Climate-Smart Smallholder Dairy Farming in the Global South: Integrating Gender Equity for Methane Mitigation

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ABSTRACT

This study explores the critical role of gender equality in reducing enteric methane emissions and improving nutrition and feeding practices to facilitate the transition toward net-zero emissions in smallholder dairy systems in poor countries. Achieving net-zero in this sector necessitates a reduction of over 50% in methane emissions. While industrialized nations have achieved notable gains in emission intensity through improved production efficiencies, progress in developing countries remains marginal. Consequently, there is an urgent need to identify cost-effective, context-specific mitigation strategies for smallholder dairy systems in these regions. Integrating climate-smart practices into smallholder dairying offers multifaceted benefits—lowering greenhouse gas emissions, enhancing food and nutrition security, boosting productivity, and improving livelihoods—particularly when intersectional and gender disparities are addressed. Recognizing the influence of gender dynamics on production systems is vital, as women often play central but underappreciated roles in livestock management. Public–private collaborations are essential to advancing innovative, affordable feeding solutions and promoting inclusive, gender-responsive mitigation strategies. This article examines how gender roles shape methane emissions in smallholder dairy farming and highlights the potential gains of embedding gender equality into emission-reduction efforts. A gender-inclusive approach not only facilitates equitable outcomes and empowers women but also significantly reduces the emission intensity of milk production. Such interventions contribute to climate resilience, enhance socio-economic wellbeing, and support environmentally sustainable dairy development. Ultimately, empowering women and closing gender gaps in smallholder dairying emerges as a pivotal strategy for achieving climate mitigation, food security, and sustainable livelihoods in the Global South.

Keywords: Gender Equality, Smallholder Dairy Farming, Methane Emissions, Climate change mitigation, Gender-inclusive strategies.

INTRODUCTION

Smallholder dairy farming plays a critical role in enhancing food and nutritional security, increasing household income, and generating economic and employment opportunities, particularly in developing regions (Feyissa et al., 2023; Etana et al., 2023; Fan & Rue, 2020). Beyond its socio-economic contributions, smallholder dairying holds significant potential for climate change mitigation—especially through the reduction of methane emissions (Chagunda et al., 2016). Globally, over 150 million farm households are engaged in milk production, the vast majority of whom are located in developing countries (Walshe et al., 1991). Between 1995 and 2005, global milk consumption grew at an average annual rate of 3.5%–4.0%, outpacing the 1.4%–2.0% growth rate observed for major staple foods (FAOSTAT, 2008). When effectively supported, dairy sector development can become a strategic avenue for poverty alleviation and climate mitigation, particularly by targeting enteric methane emissions.

Sub-Saharan Africa's dairy sector has demonstrated sustained growth, with milk production rising from 50 million metric tons in 2010 to approximately 60 million in 2017, largely driven by smallholder producers operating with herds of fewer than 10 cows (Walshe et al., 1991). Even more pronounced growth has been observed in Southeast Asia, where since 2000, per capita milk consumption has increased by 10.6%, milk production by 14.6%, and dairy imports by 3.0% annually (FAO, 2009). In mixed farming systems of South and East Asia, smallholder dairying is a profitable livelihood strategy. However, climate variability has increasingly disrupted production cycles, necessitating adaptive and mitigation-oriented interventions (Chantalakhana & Skunmun, 2002). In India alone, dairy farming sustains the livelihoods of 80 million households and contributes 22% of global milk production, with women constituting nearly 70% of the labor force (FAOSTAT, 2008). The dairy sector's role in rural development extends beyond income generation—it facilitates the redistribution of wealth from urban to rural areas, enhancing overall food and nutritional security.

Methane, a potent greenhouse gas, has more than tripled in atmospheric concentration since the Industrial Revolution and is now a key contributor to global warming (Rocher-Ros et al., 2023). Dairy cattle alone are responsible for approximately 30% of agriculture-related methane emissions (Tseten et al., 2022; FAO, 2023), making methane mitigation critical to achieving the Paris Agreement's goal of limiting global temperature rise to 1.5°C by 2050. Over the past two decades, research on enteric methane mitigation has accelerated, focusing on strategies such as production intensification, dietary manipulation, rumen modification, and genetic selection for low-emission cattle. In the European Union and United States, dairy cattle contribute 1.2% and 0.55%, respectively, to anthropogenic GHG inventories (EEA, 2011). Globally, dairy farming accounts for around 3.3% of total anthropogenic methane emissions, 70–80% of which originates from microbial fermentation in the rumen.

Climate change continues to severely affect smallholder dairy operations by altering temperature and rainfall patterns, which in turn disrupt feed production and reduce milk yields (Astuti et al., 2024; Mutekwa, 2009). This decline is often attributed to animals diverting energy towards thermoregulation and other adaptive responses. Farmers are implementing a range of mitigation strategies to sustain productivity under changing climatic conditions. Altieri and Nicholls (2017) argue that enhancing productivity and resilience in smallholder systems depends on the adoption of climate-smart forage and feeding practices. However, comprehensive data on methane emissions from smallholder systems—especially in diverse agro-ecological zones of developing countries—remains limited. A nuanced understanding of methane production in these contexts requires attention to genotype-by-environment (G×E) interactions, where genetic predispositions shape and are shaped by environmental variables (Boyce et al., 2020).

