

The Carbon Footprint Of Smallholder Dairy Farming In Sub-Saharan Africa: A Review

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Abstract – Agriculture sector is one of major sources of income and livelihood to many populations of Sub-Saharan Africa (SSA). Over the past years animal production has been playing a vital role not only in generating revenues to farmers but also as a source of high qualitative proteins and essential micronutrients (i.e iron, zinc and vitamins) and boosting the agricultural productivity due to its importance in farmyards organic fertilization (i.e manure). Livestock production and Milk market in SSA are dominated by smallholder dairy farming (SDF) which employ nearly 70% of all livestock farmers. Despite its positive impact on people and SSA countries' economy, SDF has been the major fastest growing agricultural contributors of GHG emissions such as CH₄, N₂O and CO₂ (i.e 9t CO₂e per tonne of milk; the highest in the world compared to other regions) thus accelerating global warming effect.

Although several articles have investigated the impacts of livestock production on climate change, to the best of our knowledge the existing literature doesn't contain any studies that provide insight review of smallholder dairy farming's carbon footprint (CF) in SSA. This review paper is therefore aimed at critical analysis of current knowledge in terms of CF of smallholder dairy farming in SSA and effective mitigation strategies (dietary, manure and animal management) recently proposed to reduce CH₄ and N₂O emissions from ruminants. SSA was selected because of rapid rise of SDF in the region therefore it is expected to rapidly increase its GHG emissions in future if no sustainable measures are taken.

The critical analysis, what is known and gaps in SDF from this review will help to inform the farmers, researchers, decision and policy makers interested in GHG emissions thus to provide the next direction in research and improvement of the sector for sustainability. Capacity building for raising awareness among farmers was identified as paramount to better understand the issue and the options to mitigate emissions on-farm. As longer as adaptation and mitigation strategies become paramount on national and regional agenda, SDF will make significant contribution to economies, improved livelihood and become sustainable livestock production systems in SSA at large.

Keywords – Smallholder farming, Sub-Saharan Africa, Carbon footprint, Greenhouse Gases, GHG, Global warming, Climate change, Enteric fermentation.

INTRODUCTION

The global population has been increasing dramatically over the last decades and it is projected to reach 8.5 billion by 2030 and accelerates further to 9.7 billion by 2050 [1]. Africa alone is expected to have more than half of global population growth in 2050. Recent statistics show that Sub-Saharan Africa (SSA) region (**Fig. 4**) accounts around 1.1 billion people (13.8% of global population) [2] and it is expected to double by 2050 [3]. This population growth is expected to increase with urbanization, food demand and diet changes in developing countries of Africa [4], [5]. With various eating habits there will be a tremendous demand for agricultural production in general and livestock products (e.g. beef and dairy products) (**Fig. 2**) specifically [6], [7]. Nowadays the globe's millions of poorest people mainly depend on smallholder farming systems to survive [8]. Being the major economic activity that most of the growing SSA's population rely on for living [9], [10], [11] much pressure is expected to be put on agriculture

hence impacting natural resource such as land and water resources for crop production and livestock farming. Globally agriculture, forestry and other land use activities are responsible of 24% of anthropogenic greenhouse gases (GHGs) emissions (**Fig. 7**). According to the Intergovernmental Panel on Climate Change (IPCC), GHGs are gases found in atmosphere originating naturally on one hand and from anthropogenic activities on the other hand. These gases absorb and re-emit radiation as heat causing the rise in global average temperatures.

SSA's agricultural sector is the biggest contributor of GHGs emissions accounting 27% of the total continental emissions [12]. Deforestation for expanding cropland and pasture, emissions from agricultural soils, nutrients and livestock management (e.g. manure and digestive processes) have been mentioned by many (**Table 7, Fig. 3** and **Fig. 8**) as major GHGs sources [12], [13].

Over the past years smallholder farming has provided livelihoods to many people in SSA (**Table 4**), and it will continue to play its significant role in boosting their future income [14]. In SSA, 80% of agricultural production comes from smallholder farming and employs around 175 million people [10], [15]. Although small farms provides employment to many people and produce agricultural crops and livestock, at the same time they are characterized by high emissions of GHGs emission [8], [16]. The SSA's smallholder dairy farming has been attracting various farmers and different governments and international agencies which keep on supporting this sector for eradicating malnutrition and poverty [17].

Currently smallholder dairy farmers provide more than 80% of SSA milk production. Due to rapid growth of African population milk and meat products are projected to double over the coming 20 years in Africa [18]. However livestock in general and dairy farming in particularly has significantly contributed to global warming through the emission of three major GHGs which are: Methane gas (CH₄), Nitrous oxide (N₂O) and Carbon dioxide (CO₂) [19]. These gases are also known as the carbon footprint¹ (CF) of dairy products [20]. However in this manuscript, sources of CO₂ from smallholder dairy farming (SDF) were not discussed due to the fact that emissions from CO₂ are in association of cycles of carbon fixation and oxidation through photosynthesis [21] and its Direct global warming potential (GWP) is less harmful compared to CH₄ and N₂O as shown in **Table 1** below.

Table 1: Idea on agricultural GHG emissions

Sources	Gases		
	CO ₂	CH ₄	N ₂ O
Atmosphere lifetime (year)	120	14.5	120
Direct global warming potential (GWP)	1	24.5	320
Preindustrial concentration	280ppmv	0.8ppmv	288ppmv
Current annual increase (%)	0.5	0.9	0.25
Major agricultural source	Deforestation	Ruminants Wetland rice Biomass burning	Synthetic N fertilizers Animal excreta Biological N fixation

Source: [22] ppmv: parts per million volume

According to FAO and GDP (2018) GHG emissions from dairy sector have dramatically risen by 18% between 2005 and 2015 due to the increased consumption demand globally. During this period 4% of all global anthropogenic GHG emissions have been contributed by dairy sector. In 2015 the dairy sector in developing regions such as SSA, South Asia, West Asia and North Africa were found to have higher emission ranging between 4.1 to 6.7 kg CO₂ eq. per kg fat-and-protein corrected milk (FPCM).

In terms of research a lot of work has been done to better understand GHGs emissions from agricultural sector and smallholder dairy farms in SSA[12], [24], assessing and managing smallholder ruminants and dairy systems for food security in SSA[17], [25], Climate change impacts, adaptation and mitigation in smallholder agricultural systems in SSA[10], [16], [26]. Furthermore Wilkes et al, (2020) [27] conducted a study for analysing carbon footprint of milk production on smallholder dairy farms in central Kenya. The results showed that CF was ranging between 2.2 and 3.13 kg CO₂e/kg fat and protein corrected milk (FPCM).

¹ Carbon footprint (CF) is defined as the total GHGs emissions that come from production, consumption/use and end of life of a product expressed in carbon dioxide equivalents (CO₂-eq) [20]

From the above background, there is a need of reviewing “what is already known” (current knowledge) and ‘what is not known’ (knowledge gap) in SDF of SSA so that the next research direction can be enhanced and avoid repetitions on what has been previously done in this sub-sector. Hence, this article is aimed at:

- (i) Reviewing the importance of smallholder dairy farming in SSA based on previous studies,
- (ii) Analysing the contribution of SSA's smallholder dairy farming to GHGs emissions and impacts on global warming/climate change
- (iii) Investigating the SSA' smallholder farmers’ knowledge of the issues raised in (ii)
- (iv) Proposing strategies that smallholder dairy farmers can adopt to reduce emissions of GHGs

This paper will help to understand the role of SDF in climate change and proposed strategies will facilitate the reduction of livestock related carbon footprint thus improving and promoting a more sustainable SDF (green farming) in dairy sector of SSA.

