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ORIGINAL ARTICLE

Influence of climate-smart technologies on the success of livestock donation programs for smallholder farmers in Rwanda

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Abstract

Climate change threatens the livelihoods of Sub-Saharan African farmers through increased droughts. Livestock donation programs offer a potential solution, but their effectiveness under climate stress remains unclear. This study assesses the economic viability of integrating climate-smart technologies (cowsheds and biogas plants) into these programs in Rwanda. Using a stochastic benefit–cost analysis from the beneficiary perspective, we evaluate the net gains for households receiving heifers compared to the current program. Our findings reveal that integrating climate-smart technologies significantly enhances economic viability. Households with cows and climate-smart technologies can possibly realise net benefits 3.5 times higher than the current program, with benefit–cost ratios reaching 5:1. Beyond economic benefits, adopting biogas reduces deforestation, greenhouse gas emissions, and respiratory illness risks. This study demonstrates that integrating climate-smart technologies into livestock donation programs can generate positive economic, environmental, and health benefits, leading to more resilient and sustainable smallholder systems. However, overcoming implementation challenges requires tailored policy packages addressing local barriers.

Keywords Aid effectiveness · Sustainable economic development · Low- and medium-income countries · Poverty reduction

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1 Introduction

Sustainable development goals (UN General Assembly 2015) recognise the critical role of agricultural development in poverty reduction and food security for marginalised rural populations in Sub-Saharan Africa. Agricultural development is a key poverty reduction strategy due to its potential for inclusivity compared to non-agricultural sectors (Corral et al. 2017; FAO 2018; World Bank 2016; 2018).

Sub-Saharan Africa's rural communities are particularly vulnerable to the impacts of climate change, including frequent droughts, intensified floods and storms, and variable rainfall, which undermine food security and compromise the viability of smallholder crop-livestock production systems (Abebe et al. 2022; 2023; Adesete et al. 2023; Baptista et al. 2022; Bedasa and Deksisa 2024). Sub-Saharan Africa's vulnerability to variable climate is heightened by its dependence on rain-fed, low-input, and small-scale cropping systems (Omotoso et al. 2023; Njoya et al. 2022). Increasing rates of greenhouse gas (GHG) emissions from agricultural production are projected to further exacerbate the frequency and severity of changes in weather patterns (The Intergovernmental Panel on Climate Change (IPCC), 2007, 2023). In response to the intensifying climate change threat faced by smallholder agricultural systems in low- and middle-income countries, there is a need to prioritise effective adaptation and mitigation efforts (Hansen et al. 2019; Madamombe et al. 2024; Shikuku et al. 2017) and address growth inequality issues (Manero et al. 2020). Improving access to climate-smart technological innovations can mitigate the impact of climate change on food production and the livelihoods of the region's population (Gashure et al. 2022).

Staple crop yields could decrease by up to 10–15% due to projected changes in temperature and precipitation by 2050 in Rwanda (Austin et al. 2020), highlighting the need to prioritise support for food security and climate resilience in Rwanda's agricultural sector (Mperejekumana et al. 2024; Niyitanga et al. 2015). As the impact of climate change poses a threat to Rwanda's agricultural economy, the adoption of climate-smart innovations, such as diversified livestock and crop systems and the use of renewable fuels, holds the potential to enhance the resilience of food production systems and the livelihoods of the majority of the country's population, which are reliant on rain-fed subsistence agriculture (Swarnam et al. 2024). Climate-smart technological innovations are designed to improve resilience to variable weather patterns, reduce greenhouse gas emissions, and increase agricultural productivity and income.

In Eastern Africa—namely, Uganda, Kenya, Tanzania, Rwanda, and Burundi—the variability in staple crop yields is influenced by climate variability (Mubenga-Tshitaka et al. 2023). Improving access to technological innovations, particularly among female beneficiaries, and increasing livestock and milk production can improve the resilience of food production systems and food security in the region (Ojara et al. 2022; Warinda et al. 2020). Globally, climate change, disproportionately, threatens agricultural production in vulnerable regions with concentrated poverty and rapid population growth. This is particularly evident in Africa, Central Asia, and Latin America, where frequent droughts and variable rainfall significantly constrain agricultural output (Guo et al. 2022; Ortiz-Bobea et al. 2021).

Growing evidence suggests that livestock and milk production, facilitated by livestock donation programs, can serve as an effective climate adaptation strategy for smallholder farmers in Sub-Saharan Africa, demonstrably improving incomes, nutrition, and food security in rural communities (Argent et al. 2014; Baidoo et al. 2016; Inoni 2010; Nilsson

2019). Livestock contributes to increased incomes directly through milk and meat sales and indirectly by providing organic fertilisers that improve soil fertility and increase crop productivity (Collishaw et al. 2023; Erdaw 2023). Incorporation of livestock into smallholder systems through donation programs not only diversifies food sources but also generates alternative income streams, mitigating the risks associated with seasonal fluctuations in crop production and food availability (Banda & Tanganyika 2021; Chen et al. 2021).

The increasing prevalence of livestock donation programs as a poverty reduction strategy for smallholder farmers in low- and medium- income countries presents an opportunity to mitigate the contribution of livestock production to climate change. Leveraging livestock donation programs to promote the installation of biogas plants that utilise livestock waste to generate clean energy for domestic use can simultaneously mitigate poverty, food insecurity, and climate change (Bateki et al. 2023; Ezeanya & Kennedy 2016). Most households in rural areas of Sub-Saharan Africa rely on fuelwood as their primary energy source. However, sustained population growth and accelerating deforestation compromise the long-term viability of fuelwood as a cost-effective energy source (Shackleton et al. 2022). Supporting beneficiaries of livestock donation programs to produce biogas as a cleaner and cheaper alternative energy source for domestic use can yield economic, health, environmental, and social benefits in rural parts of Sub-Saharan Africa (Dagnachew et al. 2020; FAO 2018; Rasimphi & Tinarwo 2020). In addition, integrating biogas production as a core element of livestock donation programs could reduce the net GHG footprint of livestock donation programs (Ahmad & Jabeen 2023; Brini 2021; Dagnachew et al. 2020).

This study is aimed at investigating the net household economic effect of the Girinka program through three key research questions: (1) Do program benefits of livestock donation programs for households outweigh costs? (2) Could alternative program designs that incorporate climate-smart cowsheds and biogas plants change the potential net benefit for participants? and (3) What factors influence the potential net benefit for beneficiary households? We hypothesise that the joint distribution of biogas production plants and heifers can result in positive net benefits for rural households, contributing to improved livelihoods, economic development, and environmental sustainability. Quantifying the net benefit at the household level can provide valuable insights for policymakers and practitioners working in rural development, sustainable agriculture, and climate change mitigation.

While numerous empirical assessments have evaluated the economic and social impacts of livestock donation programs in Sub-Saharan Africa and beyond (e.g. Argent et al. 2014; Baidoo et al. 2016; Hansen et al. 2019; Inoni 2010; Kafle 2014; Rawlins et al. 2014; Salazar et al. 2018; Shikuku et al. 2017), existing evaluations primarily focus on specific outcomes such as income and nutrition improvements (Kafle 2014; Kayigema 2013; Rawlins et al. 2014) or enhanced crop productivity (Christiaensen et al. 2011; Kim et al. 2013). Although the potential economic benefits of integrating climate-smart technologies, including mitigation and adaptation options, within poverty reduction strategies like livestock donation programs are widely acknowledged (Bucagu et al. 2014; Ezeanya & Kennedy 2016; Kayigema & Rugege 2014; Klapwijk et al. 2014), thorough quantitative evaluations of such benefits remain scarce. Notable examples include Shikuku et al.'s (2017) ex-post regression analysis of climate-smart livestock technologies and Hansen et al.'s (2019) ex-post econometric study assessing the impact of these technologies on agricultural production and income.