Key factors influencing dairy production in developing countries include climate variability, feed accessibility, economic constraints, consumer demand, and market infrastructure (Banda et al., 2012; Marshall et al., 2015). While smallholder farmers may produce up to 70% of feed on-farm, forage availability is seasonally constrained, particularly during dry periods (SNV, 2013). The rising demand for dairy has also led to an 18% increase in GHG emissions from the sector. Addressing this challenge requires improving feed quality and availability through balanced nutritional strategies. Such interventions have been shown to reduce methane per unit of energy-corrected milk (CH_4/ECM) by 2.5–15% (Knapp et al., 2011). However, chemical rumen modifiers have yielded only modest and short-lived reductions in emissions. Instead, improving feed conversion efficiency and optimizing rumen fermentation—such as by increasing propionate and reducing acetate production—offers a more promising pathway (Staal et al., 2008). Sustainable intensification, aiming for higher milk yield per animal, remains a pressing priority for enhancing both competitiveness and environmental sustainability in smallholder systems.

Moreover, smallholder dairy farming has the potential to reshape gender norms, strengthen rural livelihoods, and enable inclusive climate solutions. Gender equality is essential for building climate-resilient dairy systems that simultaneously reduce emissions and enhance food security (Yasmin & Ikemoto, 2015). In many regions, women are the primary caregivers of livestock and are responsible for feeding—an activity that directly influences methane output (Batool et al., 2014). Yet, gender-based disparities in labor, decision-making, and resource control continue to limit productivity in smallholder systems (FAO, 2010–11). These inequalities are often rooted in cultural norms and outdated assumptions about gender roles (Ulfina et al., 2020). Women also bear the brunt of labor in subsistence agriculture, though children contribute less than 5% of labor in dairy activities (Njarui et al., 2012). In both Africa and Asia, women's involvement in feed management presents a strategic opportunity for methane reduction (Batool et al., 2014; Rathod et al., 2011; Banda et al., 2012).

Enhancing women's access to resources, decision-making, and training is thus critical not only for gender equity but also for advancing climate mitigation goals (Obosha, 2020; Chakrabarti et al., 2024). When women's needs and knowledge are prioritized in climate policy, the adoption of sustainable practices improves markedly. Smallholder dairying could serve as a transformative platform for women's empowerment, shifting gender dynamics and enriching climate action through inclusive decision-making. Promoting gender-sensitive approaches in dairy commercialization, resource allocation, and policy design may catalyze broader shifts in both climate resilience and gender equity across developing regions.

Integrating Gender Equity into Climate-Smart Smallholder Dairy Farming for Methane Mitigation and Climate Resilience in the Global South: A Conceptual Framework

This conceptual framework illustrates how integrating gender equity into climate-smart smallholder dairy farming can effectively support methane mitigation and enhance climate resilience in the Global South. At its core, Climate-Smart Animal Agriculture (CSAA) is founded on three interconnected pillars: improving productivity, strengthening resilience to climate shocks, and reducing greenhouse gas (GHG) emissions. These foundational principles underpin climate-smart practices specifically tailored to smallholder dairy systems.

Operationalizing CSAA in smallholder contexts gives rise to Climate-Smart Smallholder Dairy Farming (CSSDF), which involves the adoption of practical interventions designed to enhance both environmental sustainability and productivity. Key practices include enhanced feeding and forage systems that improve digestion and reduce enteric methane emissions, innovations in animal health and husbandry that boost productivity and disease resistance, and sustainable manure management strategies such as biogas production, which generates renewable energy while minimizing methane leakage.

The successful implementation of CSSDF is propelled by two critical categories of enablers: technical measures and socioeconomic supports. Technical innovations such as methane-reducing feed additives, genetic selection for low-emission dairy breeds suited to smallholder systems, and efficient manure processing technologies provide the tools necessary for transformation. Equally important are socioeconomic enablers, including improved access to finance, educational opportunities, and inclusive extension services, which create the conditions for widespread and sustained adoption.

Gender equity plays a catalytic, cross-cutting role in this framework, functioning as a transformative enabler of climate-smart dairy innovation. Integrating gender equity ensures women have control over productive assets like land, livestock, and income; gain equal access to training, information, and agricultural services; and participate in decision-making at both household and community levels. These shifts not only enhance women's agency but also foster more inclusive and effective engagement in climate-smart agricultural practices.

When gender equity is embedded into the adoption of climate-smart practices, smallholder households—especially women—are more likely to adopt innovations due to reduced labor burdens, equitable benefit-sharing, and improvements in household well-being. This leads to tangible outcomes: significant reductions in methane emissions from smallholder dairy systems, greater household resilience to climate shocks, and more sustainable livelihoods and food security across vulnerable rural communities.