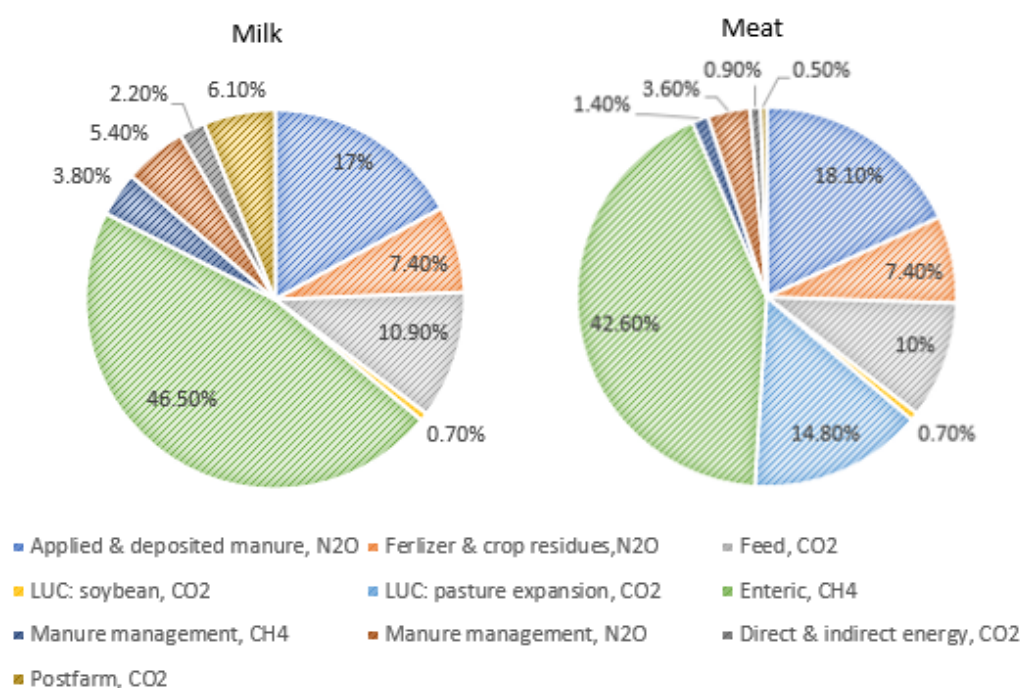


Fig. 1: Global GHG emissions from cattle milk and beef supply chains
(by emissions category)

Source: GLEAM (Global Livestock Environmental Assessment Model)

Table 2: Number of dairy cows, milk production and milk yield per cow and increase in % for different regions (between 1961 and 2009)

Year	Number of dairy cows (million)			Milk production (million tonnes)			Milk yield (tonnes per cow)		
	1961	2009	Increase	1961	2009	Increase	1961	2009	Increase
Africa	17	60	255%	8	29	270%	0.5	0.5	4%
Asia	34	94	173%	21	151	613%	0.6	1.6	161%
Europe	83	40	-52%	190	208	10%	2.3	5.2	130%
North America	20	10	-50%	65	94	44%	3.2	9.2	186%

Oceania	5	6	24%	12	25	116%	2.3	3.9	74%
Latin America	17	42	145%	18	77	322%	1.1	1.8	72%
World	177	253	42%	314	583	86%	1.8	2.3	31%

Source: [28]

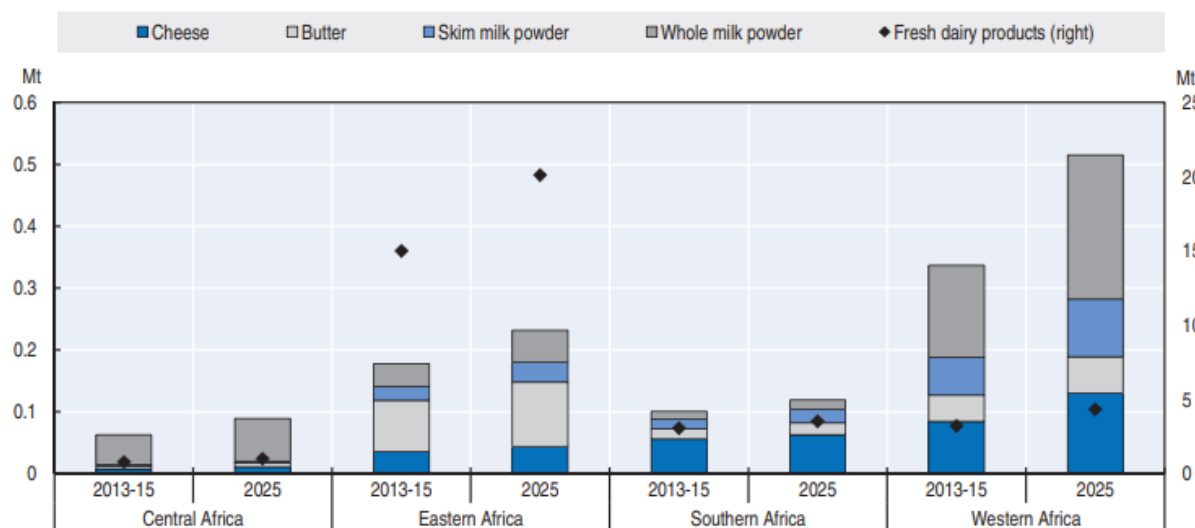


Fig. 2: Consumption trends of dairy products in SSA

Source: [29]

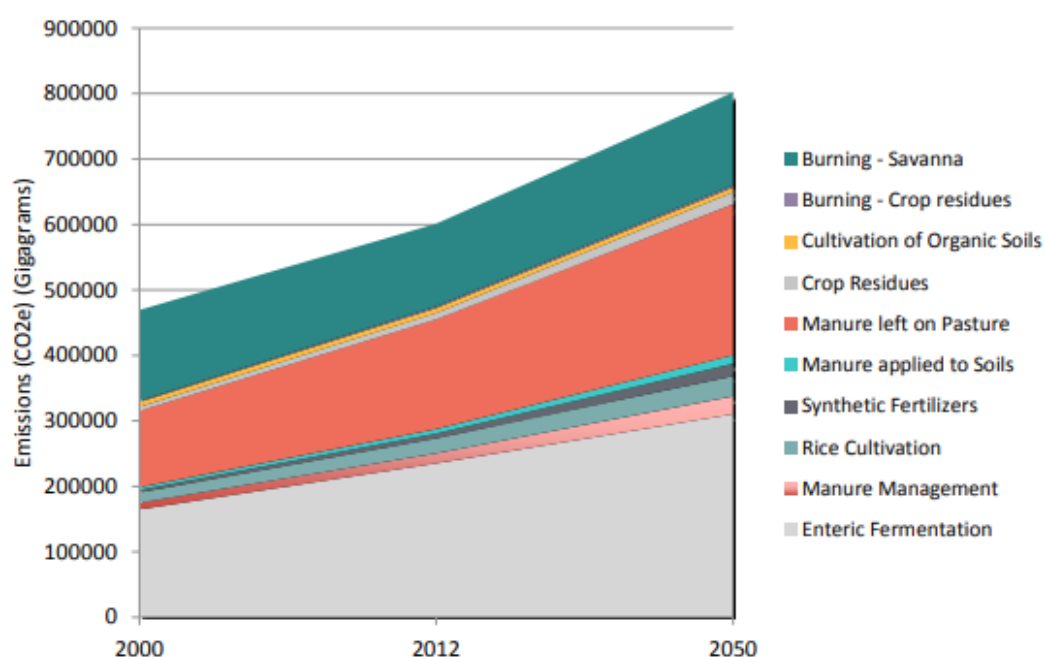


Fig. 3: Projected emissions from SSA's agricultural sector (excl. RSA), 2000-2050