This research contributes to the emerging body of literature on potential benefits of climate-smart agricultural practises in low- and middle-income countries (Li et al. 2023; Swarnam et al. 2024; Tabe-Ojong et al. 2024). Our evaluation framework utilises a stochastic household benefit–cost analysis (BCA) to explicitly quantify inherent variability in parameter values that influence the costs and benefits of adopting climate-smart technological innovations at the household level (Akinyi et al. 2022; Mutenje et al. 2019). This approach enables the comprehensive quantification of variable household costs and benefits, accounting for inter-household variation in the cost of animal feed, water, and access to artificial insemination and veterinary services (Kayigema & Rugege 2014; Mutimura & Everson 2011). The study's unique feature lies in its comprehensive consideration of a wide range of uncertain fixed capital and variable costs and benefits from the perspective of beneficiary households. It addresses the variability in the expected per-household net benefit value due to the variability in reported unit cost and benefit values. The research evaluates the potential impact of providing biogas production plants and heifers to rural households, specifically through the *One Cow per Poor Family Program* in Rwanda's Eastern and Western provinces.

While initial evidence suggests potential challenges with ground implementation (Issahaku et al. 2024), neglecting an assessment of program modifications integrating livestock donation with biogas plant distribution could overlook opportunities for improved resource allocation within development aid programs, provided such modifications deliver a net positive economic impact. The emergence of new, affordable small-scale biogas production technologies and their successful implementation in Latin America (Garfi et al. 2016; Rocha-Meneses et al. 2023; Vásquez et al. 2024) presents a significant opportunity to consider the distribution of biogas plants as a component of livestock donation programs in Sub-Saharan Africa and other low-income countries.

The rest of the paper is organised as follows: Section 2 describes the case study area. Section 3 outlines the stochastic BCA methodology to address our key research questions. Section 4 presents the findings, while Section 5 discusses the findings in the context of the reviewed literature, along with implications, limitations, and future research directions. Finally, Section 6 draws out the key study conclusions.

2 Case study area context description

Our case study area is Rwanda's Eastern and Western provinces in Eastern Africa, one of the countries in the south of the Sahara Desert considered among the world's most food insecure regions (FAO, 2018) (Fig. 1). Due to the limited observed variation between Rwanda's Eastern and Western provinces in relation to our research objectives, we opted to analyse them as a single, combined case study area. Therefore, although geographically distinct, the Eastern and Western provinces exhibited similar characteristics relevant to our investigation, justifying their amalgamation into a unified case study area for this analysis.

Rwanda is the most densely populated country in East Africa with a population of 11.6 million and a total area of 26,338 km^2, 33% of which is arable land (Ezeanya and Kennedy 2016; International Fund for Agricultural Development (IFAD), 2016). Agriculture drives Rwanda's rural economy contributing substantially to food production, rural employment, and incomes. In 2015, 81% of Rwanda's population lived in rural areas, with 68% of the rural population living below the poverty line. In Rwanda, where 67% of the poor reside in rural areas and rely on agriculture, continuous growth in agricultural productivity is essential for achieving food security and reducing poverty (World Bank 2016). In 2018, 19% of households experienced food insecurity, and 38% of children under five suffer from stunted growth due to chronic undernutrition (World Bank 2018). Land use in Rwanda typically involves mixed crops, including beans, cassava, wheat, maize, and rice, along with

Fig. 1 Map of Rwanda showing the Eastern and Western provinces (shaded). Source: Locator map adapted from eMapsWorld

smallholder livestock farming systems that cover land areas ranging from 0.2 to 1 hectare (ha) per farm. The average land holding for most farmers is 0.76 ha (Nilsson 2019). Livestock farming plays a crucial role in Rwanda's agricultural production and is integral to the economic and cultural life of the country's rural areas. It is a significant source of nutrition, income, and employment, with over 70% of agricultural households engaged in livestock husbandry (Rafael 2023). The average household in Rwanda has seven to eight members and one to three cows (RGB 2018).

The average consumption of fuelwood and charcoal in Rwanda is estimated at two kilogrammes per person per day, leading to significant pressure on 16% of the country's rural land that is forested (Bikorimana et al. 2023). This high demand for fuelwood and charcoal has also increased costs, with rural households spending up to 15% of their monthly incomes on fuelwood for cooking and lighting (Anaclet 2023). Exposure to wood smoke from using fuelwood stoves in Sub-Saharan Africa has been strongly linked to respiratory diseases, particularly among women and children traditionally responsible for cooking duties (Bede-Ojimadu & Orisakwe 2020). The introduction of alternative clean energy sources for rural household energy use, with an emphasis on biogas generated from cow dung, is widely considered a logical option due to steady increases in the availability of cow dung across rural areas of Rwanda (Onyekaozuoro et al. 2023; Rubagumya et al. 2023).

The 'One Cow Per Poor Family' program, locally known as Girinka, was initiated in Rwanda in 2006 as a poverty reduction livestock donation program. Under this program, crossbred heifers are distributed to economically vulnerable households, with the requirement that the first female calf born to the recipient family is passed on to another household (Rwanda Ministry of Agriculture and Animal Resources) (MINAGRI), 2006). Households eligible for the Girinka program in Rwanda are identified by the village community based on specific criteria. These criteria include the absence of prior cow ownership, ownership of land ranging from 0.25 to 0.75 hectares, prior construction of a traditional cowshed, and classification as ‘poor’ according to a community-based poverty assessment system. This system assigns household vulnerability scores based on various indicators such as health, housing, food security, income, and land ownership. The primary objectives of the program are to promote increased rural milk consumption to address malnutrition issues, particularly among children.

Second, the program aims to improve household food security by increasing crop yields by adopting integrated crop-dairy farming and applying organic manure for soil fertility enhancement. Third, it aims to empower rural communities by diversifying income sources via integrated farming practises. Secondary objectives include introducing environmentally friendly agricultural production systems through emphasising zero-grazing and encouraging manure utilisation through organic fertiliser production and biogas generation, offering a clean alternative to fuelwood dependence, and contributing to reduced deforestation and improved air quality.

The Girinka program is funded by the Rwandan government in partnership with the private sector, civil society organisations, local non-government institutions, and international organisations. Between 2006 and 2015, the Girinka program distributed 297,060 heifers to 297,060 rural households impacting over 1.2 million individuals, representing around 16% of Rwanda’s total rural population (Rwanda Governance Board (RGB), 2018). A more recent empirical investigation has examined the progression of the Girinka program’s implementation, coverage, and effectiveness, affirming the assertions made by the RGB (Habiyaremye et al. 2021). Figure 2 shows how cows were distributed between 2006 and 2015 across Rwanda’s five provinces under the Girinka program. The Rwandan government intends to reach more than 700,000 poor households by 2035 under the Girinka program.