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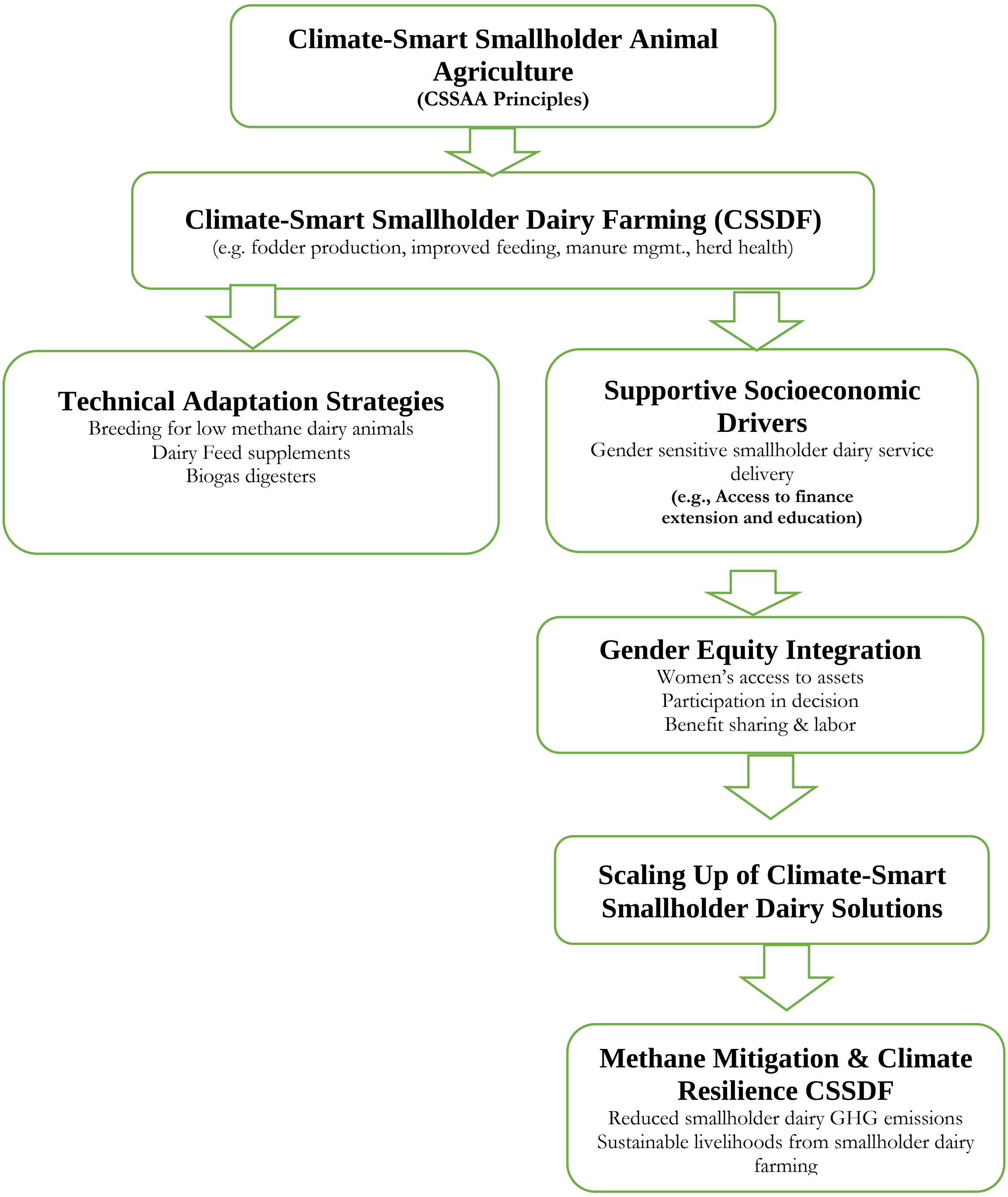

Figure 1 Gender-Responsive Climate-Smart Smallholder Dairy Farming Framework for Methane Mitigation and Resilience in

The Significance and State of Global Smallholder Dairy Production: Trends and Insights

Small-scale dairy production plays a pivotal role in the global dairy sector, particularly in developing countries, where it supports the livelihoods of millions (Washaya et al., 2023; Feyissa et al., 2023; Etana et al., 2023). Beyond contributing significantly to milk output in low- and middle-income nations, smallholder dairy systems enhance household nutrition and empower women and youth through income generation and engagement in food systems, thereby driving economic development (Fan & Rue, 2020; Lai-Solarin et al., 2021; Ayandele, 2020). While global dairy consumption has risen in response to economic growth and rising incomes, regional disparities in per capita intake persist. Although technological advances have bolstered large-scale dairy productivity, smallholder producers remain largely marginalized. Meanwhile, dairy trade has expanded, but domestic consumption dominates due to the perishability of milk products (Gerosa & Skoet, 2012).

Future growth in dairy consumption remains substantial, though it is projected to decelerate. Amid growing concerns over environmental degradation, human health, and rural livelihoods, the dairy sector must pursue a development trajectory that is both sustainable and socially inclusive (FAO, 2010). The shift in consumer preference toward environmentally responsible dairy products has increased pressure on small-scale producers to adopt sustainable practices (Bhat et al., 2022). In developing nations, dairy remains the most critical livestock subsector, underpinning rural economies and meeting the rising demand for fresh milk and its derivatives (Vyas et al., 2020). With over 150 million farming households engaged in milk production—predominantly in developing regions—the sector has experienced annual consumption growth of 3.5–4.0% between 1995 and 2005, outpacing major staple crops (FAO, 2010). The dairy sector provides employment and income for vulnerable populations, with approximately 12–14% of the global population dependent on dairy farming (Mburu, 1991). Strategic investment in smallholder dairy enterprises offers a pathway to reducing gender disparities through climate adaptation and mitigation while bolstering productivity and rural employment.

Globally, over six billion people consume milk and dairy products, with demand growing annually by more than 2% (FAO, 2016). Milk production has increased by over 50% in the past three decades, offering rapid financial returns for small-scale farmers and enhancing food security and household resilience (FAO, 2016). While some developing regions have a longstanding dairy tradition—such as the Indian subcontinent, East African highlands, and the Mediterranean—others have more recently established dairy industries, particularly in tropical zones with high humidity (Gerosa & Skoet, 2012). Ensuring smallholder competitiveness in a global market dominated by capital-intensive operations is essential for dairy sector development to serve as a tool for poverty alleviation and equitable wealth distribution (Owen et al., 2005). However, this expansion—especially in predominantly smallholder systems—raises concerns over rising methane emissions, necessitating climate-responsive interventions.