Source: [30]

I. IMPORTANCE OF SMALLHOLDER DAIRY FARMING IN SUB-SAHARAN AFRICA

Globally, livestock production has increased tremendously over the past decades (**Table 2**) mainly for animal protein food [31]. In animal production sector dairy farming plays a significant role globally as a way of achieving food security, improving farmer incomes and impacting economic growth [32]. Generally, there is no standard or universal definition of smallholder dairy farming. Many authors/researchers have provided various definitions regarding Smallholder dairy farming. Gizaw et al. (2016) [33] defined it as production, on-farm processing and marketing of milk and milk products. On the other hand Mbilu (2015) [34] defined smallholder dairy farming to be the one which has 1-10 dairy cows with a purpose of income generation through commercial milk production.

The dominating terms in provided definitions by various authors are : small herds (2-3 milking cows) with the majority located in developing countries; usually on small plots [33], [35]. Smallholder farming systems contribute around 80% of all African continent milk production [18]. In these systems producers rear less than 10 head of cattle with land sizes varying from 0.2 to 4 hectares [8], [30], [36]. Taking one example of Eastern African country (e.g. Rwanda) smallholder crop-livestock mixed farming system dominates livestock production with average land holding of 0.76 ha for the majority of farmers with Smallholder farmers keep one to three cows [37]. Other examples are Kenya, Mozambique, Malawi and Zimbabwe where the average size of smallholder farms ranges between 0.8 and 4.65 hectares [38]–[41].



Fig. 4: Regions of Sub-Saharan Africa and corresponding countries

Source: <https://www.quotemaster.org/Sub-Saharan+Africa>

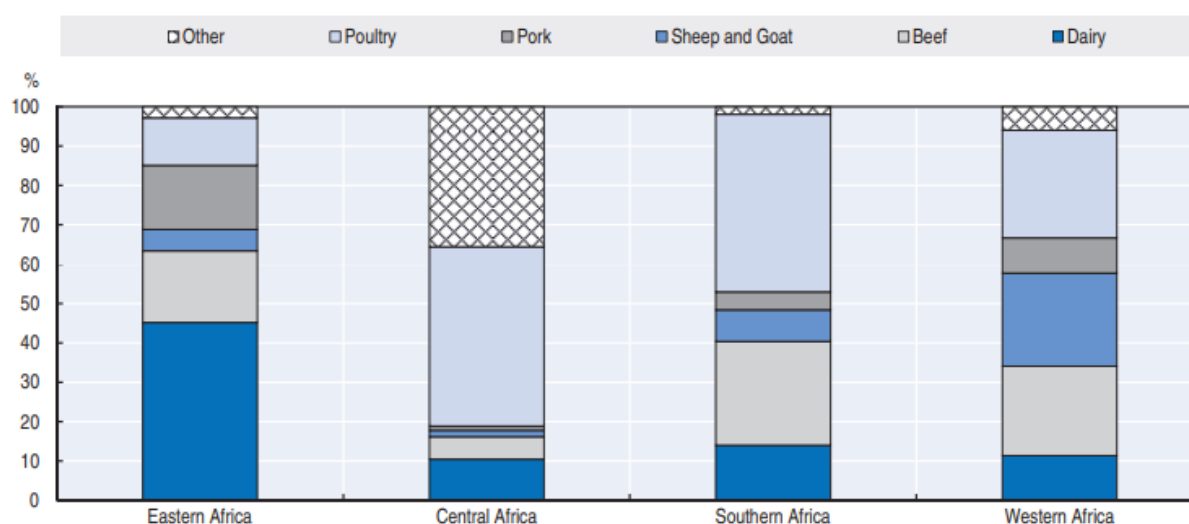


Fig. 5: Livestock mix across the Sub-Saharan African region

(Based on average value of production 2011-13)

Source: [42] FAO, <http://faostat3.fao.org/>

Table 3: Dairy production in Eastern Africa in 2011

Country	Milk (million t)	Milk (% growth rate between 200-2011)	Butter (1000 t)	Cheese (1000 t)
Ethiopia	4.4	14.2	17.6	5.8
Kenya	4.3	5.5	14.7	0.3
Rwanda	0.2	5.3	0.7	n/a
Tanzania	1.8	7.8	31.5	13.0
Uganda	1.2	8.0	n/a	n/a

Source: [43]

1.1 Nutrition, source of income and employment opportunity

In SSA smallholder farming counts approximately 80% of all agricultural farming and employs more than 175 million people directly [10], [29], [44] and a source of livelihoods for women in particular [45]. In this region, milk production is among top important agricultural sub sectors which contributes to food security and provides regular income which reduces poverty hence improving farmers' living standards [29]. Cow milk production is predominant specifically in Eastern Africa (**Table 2**), followed by goat milk, sheep milk and camel milk. Being the leading first milk-producing region in Africa, Eastern African milk production represents 68% of the continent's milk output. The dairy sector is one of the fastest growing agricultural sub-sectors in Eastern African countries, which has generated significant economic returns and employment opportunities along dairy value chains [43]. Dairy farming which includes livestock rearing, forage, feeding, milk production, distribution and sale (**Fig. 6**) employs and generates income to millions of smallholder farmers in SSA[18]. Smallholder dairy products improve household nutritional status as a result of higher milk consumption [46], [47].

1.2 Impact on national economy growth

Agricultural sector contributes significantly to the GDP of most SSA countries and taken as priority in their development agenda. Over the past decades smallholder dairy farming made important contribution to the increase of 37% in milk yield and is projected to rise at an annual average growth rate of 2.5% [29]. The livestock subsector accounts for about 5% of the total gross domestic product (GDP) in sub-Saharan Africa. **Table 4** below is an example of how this sector contributes:

Table 4: Contribution of the dairy sector to GDP and employment [43]

Country	% share of agricultural GDP	% share of GDP	Smallholder dairy farmers (millions)
Ethiopia	40	12-16	
Kenya	50	3	2
Rwanda	15	6	0.1
Tanzania	n/a	1.8	
Uganda	50	7-9	0.7



(a) Smallholder farmer feeding her milk cow, (b,c) Milk collection and transport and (d) Manure management for biogas production

Fig. 6: Some activities of Smallholder dairy production in SSA (e.g Rwanda)

II. SMALLHOLDER DAIRY FARMING GHGs EMISSIONS

Over the past decades anthropogenic activities have been increasing GHGs emissions in the atmosphere which caused global warming [48]. This phenomenon is actually happening and no longer a prediction [49]. It is estimated that human activities globally increased temperature between 0.8 °C and 1.2°C above pre-industrial levels. If emissions continue at the current rate the global warming is expected to rise up to 1.5 °C between 2030 and 2052 [50].