While the Girinka program has been primarily associated with positive impacts, such as increased agricultural production and household income (Argent et al. 2014; Nilsson et al. 2019), it has been observed that the program can impose an energy cost burden on rural households (Khundi-Mkomba et al. 2023). Limited access to veterinary services and adequate water supply imposes substantial financial burdens on program beneficiaries, potentially undermining the economic viability of the intervention for beneficiary households (Sapp et al. 2023).

Fig. 2 Distribution of cows between 2006 and 2015 (left) and across Rwanda’s five provinces (right). Source: Adapted from RGB (2018, p. 13)

While biogas technology can potentially improve rural livelihoods and reduce energy costs for low-income Rwandan households, its adoption has been remarkably low due to prohibitive capital set-up costs and high dis-adoption rates (Lwiza et al. 2017; Mukeshimana et al. 2021). The Rwandan government put in place energy policies to prioritise biogas energy production and use in recognition of the opportunity presented by the Girinka program to reduce deforestation and GHG emissions (Ezeanya and Kennedy 2016). A government subsidy program aimed at providing materials and technical support to rural households in Rwanda's Eastern Province to incentivise biogas generation at the household level has not yet proven to be effective (Ezeanya & Kennedy 2017; Roopnarain and Adeleke 2017).

This research is motivated by the widespread discussion in the literature about the potential for realising positive economic, health, social, and environmental externalities from the Girinka program through the adoption of biogas production (Berhe et al. 2017; Bucagu et al. 2014; Geddafa et al. 2023; Kayigema & Rugege 2014; Klapwijk et al. 2014). However, the potential net benefit at the household level is rarely quantified. This study addresses this gap by quantitatively assessing the potential net benefits of adopting biogas production for domestic energy use among Girinka beneficiary households. Given the potential influence of implementation challenges on the current prevalence and efficiency of biogas plants (Kalina et al. 2022), we discuss policy tools that could address these obstacles and potentially contribute to more widespread and effective adoption.

3 Methodology

A six-step ex-ante benefit–cost analysis (BCA) was conducted to estimate present values (PV) of costs, benefits, and net benefits under the current program design and three alternative program design scenarios from the perspective of beneficiary households (Fig. 3).

The baseline scenario, or 'without project' scenario, served as a reference point for identifying and quantifying additional costs and benefits of the current program and the alternative program designs. The counterfactual 'without project' scenario did not involve a control group as commonly seen in experimental designs, noting that this was not an impact evaluation, but rather a conceptual construct that explores potential future trajectories under the assumption of the project not being implemented. The analysis involved identifying relevant costs and benefits, calculating net benefits, and comparing incremental costs with additional benefits of switching to alternative program design scenarios. The costs and price values were converted to 2020 USD equivalent values to standardise the cost and benefits used in net benefit calculations. The net PV benefit to households was calculated over 25 years between 2018 and 2043, and discount rates between four and seven percent were used. The analysis also included a sensitivity analysis to test the robustness of household net benefit estimates. Cost and price values were adjusted for inflation using US government CPI data. The following sections provide further details describing how each of the six steps was implemented.

3.1 Scenario description

Table S.1 in Supplementary Material presents an overview and the assumptions considered for the baseline, current program, and three alternative program design scenarios, including program costs and household costs and benefits.

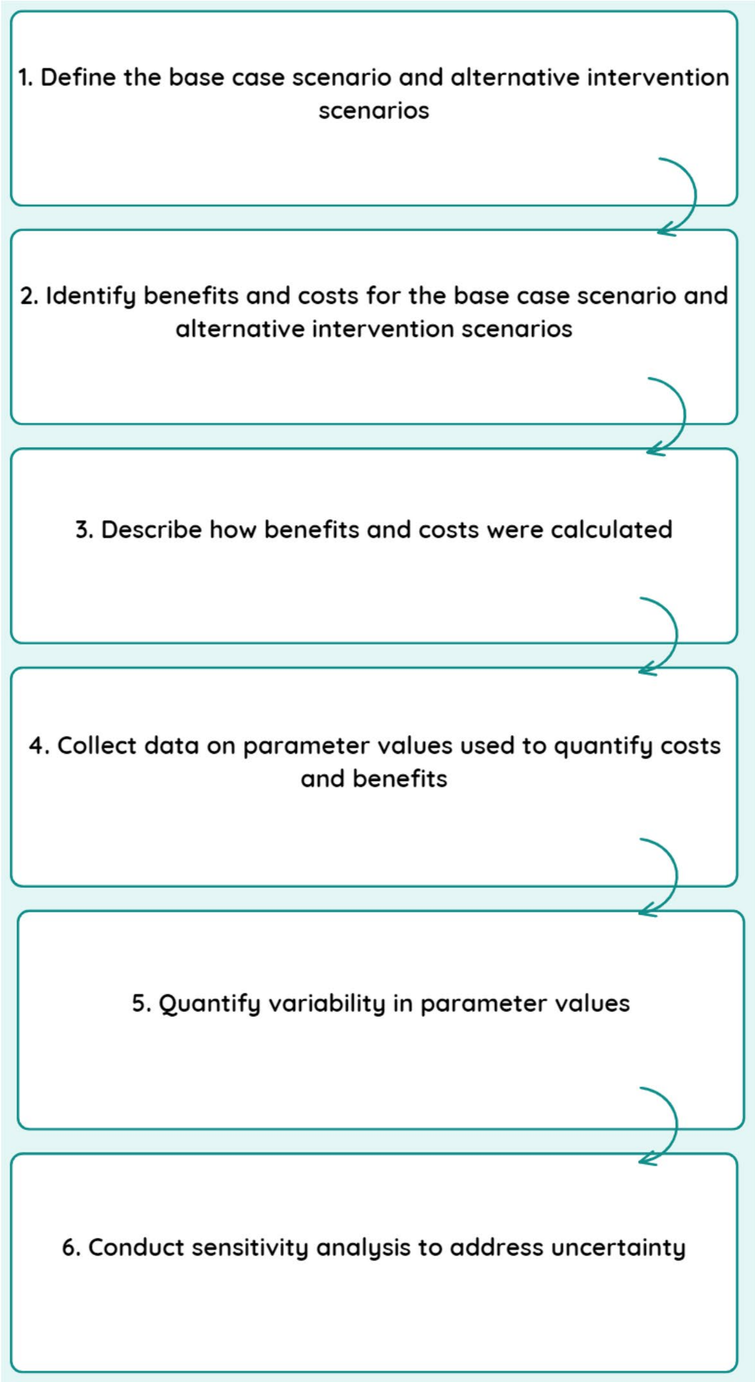

Fig. 3 Flowchart depicting the steps involved in benefit–cost analysis of integrating climate-smart technological innovations to Rwanda's livestock donation program

Our counterfactual baseline (without project) depicts a scenario with few households owning heifers and traditional cowsheds, and climate-smart technologies, including improved cowsheds and biogas plants, are virtually absent. Subsistence rainfed cropping systems predominate. Climate-smart cowsheds are equipped with effective rainwater harvesting, flooring, and waste management systems to ensure efficient removal and storage of manure and disease management. As such, climate-smart cowsheds experience less manure production loss and milk loss due to mastitis than traditional cowsheds made from locally found materials, with basic flooring and no storm and wastewater management system (IFAD 2016). Mastitis infections in dairy cows are primarily caused by poor hygiene practises, including ineffective cowshed waste management, which can lead to udder infections and a reduction in milk yield and quality (Iraguha et al. 2015). Additionally, in our sensitivity analyses, we quantified the net benefit value under various baseline scenarios to account for different initial adoptions of various combinations of heifers, climate-smart cowsheds, and biogas plants prior to program intervention, in order to adequately address varying levels of asset ownership across beneficiary households (Robinson & Hammitt 2017).