Although small ruminant milk production constitutes only 3.5% of global output, its contribution in developing countries is significantly higher (7%) than in developed regions (1.5%) (FAO, 1999). These systems are especially valuable in marginal environments where they contribute high-quality protein and optimize the use of crop residues. In developed countries, cow milk dominates the sector, but there has been notable growth in sheep and goat milk, particularly within the European Union, which produces 15% of global goat milk. In developing contexts, small-scale dairy systems support livelihood diversification, mitigate farming risks, and enable the efficient use of underutilized resources (Ngongoni et al., 2006).

While developed countries produce one-third of the world’s milk, developing nations host over two-thirds of the global dairy herd (IDF, 2010). Africa alone produced 37 million tonnes of milk in 2010, with a modest annual growth of 1.3%. Per capita milk consumption is projected to reach 104.3 kg/year (FAO, 2010b). Historically, milk demand was driven by population growth, but it is increasingly propelled by rising per capita consumption in populous developing countries. Projections suggest a 1.8% annual rise in demand, and without proportional increases in supply, dairy prices may escalate significantly (Mburu, 1991).

The growing prominence of smallholder dairy systems in global milk supply underlines the need for supportive policies that improve access to markets, credit, and technology (Gerosa & Skoet, 2012). Women's participation is especially critical; empowering them through improved access to resources and decision-making is essential for enhancing dairy productivity and sustainability (FAO, 2010). Strategic interventions targeting productivity, inclusion, and sustainability can significantly advance smallholder dairy systems and support global efforts to achieve the Sustainable Development Goals. However, increased production also presents environmental challenges. Low-yield dairy systems in Africa and South Asia tend to have disproportionately high carbon footprints per 100 kg of milk produced (FAO, 2010). A sustainable future for smallholder dairying requires productivity gains coupled with reduced environmental impact.

Climate-smart husbandry practices and improved feeding strategies offer practical, cost-effective solutions to reduce the methane footprint of smallholder dairy systems. Addressing sustainability challenges associated with intensified milk production hinges on adopting integrated, climate-resilient management frameworks. This includes a focus on key sustainability indicators and targeted improvements in nutrition, feed quality, and animal husbandry. The development of climate-smart smallholder dairy systems will be instrumental in achieving both environmental sustainability and inclusive rural development.

The Nexus Between Small-Scale Dairy Production and Methane Emissions: Implications for Climate Change.

Greenhouse gas (GHG) emissions from dairy livestock and their contribution to climate change remain a pressing global issue (Astuti et al., 2024; Berdos et al., 2023; Chag et al., 2021; Clay et al., 2020). Dairy farms are recognized as significant sources of GHGs, with methane (CH_4) and nitrous oxide (N_2O) being the predominant pollutants (Rotz et al., 2021). Among these, methane is the principal GHG linked to milk production, accounting for approximately 62% of total farm-gate life cycle emissions (Wuebbles & Hayhoe, 2002). Although CH_4 has a relatively short atmospheric lifetime—oxidizing into CO_2 and water within about 12 years—its global warming potential far exceeds that of carbon dioxide in the short term. Conversely, CO_2 from fossil fuel combustion persists for centuries, thereby contributing to long-term climate forcing (Forster et al., 2021).

The environmental footprint of the dairy industry is further compounded by climate change itself, with the production phase, particularly at the farm level, being the most vulnerable and impactful (Guzmán-Luna et al., 2021). Rising global temperatures, largely driven by CO_2 and CH_4 emissions, intensify the environmental challenges facing dairy systems (Mann, 2024). Notably, methane possesses 84 times the heat-trapping capacity of carbon dioxide over a 20-year horizon, making it a critical target for climate mitigation despite its ephemeral nature (Filonchyk et al., 2024). While biogenic methane—produced by livestock—has a higher warming potential, it originates from and cycles back into atmospheric carbon, differentiating it from fossil-derived CO_2 (Rotz et al., 2024; Forster et al., 2021).

Methane is primarily produced by ruminants through enteric fermentation, accounting for over 58% of dairy-related GHG emissions globally (Broucek, 2014). Species including cattle, goats, and sheep release CH_4 as a byproduct of ruminal digestion. Emissions are influenced by feed intake, dietary composition, energy utilization, animal size, growth rates, and environmental factors. Daily methane emissions per dairy cow range from 151 to 497 grams, with lactating cows exhibiting higher outputs than non-lactating individuals. The emission intensity averages 2.8 kg CO_2-equivalent per kg of fat- and protein-corrected milk (Broucek, 2014). Reducing CH_4 emissions across all ruminant systems—beef, dairy, and small ruminants—should therefore be a global priority.

Promoting smallholder dairy development through an enterprise-driven lens offers a viable pathway for enhancing rural livelihoods and reducing poverty, while simultaneously addressing methane emissions and climate-related impacts (Chagunda et al., 2016). Climate change directly affects dairy productivity by redirecting animal energy from production to thermoregulation and adaptation (Thornton & Gerber, 2010). Moreover, the increasing demand for dairy in the face of limited land and water resources, coupled with biodiversity concerns, underscores the complexity of sustaining smallholder systems (Sakadevan & Nguyen, 2017). The environmental consequences of dairy farming are highly variable, contingent on farm management practices (Clay et al., 2020).