In fact when the sunlight reaches the earth's surface and oceans a portion of that light (around 30%) is sent back into the space and the remaining portion is absorbed by land, water bodies (e.g oceans, lakes, etc) and air [51]. As the atmosphere is made of various gases including water vapours, ozone (O₃), methane (CH₄), carbon dioxide (CO₂) and other gases they make a kind of blanket which retain part of reflected radiations from the earth [19], [26]. These gases are commonly known as greenhouse gases (GHGs) due to their capacity of trapping heat. Once reflected back into the atmosphere the heat is trapped by the above mentioned gases hence contributing to the increase of average surface temperature higher than it would be [52]. Anthropogenic activities such as burning of fossil fuels (coal, oil, and natural gas) and deforestation are major contributor (Table 1) of GHGs emissions in the atmosphere [49].

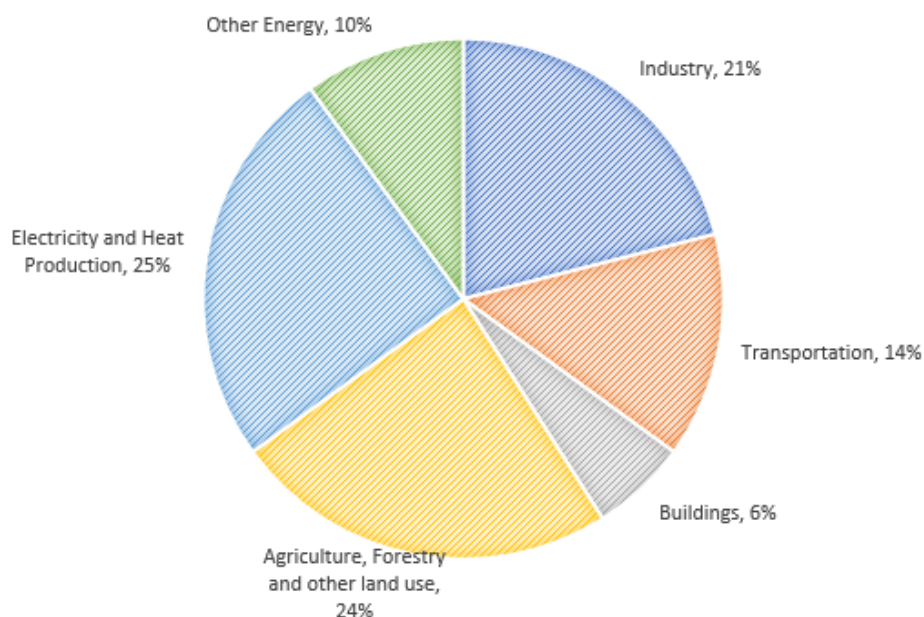


Fig. 7: Global GHGs emissions by economic sector

Source: [52]

Agricultural activities which employ 65-70% of Africa's workforce (mostly as smallholder famers) [30], [53], [54] have been put among the quickest growing GHGs emitters in the world as a result of increasing food demand due to rapid population growth [55]. A mean annual increase between 2.9% and 3.1% of GHGs emissions from agricultural sector was observed during the period 1994-2014 with enteric fermentation alone contributing more than half of the total GHGs emissions on the African continent; which points out the role of livestock (ruminants) in global warming [55] and climate change [19].

The CF of milk produced by smallholder farmers in African is high and projected to increase rapidly in the years to come [27]. Compared to other parts of the world, Africa emits highest GHGs per unit of milk and meat production. SSA alone emits 9tCO₂e per tonne of milk; the highest in the world while North America and Europe emit only 1.9tCO₂e and 1.6tCO₂e per tonne of milk respectively. It is a result of inadequate livestock's feed and low productivity [56].

The annual increase in agricultural GHG emissions (dominated by enteric fermentation emissions from smallholder farmers) makes Africa to be a suspicious continent in the future climate change due to its growing emissions (**Table 7**) [21].

Table 5: Carbon footprint of smallholder dairy farming in some countries of Sub-Saharan African

Country	FPCM emissions (kg CO ₂ e/kg)	% contribution of enteric fermentation	% contribution of feed production and transport	% contribution of manure management	Source/reference
Kenya	2.19-3.13	55.5	31.6	12.6	[27]
Ethiopia	2.07-4.71	80	-	-	[57]
Malawi		44% (CH ₄)	21% (CO ₂)	35% (N ₂ O)	[24]
SSA	7.5				[7]

Table 6: SSA regional emission levels in GgCO₂e

Region	CH ₄	N ₂ O	Total agricultural emissions
West Africa	116,959	93,600	210,560
East Africa	204,275	172,238	376,512
Central Africa	51,418	55,937	107,355
Southern Africa	22,984	24,268	47,251
Total	395,636	346,042	741,677

Source: [58]

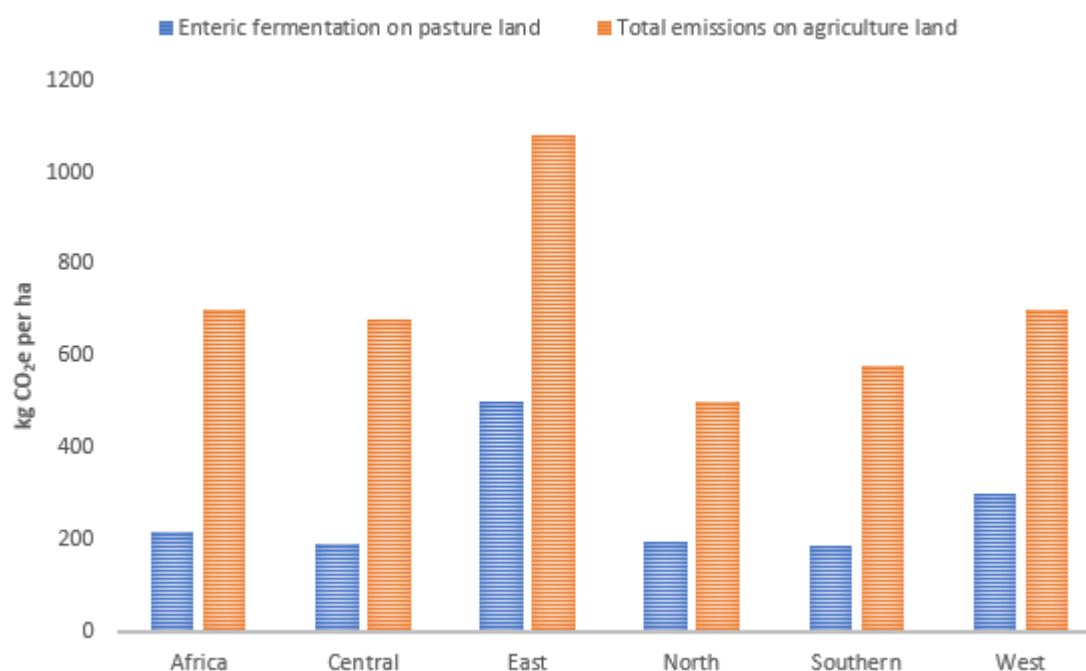


Fig. 8: GHG emission intensities per agricultural land and regions of Africa in 2010

Source: [55]

In 2013 global emissions from livestock sector were estimated at 7.1 gigatonnes CO₂-eq per year. This value represents 14.5% of anthropogenic GHG emissions; explaining the role of the sector in global warming and climate change. Beef and cattle milk production contributed the majority with 41 and 20% of the sector's emissions respectively [19], [59]. Due to rapid population growth the global demand of milk and dairy products is projected to sharply rise in the coming decades with increased emissions of GHG specifically in developing countries [60]. The growing of dairy production in many SSA countries is not only connected to rising consumer demand but also to many governments' goals to reduce poverty, expand milk production for domestic self-sufficiency hence reducing dependency on imports, improve crop production by using manure, increase income and nutrition at the household level. As reported by Tadesse & Dereje (2018) [26] raw milk (also known as unpasteurized milk) at farm level in SSA is responsible of about 70-90% GHG emissions from smallholder dairy farming products.

