337,500 per hectare per year, resulting in cumulative fertilizer cost savings of IDR 112 million over three years. These savings not only improved household economic resilience but also encouraged the substitution of chemical inputs with more environmentally friendly alternatives.

The production of liquid organic fertilizer (LOF) branded as *"Prima Bioslurry"* also generated direct income for local groups, amounting to IDR 23.3 million in sales with a net profit of IDR 9.3 million between 2023 and 2024 (Table 1). Overall, these findings highlight that the biogas initiative delivers multiple economic co-benefits, ranging from household expenditure reduction to local income generation, thereby strengthening community economic resilience.

Table 1. Summary of economic benefits (2022–2024)

Economic Indicator	Value (IDR)	Benefit Type
Household LPG savings	19,404,000/year	Cost reduction
Fertilizer savings	112,029,750 (3 years)	Input cost reduction
LOF sales profit	9,266,900	Income generation

Source: Processed from primary data collected by CARE IPB (2024

These findings align with those of others, who noted that integrating biogas and bio-slurry utilization in farming systems can substantially enhance energy self-sufficiency and reduce production costs [14]. The EIVP thus serves as a model for local-scale circular economies—turning waste into value while reducing reliance on external inputs. The successful implementation of biogas systems on a larger scale can be a contribution to Sustainable Development Goals, namely: 7. Affordable and clean energy, and 12—responsible consumption and production [13]. Beyond cost saving, biogas adoption enhanced household economic resilience by reducing exposure to volatile LPG prices and fertilizer market shocks.

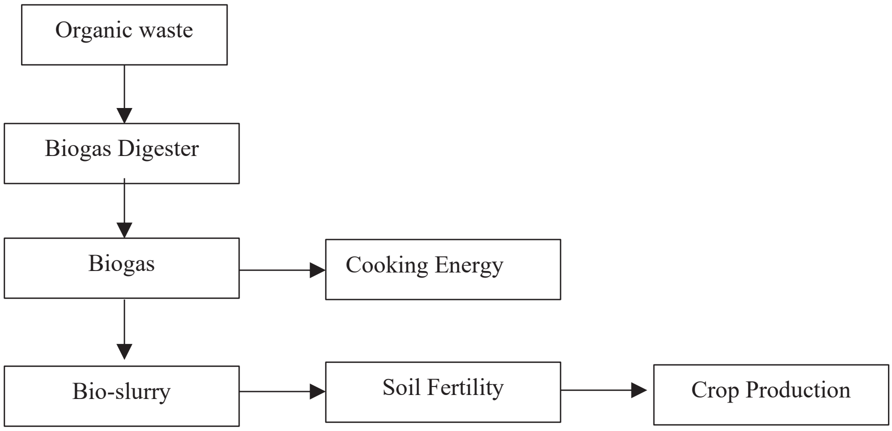

Fig. 4. Circular bioeconomy model of waste to energy and nutrient recycling

Figure 4 presents the closed-loop system of the Energy Independent village Program, where organic waste is converted into renewable energy and nutrient-rich bio-slurry, reinforcing circular bioeconomy principles. In the circular bioeconomic framework, organic waste is not treated as a disposable output. However, it is valorised through biological conversion processes such as aerobic digestion to produce renewable energy and nutrient-rich byproducts that can be returned to agricultural systems, effectively closing materials and nutrient loops and supporting regenerative resource use and ecosystem resilience.

3.4 Social transformation : behavior, knowledge, and cohesion

Beyond its environmental and economic outcomes, the EIVP fostered substantial social transformation among community members. The adoption of biogas technology encouraged behavioral changes in energy use, waste management, and agricultural practices. Households reported a transition from LPG to biogas, reducing dependence on fossil fuels and improving household security against energy price fluctuations.

Community members also gained new technical skills in biogas operation, maintenance, and bio-slurry utilization. Regular training and consultation sessions increased environmental awareness and strengthened local capacity to manage renewable energy systems effectively. This is consistent with research results Alam and Pratiwi [15], which found that community engagement in biogas programs leads to greater technology acceptance and social empowerment.

Furthermore, social cohesion improved through collaboration among farmer groups, tofu producers, Islamic boarding schools, and local cooperatives. The formation of partnerships such as Bina Muktisari Farmers Group, Biotama Agung Lestari Group, and BUMDes Berkah Amanah facilitated joint management of renewable energy resources and strengthened trust across community institutions. Notably, conflicts previously caused by unmanaged livestock and tofu waste declined markedly after the program's implementation.