Beyond GHG emissions, dairy production systems contribute to multiple ecological stressors, including soil degradation, water contamination, biodiversity loss, nutrient cycle imbalances (notably nitrogen and phosphorus), and land use changes (Eshel et al., 2014; Chang et al., 2021). Nonetheless, nutritional innovations have proven effective in mitigating GHG emissions through relatively accessible and scalable interventions (Astuti et al., 2024; Kroliczewska et al., 2023; Tseten et al., 2022).

Many high-income countries have successfully reduced methane outputs by improving animal productivity and deploying advanced mitigation technologies (Crippa et al., 2021). The *Pathways to Dairy Net Zero* initiative, led by the Global Dairy Platform and supported by over 40 international dairy organizations, seeks to align dairy production with net-zero GHG targets while fostering healthier, more equitable food systems (FAO, 2010). However, progress in developing countries remains uneven, primarily due to constraints in technological access and implementation. These challenges are exacerbated by projected surges in dairy demand, driven by population growth and rising per capita income.

A transformative shift toward sustainable, climate-smart smallholder dairy practices is therefore essential (Chagunda et al., 2016). In developed nations, methane abatement strategies encompass genetic selection, precision feeding, chemical inhibitors, microbial vaccines, and metagenomic technologies—tools that hold promise for climate resilience in animal agriculture (Berdos et al., 2023; Gharechahi et al., 2021; Manzanilla-Pech et al., 2021; Zhao et al., 2015).

Despite the growing significance of dairy in sub-Saharan Africa, empirical research on enteric methane emissions in smallholder systems is still limited. Notable studies include work by Hawkins et al. (2021) in Tanzania, Chagunda et al. (2009) in Malawi, Wilkes et al. (2020) in Kenya, and Feyissa (2023) in Ethiopia. The lack of data is especially concerning given projections that demand for milk and dairy products could rise by over 30% by 2050, intensifying methane emissions. Accelerating scientific research, fostering technological dissemination, and supporting policy reforms are critical to meeting both global net-zero targets and the nutritional needs of expanding populations (FAO, 2009).

The Interplay Between Smallholder Dairy Farming Characteristics and Resilience: Lessons for Climate Change Adaptation

Amid growing global concern over greenhouse gas (GHG) emissions from dairy production, the application of robust and scientifically credible methodologies for emissions assessment is increasingly urgent (Becciolini et al., 2022). Numerous strategies exist for mitigating enteric methane (CH_4) and related emissions in dairy systems (Ferraz et al., 2024). However, methane quantification remains underdeveloped across diverse production systems, necessitating context-specific mitigation strategies that align with the operational dynamics of extensive, intensive, and semi-intensive dairy models. The rapid expansion and transformation of smallholder dairy farming underscore its potential as a cornerstone of sustainable agricultural development.

Climate-smart smallholder dairy systems offer a "triple-win" pathway—enhancing productivity, bolstering resilience, and mitigating climate change through the reduction of GHG emissions. As a multifaceted agricultural strategy, smallholder dairying addresses both livelihood imperatives and agroecological demands while contributing to a more balanced GHG profile within the livestock sector.

In many developing regions, smallholder dairy farming is largely characterized by reliance on rain-fed agriculture, limited mechanization, small landholdings, and predominantly family labor (FAO, 2010). These producers face compound pressures—including climatic stress, socio-economic inequalities, and resource constraints influenced by gendered access to land and decision-making power (Maltou & Bahta, 2019). These intersecting vulnerabilities diminish both household resilience and the potential benefits derived from dairy development interventions. The concept of Climate-Smart Agriculture (CSA), as introduced by Lipper et al. (2014), provides a framework for addressing these challenges by simultaneously enhancing productivity, adaptive capacity, and climate mitigation.

Despite consensus on the necessity of building resilience within smallholder dairy systems, scholarly debate continues around the optimal approach. Resilience is increasingly defined as the capacity of these systems to absorb and recover from climate-induced shocks and stresses (Meuwissen et al., 2019). Smallholder dairy farming offers vital opportunities to strengthen the adaptive capacity of rural livestock keepers, improve productivity, and reduce methane emissions, all of which are crucial for climate-compatible development.

Nevertheless, smallholder systems remain acutely vulnerable to climatic variability—manifesting through increased temperatures, erratic rainfall, and the intensification of extreme weather events. These environmental shocks divert animal energy from production to survival, thereby constraining productivity and compounding GHG outputs. Overcoming such constraints requires the implementation of climate-resilient management practices, including genetic improvement, targeted nutrition strategies, chemical inhibitors, vaccines, and advanced tools such as metagenomics.

International agencies and NGOs increasingly position smallholder dairying as a critical strategy for enhancing rural livelihoods and promoting climate adaptation (Chagunda et al., 2016). Consequently, countries with agriculture-dependent economies are prioritizing reductions in methane emissions from livestock. As demand for dairy products continues to rise, driven by population growth and rising incomes, the sustainability of dairy systems—particularly in the Global South—faces mounting pressure.

Climate change also introduces systemic risks to dairy systems, notably through disruptions to forage availability, water scarcity, and heat stress (Astuti et al., 2024). Smallholder farmers, many of whom consume a large share of their own dairy output, often draw on past experiences, social memory, and indigenous knowledge to cope with climatic shocks. Livelihood diversification remains a widespread strategy to buffer against environmental uncertainty (Frank, 2000). Community-based monitoring and local ecological knowledge can complement scientific research by contextualizing climate responses (Gupta et al., 2007).