In East Africa, despite its intended goals of reducing poverty through smallholder dairy cattle farming among others; Rwanda's Girinka program (which is also known as one cow per poor family program) launched in 2006; is responsible of increasing national GHG emissions by 1174 kg CO₂e hh⁻¹ yr⁻¹ [61], [62]. As the program goes on, it is reported that most of distributed cows in this program have given birth between 1 to 4 calves; an indicator of animal population increases which will have a future rapid rise of emitted GHGs too if current management practices are not improved.

Livestock systems in Africa (SSA particularly) emit higher rates per kg of animal product compared to other parts of the world [16]. Large emissions of enteric methane (CH_4), carbon dioxide (CO_2) and Nitrous oxide (N_2O) in livestock are provided by smallholder farming systems due to the use of fodder of lower digestibility, poor management of manure, low milk yield and milking cows at ageing stage [20], [26], [63]. While the global mean is 46 and 2.8 kg CO_2 equivalent per kg of dressed weight and fat- and protein-corrected milk (FPCM) respectively, It is estimated that African beef and dairy systems emit 70 and 9 kg CO_2 equivalent per kg of dressed weight and FPCM respectively [63]. Livestock GHGs emissions can be direct or indirect. Direct emissions include enteric fermentation, urine excretion and microbial decomposition of manures. Indirect emissions describe those which are related to manure applications for crop production, fertilizers applications for growing fodder (forage), processing and transportation of refrigerated livestock products, deforestation and release of carbons from cultivated soils for expanding livestock farming (Fig. 9&14) [12], [19].

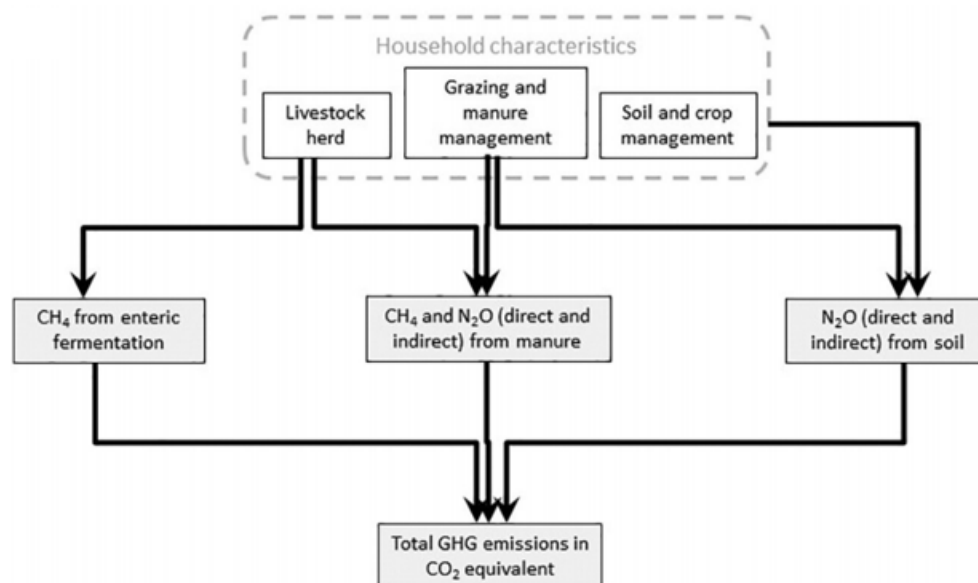


Fig. 9: Diagram indicating sources of GHG emissions (CH_4 and N_2O) from smallholder dairy farming and used approach to convert their totals into CO_2e
Source: [61]

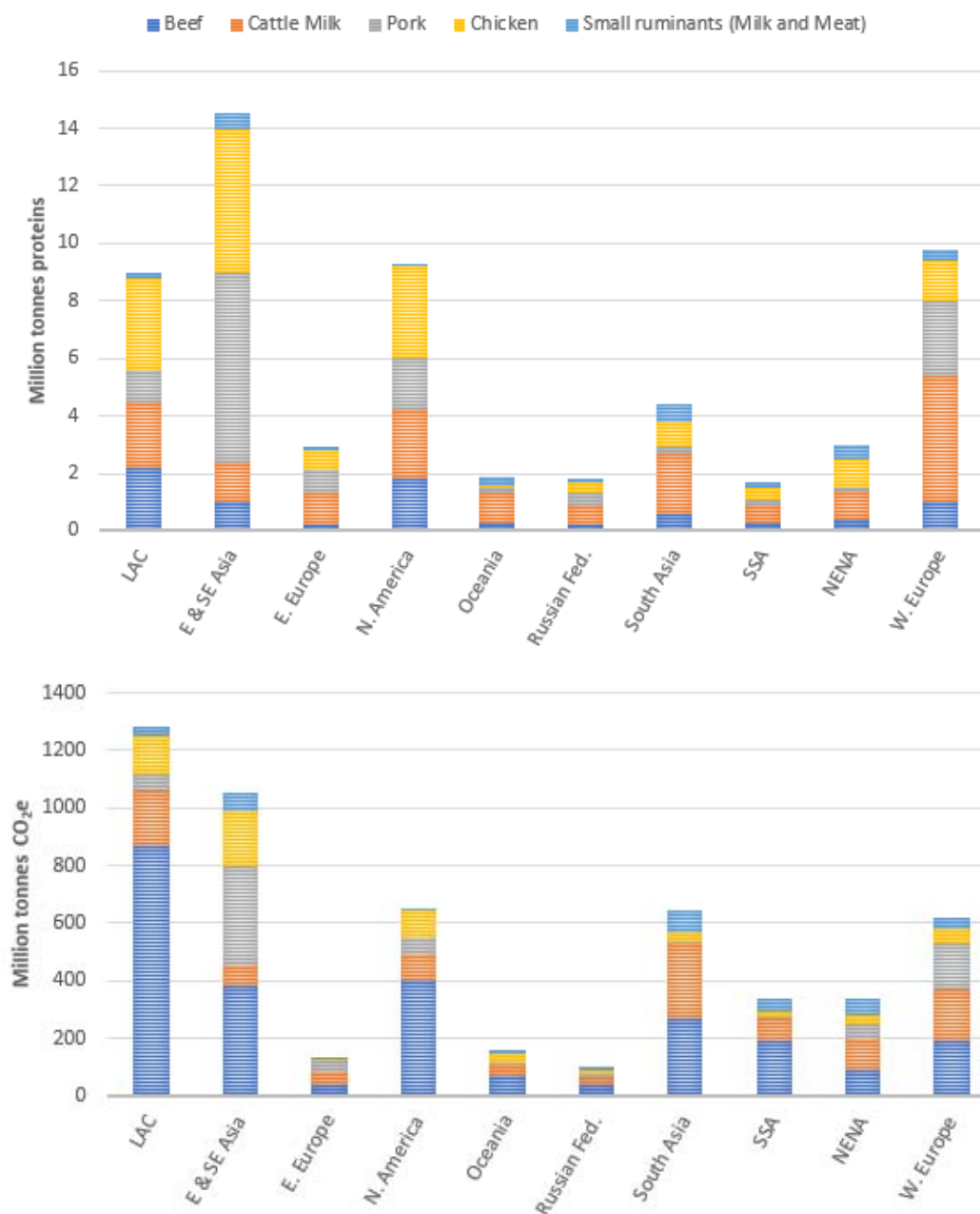


Fig. 10: Global livestock production and GHG emissions from livestock
(by commodity and regions) adopted from [59]