In the initial analysis, the baseline scenario served as a reference point to estimate the net benefit to households under the current Girinka program design, which primarily focused on providing one lactating heifer per poor rural household, along with the requirement for beneficiaries to construct a traditional cowshed. Subsequently, the net benefit of transitioning from the baseline scenario to a scenario involving the distribution of climate-smart cowsheds to beneficiary households in addition to lactating heifers was calculated. We further assessed the net benefit of adding affordable biogas production plants (tubular polyethylene biodigesters) to the traditional heifer and cowshed package. This involved accounting for the cost savings households would accrue by replacing fuelwood, their primary domestic energy source, with biogas. Moving beyond traditional program elements, we investigated the 'everything scenario', where households received all interventions: heifers, biogas plants, and climate-smart cowsheds. Net benefits were then estimated relative to the baseline for comparison. To assess the robustness of our findings, we conducted further sensitivity analyses to evaluate net benefits under various baseline assumptions.

3.2 Identifying benefits and costs

Informed by a review of literature on livestock donation programs and household biogas production, we identified costs and benefits for beneficiary households (Table 1).

The BCA framework comprises three primary cost and benefit components, namely: (1) fixed capital set-up costs, (2) variable costs, and (3) household benefits (Fig. 4).

The costs were broadly categorised into fixed capital set-up costs (cowshed construction costs) and variable operations and maintenance (O&M) costs (feed, watering, artificial insemination, and veterinary services and labour). The direct benefits of owning a heifer include manure, calves, milk, and meat consumption and revenue. Owning a biogas plant can lead to health benefits and reduced GHG emissions and reduced deforestation. Health, social, cultural, and environmental benefits are rarely quantified. The framework incorporated three main categories of fixed program costs: (1) capital set-up for lactating heifers, including purchase and distribution overhead with transaction costs; (2) augmentation of traditional cowsheds with climate-smart features like rainwater harvesting, flooring, and waste management; and (3) installation of biogas production plants. To align with the Girinka program's practise of paying a fixed fee per delivery, independent of the number of

Table 1 Summary of benefits and costs of owning a heifer and a biogas production plant to households and basic assumptions based on a review of literature

Costs and benefits	Finding
Household costs	
Capital set-up costs	
Cowshed construction costs	Households spend between USD 31 and USD 62 per cow on cowshed installation per year depending on the quality of materials used (Kayigema 2013). Top end climate-smart cattle shelter can cost up to USD165 per cow (Miklyaev et al. 2017). A climate-smart cowshed includes a rainwater harvesting system, good quality flooring, and a waste management system for efficient removal and storage of dung and urine and improved feed and watering points (IFAD 2016)
Operation and maintenance costs	
Feed	The cost of feeding a heifer varies significantly depending on the type of feed used and can range between USD 119 and USD 2837 per cow (IFRC 2016; Miklyaev et al. 2017)
Watering	Households spend between USD 15 and USD 730 per cow per year on watering (IFAD 2016; Kayigema 2013; Miklyaev et al. 2017)
Artificial insemination	The Rwandan government provides artificial insemination services at a heavily subsidised cost to smallholder dairy farmers (IFAD, 2016). Use of artificial insemination services is low, with 58% of farmers having access artificial insemination services (USAID 2016)
Veterinary services	Treating against risk of mastitis can incur a cost of up to USD26 per cow in veterinary services, and USD12 per cow for treatment (Mwabonimana et al. 2015). Annual veterinary costs can total between USD 61 and USD 70 per cow (Miklyaev et al. 2017)
Labour	The cost of labour to care for animals can range between USD 47 and USD 79 per cow per year depending on the quality of care provided (Miklyaev et al. 2017). Family labour is usually sufficient, with average household population of eight people per household (RGB 2018)
Household benefits	
Benefits of owning a heifer	
Manure	Over 90% of Girinka beneficiaries use manure, and report increased yields and improved soil fertility due to manure use (Kim et al. 2013, 2011)
Calves	Girinka beneficiaries reported selling the second calf for up to USD 329 per calf (IFRC 2016). The average calving interval is typically between 15 and 18 months (Miklyaev et al. 2017)
Milk consumption and revenue	Provision of heifers with training increased milk production for household consumption and for sale (Argent et al. 2014). Girinka contributed 89% increase in milk production between 201and 2015 (RGB 2018)

Table 1 (continued)

Costs and benefits	Finding
Meat consumption and revenue	Meat sales from post-lactation cows that have been culled can generate significant income for households (Salazar et al. 2018). Rawlins et al. (2014) found substantial impacts of cow transfers on household meat consumption and children's nutrition outcomes. The average calving interval was assumed as ranging between 15 and 18 months, and after four intervals, a heifer is culled and slaughtered to be consumed or sold for meat (Miklyaev et al. 2017)
Benefits of owning a biogas plant	
Household energy cost savings	Biogas use for household energy needs can save households from incurring monthly energy expenditures of up to USD 15 per household (Mwakaje, 2008; Surendra et al., 2014). Integrating biogas to Girinka program can yield significant energy cost savings for rural households (Ezeanya & Kennedy 2017)
Health benefit from reduced pollution	Fuelwood powered stoves used for cooking emit toxic gases linked with high prevalence of respiratory diseases (Nix et al., 2022)
Reducing GHG emissions and deforestation	Widespread adoption of biogas can reduce GHG emissions and deforestation (Garfí et al., 2016; Katuwal and Bohara, 2009; Paul et al., 2017)

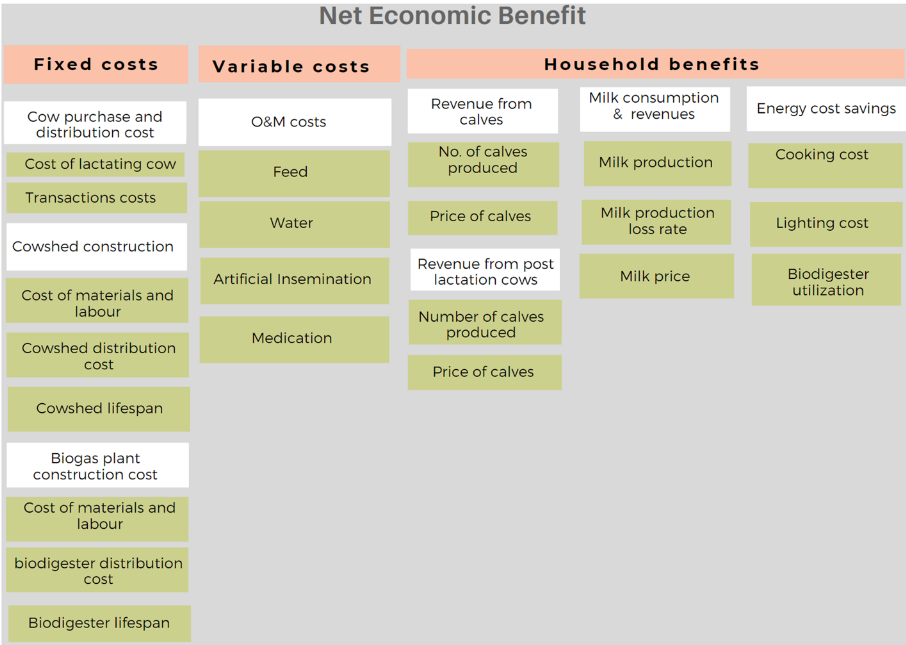

Fig. 4 Organisational structure used to estimate costs and benefits of current and alternative Girinka design programs

cows (International Federation of Red Crescent Societies (IFRC), 2016), transaction costs were treated as fixed in this study. This assumption simplifies the model while representing the program's actual cost structure. Notably, fixed capital set-up for individual households factored in the cost of a standard cowshed lacking storm and wastewater management, reflecting current Girinka program requirements.