Research to date has largely focused on adaptation, food security, and vulnerability, with insufficient attention to the mechanisms of resilience and potential maladaptive outcomes. Climate-smart interventions should be designed to manage biophysical risks—such as drought, heatwaves, and erratic rainfall—by optimizing farm management, enhancing feed efficiency, and strengthening institutional support (Makate, 2019; FAO & IDF, 2011). Precision agriculture, including the fine-tuned allocation of feed and water resources, exemplifies a promising CSA approach (Hoque & Mrutyunjay, 2024).

Enhancing resilience in smallholder dairying demands an integrated perspective that accounts for ecological, social, and economic interdependencies. Customized resilience strategies should reflect specific agroecological and socio-economic contexts, embracing diversified production and biodiversity conservation as risk-buffering mechanisms.

Agroforestry and integrated crop-livestock systems have gained traction as viable alternatives to conventional, specialized farming. These mixed systems are increasingly endorsed for their capacity to simultaneously address environmental degradation, economic volatility, and social inequality. In low- and middle-income countries, such systems are foundational to adaptive dairy production strategies, and even high-income nations are recognizing their value in climate adaptation (Hendrickson, 2020).

In developing countries, agroforestry practices integrated with crop and dairy farming represent a “win-win” for ecosystem services and smallholder resilience. Gender-sensitive approaches to these systems are crucial to ensure equitable outcomes in climate mitigation and food security (Aguilera et al., 2020). Incorporating fodder shrubs and leguminous cover crops can enhance feed quality, reduce herd sizes, and consequently limit methane emissions (Wambugu et al., 2011). Agroforestry-based fodder production contributes to on-farm feed sufficiency, strengthening the resilience of dairy systems (Pye-Smith, 2010).

Optimal fodder species are fast-growing, nutritionally rich, and tolerant of frequent harvesting. Improved forage practices, particularly the planting of high-value fodder trees, have demonstrated efficacy in both enhancing milk yields and reducing climate risks (Wambugu et al., 2006). CSA remains a central agricultural development paradigm, advancing both ecological resilience and food security while reinforcing the systemic social foundations of resilience (Place et al., 2009).

Nonetheless, failure to consider localized social-ecological dynamics in CSA implementation may result in maladaptive outcomes—undermining the sustainability of smallholder dairy systems. A nuanced understanding of the interplay between agroforestry, mixed farming, and community-specific adaptation pathways is therefore essential for delivering long-term climate resilience.

Exploring the Potential of Nutritional Interventions to Decrease Enteric Methane Production in Small-Scale Dairy Farming Systems.

Methane emissions from smallholder dairy systems in low- and middle-income countries can be significantly curtailed through the adoption of improved nutritional and feeding interventions (Chagunda et al., 2016). In tropical contexts, dairy cattle primarily consume feed derived from natural grasslands, crop residues, fodder trees, shrubs, agro-industrial by-products, and other non-conventional feed sources (Yisehak & Adane, 2024). These systems, often integrated into mixed farming models, leverage locally available resources in ways that prioritize ecological sustainability and resilience. Strategic dietary manipulation within these systems not only enhances milk yields and promotes food security but also mitigates greenhouse gas (GHG) emissions—particularly enteric methane—by improving feed digestibility and nutritional density (Shrestha et al., 2020). Climate-smart nutritional strategies, including the use of high-quality, digestible feed resources, offer a dual benefit: increasing livestock productivity while contributing to climate change mitigation. Outcomes of these interventions include: (i) reduced methane emissions from smallholder dairy operations and (ii) improved livelihoods and income generation, particularly for women, through enhanced productivity and production efficiency.

Despite the expansion of smallholder dairy farming in developing regions, feed scarcity remains a persistent constraint (Duguma et al., 2017). Over 84% of surveyed farmers report feed deficits during dry seasons, and 50% during wet seasons, driven largely by the limited availability of forage and diminishing pasturelands. Farmers adopt coping mechanisms such as increasing reliance on bulule, crop residues, unconventional feedstuffs, hay conservation, and in some cases, herd size reduction. Feed availability is highly seasonal and region-specific, comprising sorghum stover, maize stover, *Eragrostis tef* straw, and various pulse residues, with limited use of industrial by-products due to prohibitive costs and accessibility issues (Gebremariam & Belay, 2016). In arid and semi-arid zones, both the quality and quantity of available feed are inadequate to support optimal milk production. Thus, participatory research and development of low-cost, context-appropriate technologies are vital to ensuring sustainable forage supply, boosting milk yields, and reducing methane emissions.

Evidence suggests that proper feeding regimes and improved efficiency can substantially lower methane outputs from dairy farming (Steinfeld & Gerber, 2010). Enhanced digestibility of fibrous feeds is particularly crucial to reducing enteric methane (Gerber et al., 2010). Even marginal gains in productivity, coupled with targeted feeding practices, can lead to meaningful reductions in methane per unit of milk produced (Hawkins et al., 2021). Integrating climate-smart feed practices—such as forage cultivation, postharvest crop residue management, and the use of conserved feed like hay and silage—can simultaneously support production goals and limit GHG emissions (Herrero et al., 2013). Smallholder dairy systems in tropical regions can increase feed conversion efficiency (FCE) and reduce methane through optimized diet formulation and nutrient balancing (Maleko et al., 2018). These approaches also include leveraging locally sourced ingredients, incorporating agro-industrial by-products, and reducing crude protein levels without compromising performance (Chisoro et al., 2023; Swetha et al., 2024).