Despite lower output in proteins and in other dairy nutrients, GHG emissions of livestock farming in SSA are on a rise [59]. CF of dairy farming which is estimated to 7.5 kg CO₂ eq per kg milk; is the highest by counting all emissions from livestock sector in SSA [20]. The CF of this sub-sector in SSA countries is projected to continue rising in the coming decades (**Fig. 3**) as a result of high number of smallholder dairy farmers which dominate this sub-sector characterized by poor farm management and inadequate livestock feeding [27], [32]. Smallholder dairy systems in SSA are generally characterized by mixed systems whose main output is milk for sale. Livestock production is integrated with the growing of subsistence crops (e.g maize, beans, potatoes, etc) [25].

Livestock GHG emissions in regions of SSA mainly come from three major sources: enteric fermentation from ruminants (CH₄), manure management (N₂O) and changes in land use (CO₂) [26], [64]:

Table 7: GHG emissions in Gigatons (Gt) CO₂eq sources in Sub-Sahara African regions

	1994		2000		2005		2010	
	CH ₄	N ₂ O	CH ₄	N ₂ O	CH ₄	N ₂ O	CH ₄	N ₂ O
Total	0.360		0.417		0.469		0.541	
Sub-Saharan Africa	0.236	0.124	0.273	0.144	0.307	0.162	0.354	0.187
Enteric fermentation	0.226		0.262		0.295		0.340	
Manure management	0.009	0.002	0.010	0.003	0.011	0.003	0.013	0.004
Direct soil		0.014		0.016		0.018		0.020
Pasture, range and paddock		0.099		0.114		0.129		0.149
Indirect soil		0.009		0.011		0.012		0.014
Burning agricultural waste	0.001	0.000	0.001	0.000	0.001		0.001	0.000
Sub-Total	0.026		0.030		0.033		0.036	
Central Africa	0.017	0.009	0.020	0.010	0.022	0.011	0.023	0.013
Enteric fermentation	0.016		0.019		0.021		0.022	
Manure management	0.001	0.000	0.001	0.000	0.001	0.000	0.001	0.001
Direct soil		0.001		0.001		0.001		0.001
Pasture, range and paddock		0.007		0.008		0.009		0.010
Indirect soil		0.001		0.001		0.001		0.001
Burning agricultural waste		0.000		0.000		0.000		0.000
Sub-Total	0.150		0.174		0.203		0.248	
East Africa	0.103	0.047	0.118	0.056	0.138	0.065	0.169	0.079
Enteric fermentation	0.099		0.114		0.133		0.163	
Manure management	0.004	0.000	0.004	0.001	0.005	0.001	0.006	0.001
Direct soil		0.002		0.003		0.004		0.004
Pasture, range and paddock		0.042		0.048		0.056		0.069
Indirect soil		0.003		0.004		0.004		0.005
Burning agricultural waste		0.000		0.000		0.000		0.000
Sub-Total	0.104		0.117		0.122		0.127	
Southern Africa	0.064	0.040	0.073	0.044	0.075	0.047	0.078	0.049
Enteric fermentation	0.062		0.071		0.073		0.076	
Manure management	0.002	0.001	0.002	0.001	0.002	0.001	0.002	0.001
Direct soil		0.008		0.008		0.009		0.010
Pasture, range and paddock		0.028		0.032		0.033		0.034
Indirect soil		0.003		0.003		0.004		0.004
Burning agricultural waste		0.000		0.000		0.000		0.000
Sub-Total	0.080		0.096		0.111		0.130	
West Africa	0.052	0.028	0.062	0.034	0.072	0.039	0.084	0.046
Enteric fermentation	0.049		0.058		0.068		0.079	
Manure management	0.002	0.001	0.003	0.001	0.003	0.001	0.004	0.001
Direct soil		0.003		0.004		0.004		0.005
Pasture, range and paddock		0.022		0.026		0.031		0.036
Indirect soil		0.002		0.003		0.003		0.004
Burning agricultural waste	0.001	0.000	0.001	0.000	0.001	0.000	0.001	0.000

Source: Data to create this table was obtained from [55]

2.1 Enteric fermentation

Enteric fermentation is a digestive process by which microbes decompose and ferment plant materials such as celluloses, fibre, starches and sugars in their digestive tract or rumen. This anaerobic fermentation process produces hydrogen (H_2), carbon dioxide (CO_2) and methane (CH_4). In normal feeding conditions, methane (CH_4) produced by enteric fermentation process ranges between 15-30% of the total ruminal gas [65], [66]. Methane gas (CH_4) is the major source of ruminants' GHGs emissions with 90% resulting from enteric fermentation and 10% from manure [7]. Globally methane gas has a warming potential 25 times greater than CO_2 over a 100-year time horizon [67]–[69]. Enteric methane represents from one to two thirds ($1/3$ to $2/3$) of milk CF at farm level [70].

The production of enteric methane (CH_4) (i.e approximately 8% of ingested food) which is expelled by the animal through burping is directly related to amount, type and quality of feed, animal weight, production level and environment (e.g temperature, etc). Enteric methane emissions change significantly from one region to another globally and in developing countries emissions are very high due to lower productivity and output (e.g milk and meat) is growing fast to meet demand [71]. For example in 2010 according to [72] 75% of total emitted enteric methane globally (1.0–1.5 Gt CO_2 eq/yr) was from developing countries with an average annual emission increase of 2.4% in Africa. These emissions are projected to rise resulting from extension of smallholder dairy production in Sub-Saharan Africa for meeting high demand of milk (**Table 2**) and meat of rapid growing population. Most of this growth in livestock population is expected to occur in East and Western Africa worsening their CF [73]. **Fig. 11** shows that East Africa and West Africa are major contributors of Enteric fermentation emissions in SSA.

Recent studies showed that South Africa; one of SSA countries had enteric methane emission factors for dairy cattle of 76 kg CH_4 /head/year and 72 kg CH_4 /head/year for concentrate fed and pasture-based production systems, respectively; emissions rates which are higher than those reported by other developing countries, as well as the IPCC default value of 46 kg CH_4 /head/year for developing countries [74], [75]. On the other hand Kenya whose one of the most developed dairy sub-sector in SSA; contributes around 12 million tonnes CO_2 eq. 88% of these emissions come from cow's enteric fermentation and 11% from manure management. On average at national level the milk production sector emits 3.8 kg CO_2 eq./kg of fat and protein corrected milk (FPCM). On the other hand Tezera & VHL (2018) [57] in their study on CF of milk at smallholder dairy production in Ethiopia concluded that enteric fermentation contributed 80% of all GHG emissions in smallholder dairy farming. This sector is currently dominated by smallholder farming and contributes to the livelihoods of many through income generation, food and employment [76].