Variable costs encompassed ongoing O&M expenses for feed, water, artificial insemination (AI), and veterinary services. Household benefits included both consumption and revenue streams from milk, calves, and post-lactation cow sales. While potential yield increases from increased manure application in subsistence farming (Kim et al. 2013, 2011) were acknowledged, they were not quantified due to a potential trade-off with labour allocation for heifer husbandry, expected to decrease crop yields.

3.3 Calculating costs and benefits

This section illustrates the calculation of individual component costs and benefits, ultimately contributing to the household net benefit estimation. Parameter descriptions, notations, units, value ranges, underlying assumptions, and source references for the subsequent mathematical equations are provided in Table 1 and S.3 in Supplementary Material.

3.3.1 Fixed capital set-up costs

In the 'without project' scenario, households bore the full cost of acquiring a lactating heifer. Fixed program costs during the initial year encompassed heifer procurement and distribution, including transaction costs. These transaction costs covered delivery logistics, with maintenance during transit (hiring and operating facilities, staff for transport, feeding, watering, cleaning, and cow dung disposal), and institutional overheads (hiring program leaders, focus group workshops for beneficiary identification and validation, basic animal husbandry training, and cowshed construction support) (IFAD 2016; IFRC 2016).

The PV of fixed costs of constructing a traditional cowshed, $\mathrm{PV\_Constr}_{T\mathrm{trad}}$, was calculated as the sum of the initial construction's PV in year t_0 and the PV of its replacements at the end of its lifespan throughout the 25-year analysis period. This can be expressed as:

$$\mathrm{PV\_Constr}_{T_{\mathrm{trad}}} = \sum_{t_{\mathrm{trad}}} \frac{\mathrm{Constr}_{\mathrm{trad}}}{(1+\mathrm{DR})^{t_{\mathrm{trad}}}} \quad \text{for } t_{\mathrm{trad}} = 0, 4, 8, 12, 16, 20 \tag{1}$$

where t_{trad} is the year that a replacement traditional cowshed is constructed every five years after the initial construction year, t_0 (i.e. $t_{\mathrm{trad}}=0$ inclusive) with the average lifespan of a traditional cowshed estimated at 5 years. DR is the discount rate.

The PV of fixed capital costs of constructing climate-smart cowsheds with a longer lifespan, estimated at 12 years ($\mathrm{PV\_Cowshed}_{\mathrm{Tcs}}$), were calculated as:

$$\mathrm{PV\_Cowshed}_{T_{\mathrm{cs}}} = \sum_{t_{\mathrm{cs}}} \frac{\mathrm{Dist}_{\mathrm{cs}}+\mathrm{Constr}_{\mathrm{cs}}}{(1+\mathrm{DR})^{t_{\mathrm{cs}}}} \quad \text{for } t_{\mathrm{cs}} = 0, 11, 22 \tag{2}$$

where $\mathrm{Dist}_{\mathrm{cs}}$ is the cost of distribution, $\mathrm{Constr}_{\mathrm{cs}}$ is the cost of construction, and t_{cs} denotes the year of replacement for a climate-smart cowshed. This occurs every 11 years, starting from the initial year of program implementation, t_0, considering the average lifespan of 11 years.

The PV cost of constructing a tubular polyethylene biodigesters ($PV\_Biod_{Tbiogas}$) considered the most cost-effective biogas technology based on Garfi et al. (2016) was calculated as the sum of two components: (1) the PV of initial distribution and construction costs incurred in the program's first year, and (2) the PV of periodic replacements throughout the 25-year analysis period. Each replacement cost, discounted to its PV, was factored in for the years coinciding with the end of the biodigester's five-year lifespan, t_{biogas}:

$$\begin{gathered} PV\_Biod_{T_{\text{biogas}}} = \sum_{t_{\text{biogas}}} \frac{\text{Dist}_{\text{biogas}} + \text{Constr}_{\text{biogas}}}{(1+DR)^{t_{\text{biogas}}}} \\ \text{for } t_{\text{biogas}} = 0, 4, 8, 12, 16, 20 \end{gathered} \tag{3}$$

where $\text{Dist}_{\text{biogas}}$ is the fixed capital costs of distributing biogas plants, and $\text{Constr}_{\text{biogas}}$ denotes biogas plant construction costs comprised of two main components: the acquisition of all necessary materials and the fees associated with soliciting technical support to supervise the installation process, as recommended by Garfi et al. (2016).

For each scenario, i, the total fixed cost (PFC_i) per household was calculated as the sum of the cost of a lactating heifer (Heif), transactions costs (Trans), cost of a cowshed (Cowshed), and the cost of a biodigester (Biod):

$$PFC_i = \alpha(\text{Heif}) + \beta(\text{Trans}) + \sigma(\text{Cowshed}) + \gamma(\text{Biod}) \tag{4}$$

where $\alpha = 1$ and $\beta = \gamma = 0$ under the baseline scenario with the household incurring the cost of a lactating heifer. $A = \beta = \sigma = 1$ and $\gamma = 0$ under the current Girinka program and under the scenario that incorporates distribution of climate-smart cowsheds under the current program design with the household incurring the cost of constructing a traditional cowshed. $A = \beta = \sigma = \gamma = 1$ under scenarios that incorporate distribution of biogas plants with the household incurring the cost of constructing a traditional cowshed.

3.3.2 Variable costs

The PV of total household O&M costs, PVC_I, was calculated by aggregating the PVs of individual cost components: feed, water, artificial insemination, and veterinary services:

$$\begin{gathered} PVC_I = \sum_i \frac{O\&M_i}{(1+DR)^T} \\ \text{for } i = \text{feed, water, AI, veterinary} \end{gathered} \tag{5}$$

where $O\&M_i$ is the annual operations and maintenance cost. In the initial year of program implementation, t_0, artificial insemination costs were assumed to be zero, reflecting the current program's common practise of distributing lactating (pregnant) cows, negating the immediate need for artificial insemination services.

3.3.3 Household benefits

Household benefits were estimated as the present value of revenues from milk sales (including the imputed value of household consumption), m, calf sales, k, and post-lactation cow sales, p. Additionally, scenarios featuring biogas production plant distribution incorporated the PV of energy cost savings as a further benefit.

The PV of revenues from milk sales, PV_Rev_{Tm}, was calculated as:

$$\text{PV\_Rev}_{T_m} = \sum_j \frac{\text{Prod}_m \times \Delta P\_\text{waste}_j \times \text{Price}_m}{(1+\text{DR})^T} \quad (6)$$
$$\text{for } j = \text{traditional cowshed, climatesmart cowshed}$$

where Prod_m is the total volume of milk produced, ΔP_waste is production loss rate, and Price_m is the market price of milk. Higher mastitis risk in traditional cowsheds (Iraguha et al. 2015; Juozaitiene et al. 2006) led to greater milk loss compared to climate-smart designs. Notably, milk losses under climate-smart cowsheds were primarily attributed to the lack of milk storage facilities (IFAD 2016).