The implementation of climate-resilient forage species and drought-tolerant feed crops is critical for reducing the environmental footprint of dairy systems while maintaining productivity. However, decreasing methane through feed modifications may sometimes reduce fiber digestibility, potentially limiting animal energy intake. Therefore, interventions must be nuanced and adapted to specific agro-ecological contexts. Training programs targeting men, women, and youth in sustainable forage management, ration formulation, and improved feeding practices are essential. These efforts can simultaneously address gender disparities and strengthen community resilience to climate stressors. Promoting inclusive access to forage technologies fosters equitable benefits and contributes to environmentally sound dairy production.

The nexus between dietary quality and methane output follows well-established patterns: higher-quality diets and greater intake typically correlate with increased absolute methane emissions, but also improved productivity. However, supplementation with high-quality forage species, particularly legumes such as *Leucaena* and *Desmanthus*, can reduce methane emissions by up to 20% while maintaining or improving animal performance (Suybeng et al., 2019). Verma et al. (2021) highlight the variability in anti-methanogenic properties among forages, linking plant metabolomics and physiology to their potential in mitigating GHG emissions. Supplementation in smallholder systems thus serves as both a climate adaptation and mitigation strategy, helping stabilize productivity during feed-deficient periods (Thornton & Herrero, 2010).

Enteric methane emissions are influenced by feed type, nutrient content, and intake levels (Duguma et al., 2017). Diets with higher concentrate proportions increase digestibility and reduce methane per unit output.

Therefore, context-specific technical solutions and participatory development of low-cost feeding innovations are essential for reducing the carbon footprint while enhancing dairy productivity (Getiso & Mijena, 2021).

Further research is warranted on the use of improved forages, fodder trees, and postharvest innovations that can be scaled to meet smallholder needs (Mekonen et al., 2022). Participatory needs assessments should inform priorities for forage breeding, dissemination, and utilization, ensuring broad relevance and adoption (Francis & Sibanda, 2001). High-biomass, nutrient-rich forages offer potential to increase milk yields, enhance food security, and bolster system resilience.

Ultimately, scaling up climate-smart forage production and conservation techniques remains a cornerstone for climate-resilient, low-emission smallholder dairy farming. Seasonal variability—particularly during dry periods—continues to undermine feed security, productivity, and sustainability. The reliance on nutritionally poor forage during feed-scarce seasons may inadvertently increase methane emissions. Therefore, building adaptive capacity through improved nutrition, sustainable feeding practices, and private sector investment in feed quality must be prioritized. Seasonal fluctuations, feed conservation gaps, and drought impacts underscore the need for expanded fodder production, strategic feeding technologies, and holistic support mechanisms to sustain and transform small-scale dairy systems (Sraïri et al., 2011).

Gender, Climate Action, and Methane Reduction: Understanding Roles, Responsibilities, and Opportunities in Small Scale Dairy Production.

Dairy farming in rural communities should serve not only as a livelihood strategy but also as a transformative platform for gender equality and environmental sustainability. Small-scale dairy systems, when strategically supported, have the potential to reduce methane emissions while simultaneously enhancing rural livelihoods and strengthening community resilience. Integrating dairy production into national gender action plans on climate change can reinforce gender-responsive policies, promote equitable participation—particularly of women—and inform inclusive, pragmatic approaches to climate adaptation and mitigation.

A nuanced understanding of gender-specific roles in smallholder dairy systems is essential for designing effective methane-reduction strategies. In many developing countries, entrenched gender disparities make women disproportionately vulnerable to climate shocks and food insecurity. These inequalities also constrain the potential of smallholder dairy operations. Bridging the gender gap in this sector is not only imperative for achieving gender equality and food security but also for minimizing methane emissions through improved productivity and sustainable practices.

Gender dimensions play a pivotal role in shaping climate outcomes, as access to resources, decision-making authority, and labor divisions are deeply gendered (Elias et al., 2021; FAO, 2017). Advancing gender equity is central to building a climate-smart dairy sector capable of achieving long-term emission reductions and food system resilience (Flintan, 2006). Key constraints to smallholder dairy productivity include gender-based differences in resource control, labor allocation, household decision-making, and recognition of women's contributions (Banda et al., 2021). For landless rural populations—particularly women—dairy farming remains a critical livelihood strategy (Assan, 2022). Gender-responsive dairy development initiatives are vital to catalyze rural transformation and climate action (Kumati et al., 2021).

Women are key contributors to various dairy activities including forage cultivation, feeding, animal health management, and record-keeping (Pandey et al., 2024). Yet persistent gender gaps in access to extension services, markets, and capital hinder their full participation. Women's empowerment in dairy systems not only promotes economic independence and community development but also enhances their role in methane mitigation. Creating enabling environments—through inclusive institutions, supportive policies, and access to innovation—is crucial to harness their potential as agents of change (Chayal et al., 2013; Ravichandran et al., 2021).

Despite obstacles such as inadequate policy support and market exclusion, women's contributions to dairy systems significantly enhance nutritional outcomes, educational access, and livelihood security, fostering inclusive rural development (Banda et al., 2021; Chayal & Dhaka, 2016). Dairy cooperatives are instrumental in promoting gender-inclusive economic growth and delivering livelihood opportunities to marginalized groups (Prajapati, 2021; Thaker et al., 2020). Climate-resilient fodder innovations, including high-yielding varieties like *Brachiaria*, have shown promise in improving feed security, especially in arid zones (Lahoti et al., 2012). Development programs must also raise awareness of women's potential leadership roles in dairy cooperatives (Basu, 2009), ensuring their representation across decision-making levels. Countries that have mainstreamed women into dairy development report broader social and economic gains, highlighting the link between gender equity, climate resilience, and national development (Bosire et al., 2019).