These social outcomes confirm that renewable energy initiatives, when embedded in community participation and CSR collaboration, can serve as catalysts for broader social and institutional transformation. The EIVP thus exemplifies how technological innovation can be socially internalized, forming part of a *"green social contract"* between corporations and rural communities.

The findings support the concept of technology domestication, in which biogas systems are gradually integrated into daily routines, social norms, and local institutions rather than remaining as external technological interventions.

3.5 Systemic feedback structure of The EIVP

To synthesize the empirical findings, a causal loop diagram is constructed to illustrate the feedback mechanisms linking waste utilization, energy substitution, economic savings, and social adoption within the EIVP System.

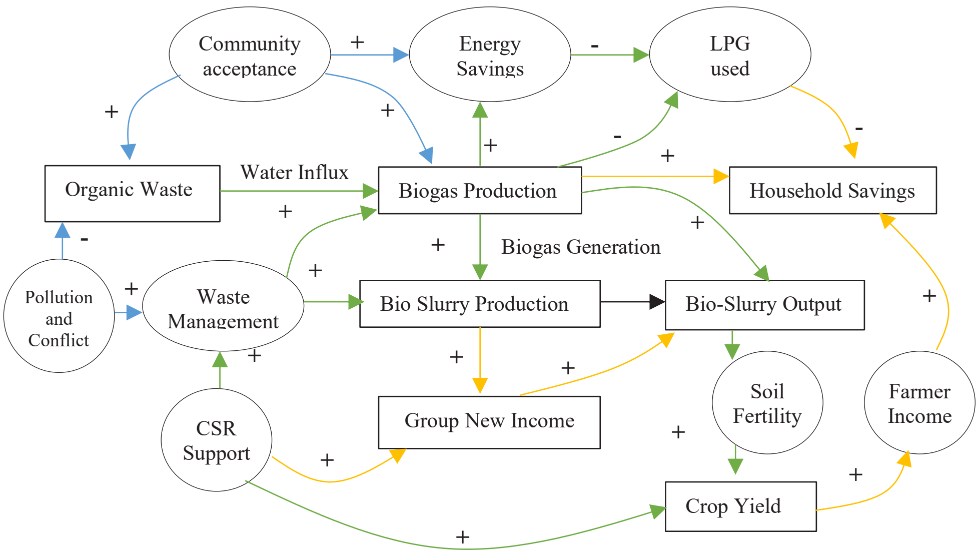

Fig. 5. Causal loop diagram: the EIVP

Figure 5 shows green arrows representing a causal relationship in the environmental subsystem. Yellow arrows illustrate operational resource flows and the circular bioeconomy mechanism linking biogas production, nutrient recycling, and economic benefit. The blue arrow represents social relationships that influence community acceptance, technology adoption, and institutional collaboration.

The environmental subsystem shows that organic waste utilization increases biogas production. Higher biogas production substitutes for more energy saving and reduces LPG consumption. At the same time, biogas production generates bio-slurry. Bio-slurry improves soil fertility and increases crop productivity.

The economic subsystem showed that more LPG is used, thereby increasing household fuel use. Biogas production generates household cost savings. The bio-slurry has an impact by increasing crop productivity, generating more income for farmers and households, and saving. Bio-slurry also generates new business for the Farmer Group.

The social subsystem explains that CSR support enhances infrastructure development and training, increases community acceptance and awareness of organic waste and biogas production. Waste management also reduces pollution and community conflict.

4 Conclusion

This study showed that the CSR-led biogas initiatives implemented through the EIVP IN Kampar Regency generate integrated environmental, economic, and social benefits within its specific local context. At the village level, the program contributes to reduced methane emissions, lowers household expenditures, and supports sustainable agricultural practices through the use of bio-slurry.

The waste-to-energy conversion process demonstrated a localized circular bioeconomy mechanism in which organic waste is transformed into renewable energy and nutrient resources. However, the outcomes observed are closely linked to the particular institutional setting, corporate support, and community characteristics in the study area. The scale and sustainability of the initiative are strongly influenced by CSR commitment, technical assistance, and local participation.

Therefore, the finding should be interpreted within the limits of this case study and not generalized without considering contextual differences in governance capacity, financial arrangements, and waste availability. While the program indicates potential contributions to SDGs 7 and SDGs 12, broader applicability depends on supportive institutional and socio-economic conditions. Future research should examine comparative cases and long-term sustainability to assess better the transferability of CSR-supportive initiatives beyond the realm of CSR.

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