The value of the benefit of producing calves was calculated as the sum of the PV of revenues from sale of the thirdborn calf, PV_Rev_{Tk}. Consistent with Girinka program requirements, we assumed households gifted the firstborn calf, retained the second for herd expansion, and sold the third as an income source (Miklyaev et al. 2017). Fourth-born calves were kept as replacements for culled cows. Given a heifer's 3–5-year lactation cycle and 1–1.5-year calving interval, only the third calf, born after seven years (three intervals), entered the revenue calculation (IFRC 2016).

$$\text{PV\_Rev}_{T_k} = \sum_{t_k} \frac{\text{Price}_k}{(1+\text{DR})^{t_k}} \quad (7)$$
$$\text{for } t_k = 7$$

where Price_k is the market price of a calf.

The PV of revenue from post-lactation cow sales, PV_Rev_{Tp}, was determined by summing the PV of two components: (1) the initial sale of the first cow at the end of its nine-year lactation cycle (eight years after program implementation) and (2) subsequent sales of replacement cows at nine-year intervals throughout the 25-year analysis period:

$$\text{PV\_Rev}_{T_P} = \sum_{t_P} \frac{\text{Price}_P \times D}{(1+\text{DR})^{t_P}} \quad (8)$$
$$\text{for } t_p = 8, 16, 24$$

where Price_p is the market price of a cow. The analysis assumes a potential depreciation in market value, D, reflected in lower sale prices, for culled cows due to anticipated diminished meat quality (International Finance Corporation (IFC), 2007; IFRC 2016).

The PV of household energy cost, PV_Energy_i, was estimated by quantifying the financial benefit of substituting biogas for expensive traditional energy sources, primarily fuelwood, used predominantly for cooking:

$$\text{PV\_Energy}_j = \sum_j \frac{(\text{EC}) \times \text{Util}_j}{(1+\text{DR})^T} \quad (9)$$
$$\text{for } j = \text{traditional cowshed, climate smart cowshed}$$

where EC is the cost of energy and Util_j is the utilisation rate of biogas plants. Higher biogas plant utilisation was projected for climate-smart cowsheds compared to traditional designs due to enhanced manure management efficiencies. Climate-smart structures facilitate effective manure collection and storage, minimising losses and maximising biogas production potential and biogas plant utilisation rate. Consequently, energy cost savings, calculated as the difference in energy costs under traditional and climate smart cowsheds, were only factored into scenarios involving biogas plant distribution.

For each scenario, *i,* the total PV benefit (PVB_i) per household was calculated as:

$$\mathrm{PVB}_i = \mathrm{PV\_Rev}_{T_m} + \mathrm{PV\_Rev}_{T_k} + \mathrm{PV\_Rev}_{T_P} + \lambda(\mathrm{PV\_Energy}_j) \tag{10}$$

where λ = 1 for scenarios involving biogas plant distribution, and λ = 0 for all the other scenarios.

The net benefit per household was calculated as the difference between total household benefits and costs. To capture inherent variability in parameters, input values for these calculations were drawn from pre-defined ranges. A comprehensive description of this parameter value selection process, designed to adequately quantify uncertainty, follows in the subsequent section.

3.4 Data

This study utilised data from both existing primary survey data and local studies (peer-reviewed publications and consulting reports). This study leverages data collected from a 2018 cross-sectional survey of Rwandan Girinka program participants conducted by our co-authors, focusing specifically on household financial costs and benefits, to further explore the program's economic impact. Conducted by the University of Rwanda's College of Agriculture, Animal Sciences and Veterinary Medicine, the survey aimed to understand the program's impact on household costs, income, and food and nutrition security. For a detailed description of the survey design and implementation procedures, please refer to the Supplementary material.

Parameter values were drawn from both survey data and local studies (peer-reviewed publications and consulting reports). Instead of relying solely on averages or medians, value ranges and probability density functions (PDFs) were derived for key parameters. This approach incorporated variability observed in survey responses and peer-reviewed literature (IFAD 2016; Kayigema & Rugege 2014; Mutimura & Everson 2011). Validation by a local expert with field experience at the Rwanda Agriculture Board, in consultation with program coordinators, ensured alignment with real-world conditions. For example, ranges for animal feed costs, water, artificial insemination, veterinary services, and milk prices were adjusted to reflect estimates from similar studies. A summary of parameter descriptions, notations, units, ranges, and data sources is provided in Supplementary Material (Table S.3). Values in Table S.3 were converted to per year per household equivalents to facilitate subsequent calculations of present value costs, benefits, and net benefits for each household. Additionally, sensitivity analyses were conducted to explore the sensitivity of the results of our analysis under varying assumptions about respondents, further strengthening the confidence in our conclusions.

3.5 Quantifying variability in parameter values

We quantified the variability in key parameters influencing net benefit calculations by fitting probability density functions (PDFs) to observational data from the survey and secondary data from the literature. Various functional forms, including exponential, log-logistic, and lognormal, were employed to model the variability in parameters such as income, feeding costs, water costs, artificial insemination costs, veterinary service costs, milk consumption, and revenue values (Fig. 5). The optimal PDF for each parameter was selected based on chi-squared goodness-of-fit tests.

For all other parameters, variability was modelled using the beta distribution. This continuous PDF resembles a truncated normal distribution, offering a symmetrical bell-shaped

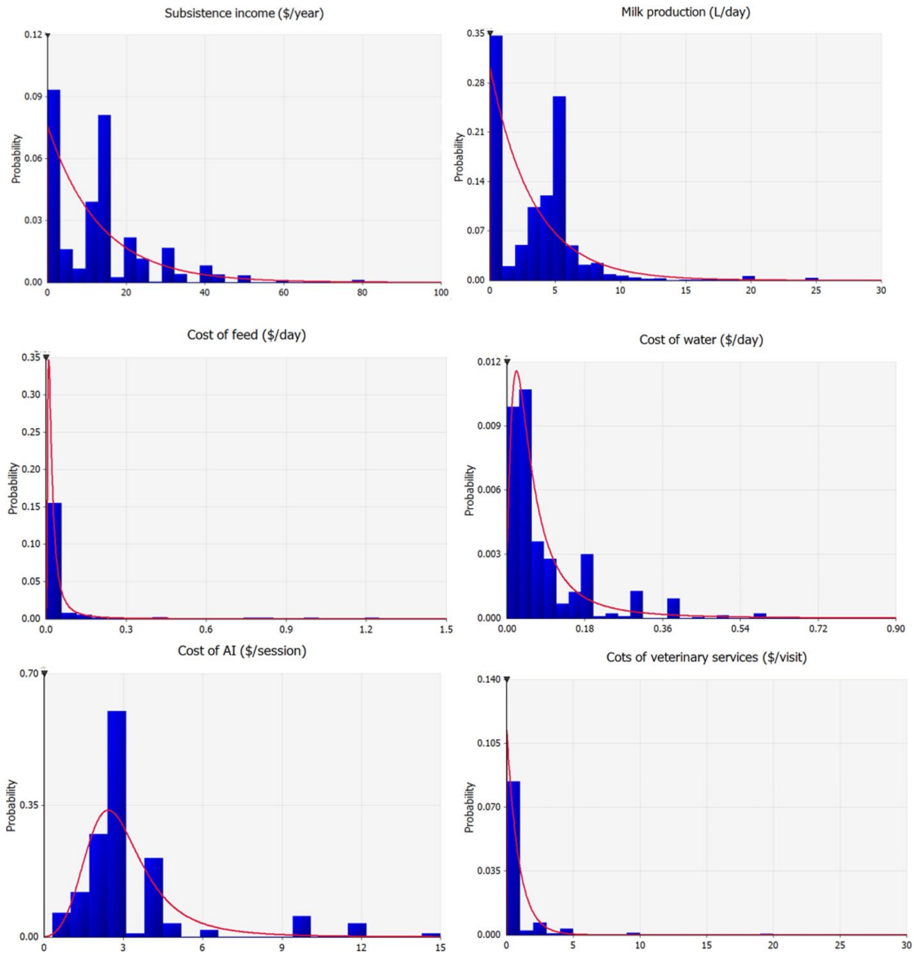

Fig. 5 Fitting probability density functions (red line) to frequency distributions from cross-sectional 2018 survey data from Eastern and Western Rwandan provinces