Furthermore the study conducted by Kouazounde et al.,(2015) [77] on enteric fermentation emission factors (EF) of cattle from Benin (a west African country) revealed the national EF of 39.5 kg CH_4 /head/year. This estimated EF value was 27% higher than the African cattle default EF recommended by IPCC. Generally ruminant livestock in SSA emits 16% of all GHG emissions [30].

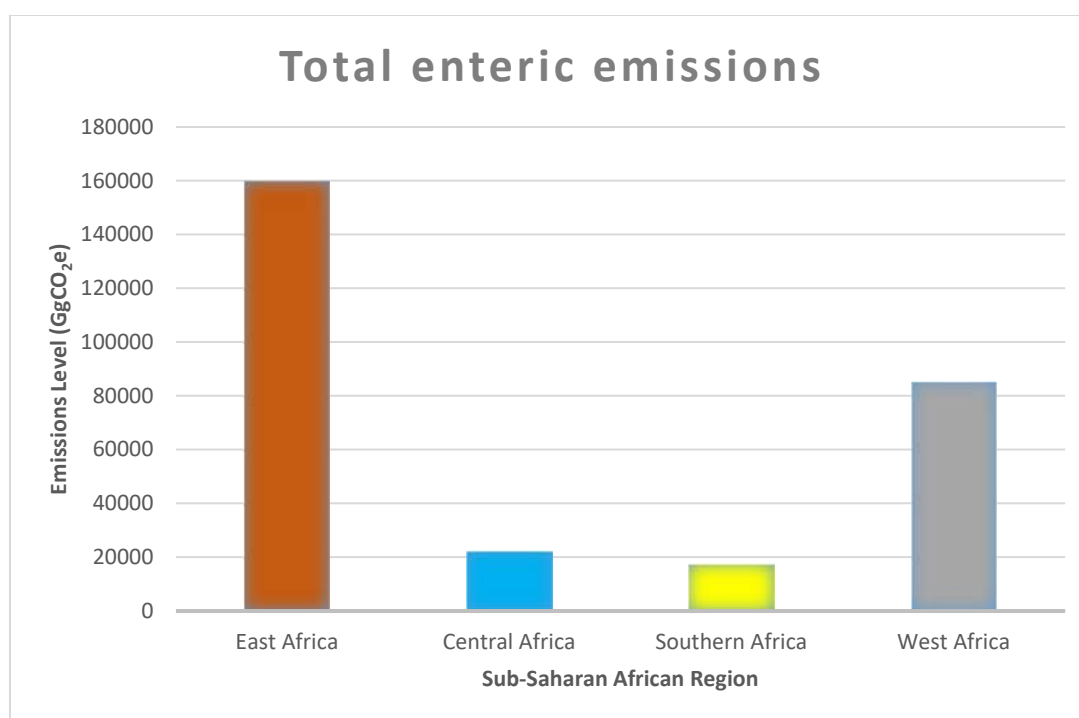


Fig. 11: 2016 Emissions from livestock's enteric methane

Source: [12]

2.2 Manure management practices

Livestock manure is an asset and source of nutrients for increasing crop production for many smallholder farmers of SSA. Most of them depend mainly on cattle manure for improving the soil fertility because they cannot afford synthesized fertilizers [78], [79]. Unfortunately the mismanagement of manure is leading to increased environmental contamination and GHG emissions in smallholder agriculture [78]. In fact, large emissions are from manure deposited on pasture compared to the one applied agricultural soil as organic fertilizer (**Fig.s 3&12**). For example, 80% of GHG emissions (mainly N₂O and small portion of CH₄) were from developing countries between 1961 and 2010. During this period Africa had a large average emission rate of 2.5%/year followed by Asia with 2.3%/year. Two-thirds of these emissions came from grazing cattle with small portion from small ruminants such as goats and sheep [72], [80].

Manure is the 3rd largest GHG contributor from agricultural emissions on the African continent with accounting 6.5% of total sectoral emissions [55]. Livestock manure includes dung and urine [81]. Globally manure is responsible for around 7% of agricultural emissions GHGs (e.g CH₄ and N₂O) emissions [82], [83]. It is the second source of farm GHG emissions after enteric fermentation process which emits methane (CH₄) [83]. NH₃ emitted from livestock manure can travels multiple distances, contaminates the environment [84] and could transform into Nitrous oxide (N₂O). Manure storage emissions depend mainly on animal species, storage type and storage temperature [85]. Livestock manure in solid state emits less methane gas compared to its liquid state. However, the dry anaerobic manure systems create favourable environment for Nitrous oxide production. This gas (N₂O) has a relative global warming potential 320 times that of CO₂ (or around 16 times more potent than CH₄) at a 100-year period. Manure systems in liquid state are suitable environment for microbes multiplication, which in turn enhances the production of methane gas (CH₄) [81]. The major components of dairy livestock manure are: Nitrogen (N), Phosphorous (P) and Potassium (K). These nutrients are important for plant growth but have negative impacts on the environment (e.g eutrophication and contamination of water resources) if applied in excessive quantity [84], [86]. Storing manure for long time without processing it can also lead to significant contribution of GHG emissions [83]. Livestock manure contains organic matter and nitrogen which influence methane and nitrous oxide emissions respectively [87].

The increase in methane gas emitted by manure mainly depends on the quantity of stored manure, temperature rises of manure, long time storage of manure, chemical composition and the amount of organic matter [88]. On the other hand, N₂O emissions from livestock manure mainly depend on nitrogen (N) and carbon (C) contained in the manure, manure storage time and treatment method in place. When the manure is stored its oxygen, content slows down; at the same time affecting nitrification and denitrification processes. N₂O can be formed as a by-product (as a second product), particularly if the oxygen concentration is low. Generally the insufficiency of oxygen reduces nitrification process in slurry manure (liquid) causing it to emit less N₂O in comparison with solid manure (dung) [89].

Smallholder dairy farming (cattle farming) dominates livestock sector in East Africa (e.g in Kenya it accounts 80% of all milk production) and it is characterized by variation in farming conditions and manure management (e.g collection and storage) with dominating cattle manure type. Most of smallholder farmers rely on manure nutrients for improving their agricultural soils hence increase the crop production [79], [90]. As shown on **Fig. 12** current and projected GHG emission levels from manure applied to soil and manure left on field have East Africa leading in emissions followed by West Africa [12]. The manure storage in smallholder farming is mainly characterized by solid manure storage (dung) without collection facility of urine. The most common livestock keeping fences in SSA are Kraal where animals deposit much of the manure and pile up before collection. Some farmers also collect dung and store it in heaps on uncover floor in most cases. Only few number of small farmers collect liquid manure in silos, pits or lagoons in connection of anaerobic biodigesters for producing biogas [78]. However most of liquid manure storing facilities in smallholder farms are not well managed and store the manure in liquid state for long of time without processing it; which contributes to significant GHG emissions (CH₄) [78], [83].