Synergizing Gender Dynamics and Agroforestry for Climate-Responsive Adaptation

Recent studies (Salcedo-La Viña et al., 2023; Diop, 2021) emphasize the critical role of gender-sensitive nature-based solutions—such as agroforestry—in promoting agricultural resilience, reducing greenhouse gas emissions, and conserving biodiversity. Agroforestry systems, often gendered in roles and responsibilities (Degrande & Arinloye, 2015), mirror smallholder dairy operations in their labor dynamics and sustainability potential. The integration of trees into livestock systems reduces the carbon footprint and enhances ecological balance (Nair, 1993; Kamuti, 2021).

Agroforestry enhances dairy systems by improving fodder availability, soil fertility, and climate resilience, while promoting gender inclusion (Catacutan & Naz, 2015; Lecegui et al., 2022). Women play essential roles in these systems—particularly in gathering and managing fodder—thus reinforcing both adaptation and mitigation efforts. The integration of dairy animals into agro-silvopastoral systems is a key component of climate-smart agriculture, offering co-benefits such as enhanced productivity, diversified income, and reduced methane emissions (Pitesky et al., 2010; Kurgat et al., 2020).

The increasing appeal of agroforestry lies in its multifaceted benefits—boosting milk production, stabilizing feed supply during climate extremes, and offering GHG mitigation potential (Mbow et al., 2014). Nonetheless, the contributions of dairy animals within these systems remain underexplored. Agroforestry-dairy integrations represent a pathway toward equitable, climate-resilient rural development, ensuring that both men and women benefit from and contribute to climate-smart practices (CGIAR, 2021).

Gender Dynamics and Mixed Crop–Livestock Systems for Climate-Smart Dairy Production

Mixed crop–livestock systems form the backbone of agriculture in low- and middle-income countries, providing essential ecosystem services and sustaining millions of livelihoods (Srivastava et al., 2025). These systems account for the bulk of global milk production and are central to the food security of rural populations (Lemaire et al., 2019). They provide diverse and seasonally available feed resources that support smallholder dairy productivity while reducing the environmental burden.

The integration of dairy cattle into mixed farming systems harnesses the synergies between crop residues and livestock feed, enhancing resource efficiency, improving milk quality and quantity, and reducing methane emissions. However, more targeted research is needed to understand the socioeconomic and environmental conditions that support adoption of these systems, particularly under climate stress.

Gender dynamics in these systems reflect broader social norms, with men typically managing herds while women engage in feeding, dairy processing, barn hygiene, manure handling, and milk marketing. Although roles are differentiated, they are often complementary and overlapping (Yisehak, 2010).

Empirical studies show that mixed systems, compared to extensive grazing systems, emit 24–37% less GHGs per unit of milk due to better-quality feed and improved feed conversion efficiency (Nkeme & Ndaeyo, 2013). This makes them an attractive option for methane mitigation. However, a comprehensive evaluation of their potential, including carbon sequestration, water-use efficiency, and feed-to-milk conversion under changing climatic conditions, is urgently required.

Adopting a food systems approach that incorporates value chain actors, gender roles, and environmental considerations is essential for developing robust climate-smart adaptation and mitigation plans. The complexity and interconnectivity of crop-livestock systems demand inclusive and integrated strategies to support sustainable dairy development in the face of climate change.

IMPLICATIONS AND CONCLUSION

In summary, smallholder dairy farming systems are pivotal in both climate change adaptation and mitigation, especially in low- and middle-income countries where they serve as a primary source of livelihood, nutrition, and income for rural populations. These systems not only sustain food security but also offer a strategic entry point for reducing methane emissions through targeted innovations and inclusive development approaches.

The transformation of smallholder dairy into climate-smart systems requires an integrated approach that addresses multiple dimensions: environmental sustainability, gender equity, and technological advancement. Prioritizing climate-resilient practices—such as improved forage cultivation, efficient feeding regimes, and manure management technologies—can significantly curtail methane emissions while simultaneously boosting milk productivity and resource-use efficiency.

Gender-responsive strategies are central to this transformation. Women are critical actors in dairy value chains, contributing substantially to animal care, feeding, and milk processing. However, they remain marginalized in terms of access to extension services, land, financial capital, and decision-making power. Addressing these structural inequalities through inclusive policies and institutional reforms can unlock women's potential as agents of climate resilience and innovation in dairy systems. Bridging the gender gap is not only a matter of social justice but also a strategic necessity for achieving the full benefits of climate-smart dairy farming.

Investments in feed production and conservation technologies, such as drought-tolerant forage species, agroforestry integration, and silage techniques, are also essential for enhancing productivity and system resilience under increasing climate variability. Furthermore, recognizing the importance of mixed crop–livestock systems and agro-silvo-pastoral models can optimize resource cycling, diversify household incomes, and provide co-benefits for both adaptation and mitigation.

Policymakers and development actors must promote enabling environments that support smallholders—particularly women—in accessing climate-smart technologies, cooperative networks, markets, and training. Efforts to mainstream gender into climate and agricultural policies, alongside investments in research and capacity building, will be critical to ensure that mitigation strategies do not exacerbate existing inequalities.

Ultimately, smallholder dairy systems hold immense untapped potential to contribute to sustainable development goals. Through the adoption of gender-inclusive, environmentally sound, and economically viable practices, they can become a cornerstone of equitable rural transformation, low-emission agriculture, and climate-resilient food systems. Achieving this vision will require sustained commitment from governments, researchers, civil society, and farmers alike to co-create solutions that are both locally relevant and globally impactful.

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CONFLICT OF INTEREST

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