curve centred around the median value and confined by the known range. The beta distribution is well-suited for representing uncertainty in parameters with known medians and ranges, making it ideal for incorporating data gathered from the reviewed literature of the case study region. Further technical details regarding selecting appropriate PDFs for uncertainty quantification in net benefit calculations can be found in Kandulu and Connor (2017). We calculated Pearson correlation coefficients using survey data to assess potential correlations between milk production and key cost/revenue factors. This analysis examined the relationships between milk production and the costs of feed, water, and veterinary services, as well as the relationship between milk production and milk price.

We employed stochastic Monte Carlo simulations to simulate the inherent variability in key parameters and understand its impact on net benefit. This approach involved iteratively drawing random parameter values from the pre-defined PDFs. These parameter values were then implemented in the established net benefit equations, resulting in 1000 unique net benefit calculations per scenario. The simulations incorporated correlations between certain parameters, ensuring realistic variability patterns. The resulting 1000 net benefit values for each scenario were then used to generate frequency distributions, characterising the potential range and distribution of net benefits under each simulated condition.

3.6 Sensitivity analysis

To explore the impact of existing asset ownership on the projected benefits of the Girinka program, we conducted a sensitivity analysis by examining net benefits under three alternative baseline scenarios. These scenarios varied the initial levels of adoption of key program components—heifers, climate-smart cowsheds, and biogas plants—among the reference households prior to program intervention. Our reference household practised subsistence cropping and did not own a heifer, reflecting the target population of the program with no prior livestock ownership. An alternative baseline scenario introduced additional complexity by assuming the reference household already owned a heifer, but still received a climate-smart cowshed and biogas plant. This allowed isolation of the net benefit contributions of these interventions beyond heifer ownership. In a third 'partial adoption' baseline scenario, the reference household already owned a heifer and a biogas plant, but received a climate-smart cowshed. This analysis focused on the incremental benefit of the cowshed in a context where other program components were already present. By examining net benefits across these diverse baseline scenarios, a more nuanced understanding of the program's potential impact under different existing asset ownership conditions is provided.

4 Results

Table 2 presents present value (PV) costs, benefits, net benefits, and benefit–cost ratios for households under the existing Girinka program design and three alternative program scenarios.

Without the Girinka program, even the few resource-constrained rural households who could afford a heifer would face a PV cost of USD 1660. However, these households could also anticipate an average PV benefit of USD 3050, resulting in a net benefit of USD 1390 per household on their investment. The current Girinka program delivers an average net benefit of USD 2277 per beneficiary household, translating to a benefit–cost ratio (BCR) of 4:1. Incorporating climate-smart cowsheds and biogas production plants into the program design could generate an even higher BCR of 5:1.

Table 2 Expected present value household costs, benefits, net benefits (USD), and benefit–cost ratio estimates under alternative program designs

Scenario	Program cost	Household cost	Total household benefit	Net household benefit	Household benefit–cost ratio
Current Girinka program	910	763	3040	2277	4.0
Girinka + climate-smart cowsheds	957	805	3280	2475	4.1
Girinka + biogas plants	3792	1185	5425	4271	4.6
Girinka + climate-smart cowsheds + biogas	3839	1228	6157	4929	5.0

Implementing climate-smart cowsheds and biogas production plants alongside heifer distribution in the Girinka program would incur an additional program cost of USD 2929 per household (USD 910 baseline cost increasing to USD 3839). This scenario would yield a net benefit of USD 3117 per household (from USD 6157 to USD 9274, USD 1727 higher than the base scenario). Introducing biogas plants alone, at an additional cost of USD 2,882 per household, generates a net benefit of USD 2385 per household.

Our sensitivity analysis considered the incremental net benefit under three alternative baseline scenarios. Under the first alternative baseline scenario where our benchmark household practised subsistence rainfed cropping and did not own a heifer, receiving a lactating heifer, climate-smart cowshed, and biogas plant generated a net benefit of USD 4929 per household and a BCR of 5:1. In an alternative analysis where our reference household already owned a heifer, the net benefit from receiving a climate-smart cowshed and biogas plant decreased to USD 2652 per household, with a BCR of 7:1. For households already owning both a heifer and a biogas plant, the net benefit from adding a climate-smart cowshed decreased to USD 689 per household.

Figure S.1 in the Supplementary Material presents the frequency distributions and summary statistics of net benefit values calculated using 1000 random samples drawn from the PDFs of variable cost and benefit parameters. For the baseline scenario where households only incur the cost of a lactating heifer, net benefit estimates were predominantly positive, with minimal probability of net losses. However, net benefit values varied substantially, with standard deviations ranging from 29 to 50% of the expected value.

Figure S.2 in the Supplementary Material presents tornado graphs quantifying the sensitivity of net benefit calculations to various parameter values used to estimate costs and benefits under each scenario. The analyses reveal that milk price and production consistently contributed the most to variability in net benefit estimates across all scenarios. Importantly, even for these influential parameters, variability within their probable ranges did not significantly alter the key conclusion: households experience a substantial net benefit increase when the current Girinka program design is augmented with climate-smart cowsheds and biogas production plants. This is illustrated, for example, by varying milk prices (the most sensitive parameter) across its entire range while holding other parameters at their medians. This manipulation only caused net benefit estimates to range between USD 1229 and USD 2988 under the current program and between USD 3617 and USD 5942 under the scenario with climate-smart technologies.

In addition, our analysis revealed positive correlations between key inputs and milk production in the Girinka program, mirroring existing literature. Consistent with Gonzáles et al (2016), the correlation coefficient between animal feed expenditure and milk production was calculated at 0.29. Similarly, the correlation between water consumption and milk productivity aligned with Kayigema (2013) at 0.30. Additionally, the calculated correlation between veterinary visits and milk production of 0.21 resonated with Argent et al. (2014). These findings provide empirical support for the importance of these factors in influencing milk production outcomes for beneficiary households.

5 Discussion

This study uses a case study in Rwanda's Eastern and Western provinces to evaluate the economic performance of the current Girinka program and three alternative designs. These alternative designs focus on incorporating the distribution of climate-smart cowsheds and biogas plants alongside the program's current core element: distributing heifers to low-income households. To assess economic viability, we utilise a BCA framework to account for the inherent variability in key parameters affecting costs and benefits. The variability reflects the disparate circumstances of beneficiary households, particularly regarding the cost of animal feed, water, artificial insemination, and veterinary services.

Our analysis reveals that the Girinka program consistently delivers positive, albeit highly variable, net benefits to beneficiary households. While introducing climate-smart cowsheds alone alongside, the current heifer distribution offers a limited additional economic advantage, a combined package of climate-smart cowsheds and biogas production plants significantly enhances household net benefits. While the current Girinka program already delivers a substantial average net benefit of USD 2277 per household (BCR: 4:1), incorporating climate-smart cowsheds and biogas production plants presents even greater potential. This enhanced program design could yield a BCR of 5:1, suggesting significant benefits for beneficiary households. The findings of our study are consistent with a growing body of literature indicating the positive net benefits of incorporating climate-smart technological innovations into livestock donation programs, although these benefits have not been quantified (Berhe et al. 2017; Bucagu et al. 2014; Geddafa et al. 2023; Kayigema & Rugege 2014; Klapwijk et al. 2014). Estimates of net benefits exhibit sensitivity to fluctuations in milk production and prices, suggesting that substantial increases in milk supply could potentially diminish net benefits through price reductions. The differences in milk production among households may be attributed to varying cow-feeding intensities, which in turn are influenced by the affordability of food supplements such as commercial feed and vitamins (Manzi et al. 2020; Wilkes et al. 2020; Wright et al. 2016). Despite documented positive impacts like increased agricultural production and household income (Argent et al. 2014; Nilsson et al. 2019), the Girinka program has also revealed potential drawbacks. Khundi-Mkomba et al. (2023) suggest that limited access to veterinary services and water supply can impose significant financial burdens on beneficiary households, potentially negating the program's economic viability (Sapp et al. 2023).

This study exclusively focused on the economic benefits of incorporating biogas production into the Girinka program. However, a comprehensive BCR assessment would necessitate quantifying the additional health and social benefits accrued by households. These include reduced reliance on fuelwood, leading to potential decreases in respiratory infections, time and effort spent fetching fuelwood, and domestic chores traditionally carried out by women and children (e.g. fire preparation, kitchen cleaning, and dishwashing) (Njenga et al. 2023; Sepee & Tesfahun 2023). Furthermore, incorporating the environmental benefits of reduced deforestation and greenhouse gas emissions associated with biogas adoption would likely further enhance BCR estimates.

Our findings support the growing calls to harness the broader environmental and social benefits achievable through integrating biogas plant installations to livestock donation programs (Ahmad & Jabeen 2023; Khundi-Mkomba et al. 2023; Onyekaozuoro et al. 2023). Our study demonstrates that community-scale interventions targeted at low-income households can yield high BCRs, delivering direct, quantifiable benefits directly attributable to the interventions. This work gains relevance in light of recent advancements in affordable small-scale renewable energy technologies (Clemens et al. 2018; Gitau et al. 2019; Jagger & Das 2018; Keerthana Devi et al. 2022). Future research can build upon this foundation by quantifying the GHG emissions and health benefits associated with climate-smart technology adoption. In addition, non-market valuation techniques can be employed to quantify social impacts to broaden the scope of quantified costs and benefits.

While awareness of fuelwood's negative health and environmental impacts grows, and cleaner alternatives become increasingly available, its dominant use for cooking persists in low- and middle-income countries. This can be partly explained by disparities in the perceived value of male and female labour within households, impacting the adoption of innovations with potential net benefits (Overfield 1998). Specifically, fuelwood collection often falls to women, and their limited bargaining power in household decision-making can hinder the adoption of cleaner options. This is supported by Behera and Ali (2016), who found female-headed households in Sub-Saharan Africa to be more likely to adopt cleaner energy sources and less reliant on fuelwood. Consequently, parallel programs promoting women's financial empowerment through improved microcredit access could contribute to increased adoption of cleaner technologies by enhancing their bargaining power within the household.

Recent evidence suggests potential challenges with ground implementation of small-scale biogas digesters, which may hinder their adoption (Issahaku et al. 2024; Kalina et al. 2022). These challenges include high capital and ongoing O&M costs, poor monitoring and maintenance of existing digesters, and failures shortly after installation negatively. Recognising the potential obstacles associated with implementing climate-smart technologies like biogas plants and climate-smart cowsheds, we recommend a multi-faceted policy approach to overcome barriers hindering the widespread adoption of climate-smart technologies like biogas plants and climate-smart cowsheds. This includes (1) cost reduction through technological innovation, locally adapted models, and utilisation of cheaper materials; (2) implementation of microfinance schemes with low-interest rates and flexible payback periods to address financial constraints; (3) investment in education and training programs to empower the private sector and ensure quality construction; and (4) active participation of women, as primary users and beneficiaries, in decision-making, training, and maintenance to promote skill development and positive social acceptance. Multi-faceted policy approaches tailored to local contexts and encompassing a range of adoption barriers are demonstrably more effective in promoting the uptake of climate-smart technologies than simplistic, single-objective interventions (Mukeshimana et al. 2021; Ogisi & Begho 2023). Future research should explore the impact of cost-sharing arrangements between government/aid agencies and households on net benefits. Evaluating various cost-sharing models could offer valuable insights into program affordability and long-term sustainability.

6 Conclusion and policy implications

6.1 Conclusions

This study quantifies the net benefits of incorporating climate-smart cowsheds and biogas plants into the Girinka livestock donation program in Rwanda, demonstrating the potential for these technologies to enhance economic viability, foster environmental sustainability, and deliver direct, quantifiable benefits. Our study finds that integrating climate-smart cowsheds and biogas production plants along with heifer distribution can significantly improve the economic viability of the Girinka program. Households owning cows under this improved program design can realise net benefits 3.5 times higher than under the current design, with BCRs reaching 5:1. This finding underscores the need to integrate climate-smart technologies into agricultural development programs in low-income countries, particularly for resource-constrained smallholder communities. While variability in milk production and prices is an important consideration, the substantial net benefit achieved through a combined package of climate-smart cowsheds and biogas plants surpasses traditional program designs and highlights the superiority of multi-dimensional interventions in rural development. Incorporating non-market valuation techniques into future research, such as willingness-to-pay surveys to estimate the value of improved health outcomes and life cycle assessments to quantify greenhouse gas emission reductions, would enhance the comprehensiveness of the program's evaluation and inform evidence-based policy decisions.

6.2 Policy implications

Multi-faceted policy packages, tailored to address the diverse and localised barriers specific to climate-smart technologies, can achieve higher adoption rates than interventions with singular objectives. The combined implementation of (1) training and education programs for households to build their capacity in the maintenance and effective utilisation of biogas plants; (2) cost reduction strategies, such as pursuing technological innovation for cheaper solutions and utilising affordable local materials to decrease prohibitive upfront capital costs; (3) microfinance schemes with flexible payback periods and low-interest rates to enhance affordability and facilitate uptake; and (4) education and training programs for the private sector to ensure quality construction and installation further promoting high adoption rates. In addition, actively involving women in training, maintenance, and decision-making processes to promote skill development, encourage positive social acceptance, and acknowledge the predominant role women play in domestic energy decisions, such as firewood collection can increase uptake. This can be further reinforced by parallel programs to enhance women's financial empowerment through improved microcredit access. By simultaneously addressing multiple adoption barriers through such multifaceted and context-specific policy packages, the uptake of climate-smart technologies like biogas plants can be significantly increased compared to single-objective interventions.

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Declarations

Conflict of interest The authors declare no competing interests.

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