Open manure collection systems like kraal and heaps accelerate the Nitrogen (N) and nutrients loss contained in manure as a result of weather (e.g rainfall&tempeartures cause leaching and volatility of Nutrients) therefore reducing the effect of manure during its application in soil for raising fertility [91].

Livestock manure GHG emissions should be taken into account from animal excretion to the final destination (e.g incorporation of manure to soil, etc) [92]. These emissions are allocated through the following processes: Emissions related to manure storage, Emission from manure applied on land for feed and crops production and Emissions from manure discharged into the environment [19].

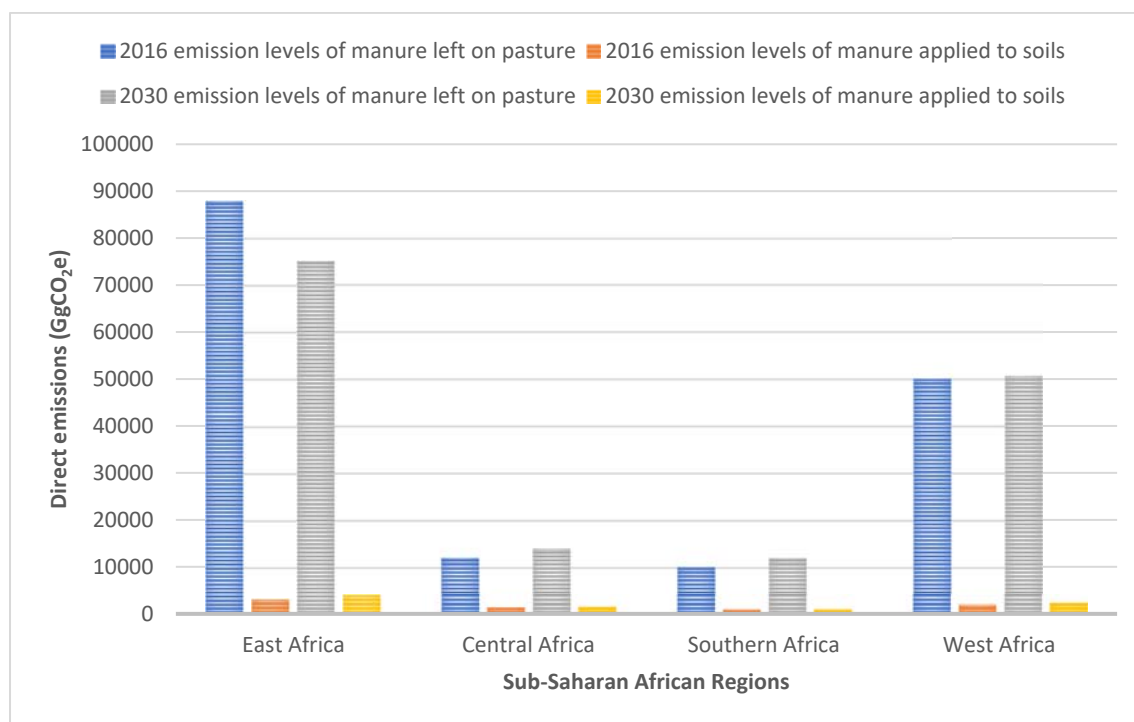


Fig. 12: Current and projected manure emission levels in SSA

Source: [12]

Table 8: Summary of advantages and disadvantages of major manure management options in SSA [78]

Manure treatment	Brief description	Advantages	Disadvantages
Fresh application (solid and liquid manure)	Direct application of either solid or liquid fresh manure to pastures or crops	• Fresh manure, like any other form of organic manure improves the structure of the soil which allows better aeration of the soil, improves drainage, and reduces erosion. • Manure nutrients become slowly available as plant food and can have effects on crops for several years. • Good crops can be obtained with reduced need for extra chemical inputs	• Minerals from manure may not be immediately available to plants; mainly for ruminant manure. • There can be a mismatch in time between nutrient release and plant uptake; • Risks associated with transmission of zoonotic diseases if crops are consumed; • Seeds of weed can be transferred to the field through fresh manure.
Drying	When manure is left in heaps on natural earth for a long periods till it dries up. Manure is also actively molded and dried for fuel in some countries like Ethiopia	• Drying makes manure less bulky and easier to transport. • Dried manure contains organic matter that provides similar advantages of using organic fertilizer as in fresh manure.	• During drying, nitrogen is lost from manure through volatilization of NH_3. • Also, if dried manure is not protected from rain, rewetting events can lead to GHG emissions. These N losses will also result in a poorer quality fertilizer. • Nitrogen and organic matter are lost when manure is used as fuel
		• Provides energy and fertilizer value is maintained or even enhanced. • It provides the same advantages of organic fertilizers to the soil as manure and in	

**Anaerobic Digestion
(with use of bio-slurry
as fertilizer)**

This is the conversion of manure by anaerobic bacteria into biogas and digestate. The digestate which is also called bio-slurry is a mixture of digested dung and water having a dry matter content of ~7%

addition:

- Reduce labor especially of women and girls who spend many hours searching for fuel wood.
- Reduce cost on purchase of synthetic fertilizers, which will be (partly) replaced by the bio slurry
- Lower risk of infection due to the hygienization during digestion affordable lighting in rural (for learning and doing house chores in the evenings)
- Reduce risk of respiratory diseases linked to the use of fuel wood, dung cakes, and charcoal.
- Reduced greenhouse gas emissions as the produced CH₄ is captured and used for cooking.
- Bio-slurry is odorless as compared to manure

- This requires a very high initial investment, often not affordable to smallholder farmers, except through subsidies.
- It requires continuous availability of water.
- Requires frequent feeding of manure
- Liquid digestate is more difficult to manage than dried manure due to high water content

2.3 Land use change for feed production

Land-use change has an impact on amount of GHG emissions due to changes in vegetation, soil physical/chemical properties, hydrology and soil nutrient management [93]. Soil organic matter can be progressively oxidized and resulting in emission of CO₂ and N₂O as a result of land use change [6].

In livestock production land use change occurs in expansion of grazing lands for forage production (feed crops) which increase the number of cut trees (deforestation); the second major global anthropogenic sources of carbon dioxide (CO₂) from agricultural sector [10], [19]. Carbon dioxide emissions from agriculture and livestock production are highly associated with energy use (for milking, grain drying, etc) , production and transport of inputs, transport of production, processing of dairy products and land use and land use change [23], [81].

Furthermore around 60% of the global biomass harvested enters the livestock subsystem as feed or bedding material. In dairy farming large sources of carbon dioxide (CO₂) emissions are plants, animal microbial respiration [92], aerobic digestion of manure organic matter by micro-organisms and combustion of materials rich in carbon (e.g fossil fuels and organic waste) [31]. In this sector milk and beef emit 35–45% of the overall feed production GHG emissions. Manure application to agricultural fields as fertilizer for feed crops also represent significant GHG emissions [87].

In SSA burning of crop residues and savannah are commonly practiced by smallholder farmers for the development of agricultural and pasture lands. This practice is for nutrient mobilization and pest control of agricultural fields but also it is responsible of emitting GHG such as CO₂, CH₄ and N₂O [12]. However CO₂ emissions are considered as neutral due to annual cycles of carbon fixation and oxidation through photosynthesis [94]. **Fig. 13** below indicates GHG emissions from burning of savannah in SSA where central and East Africa have the highest emissions:

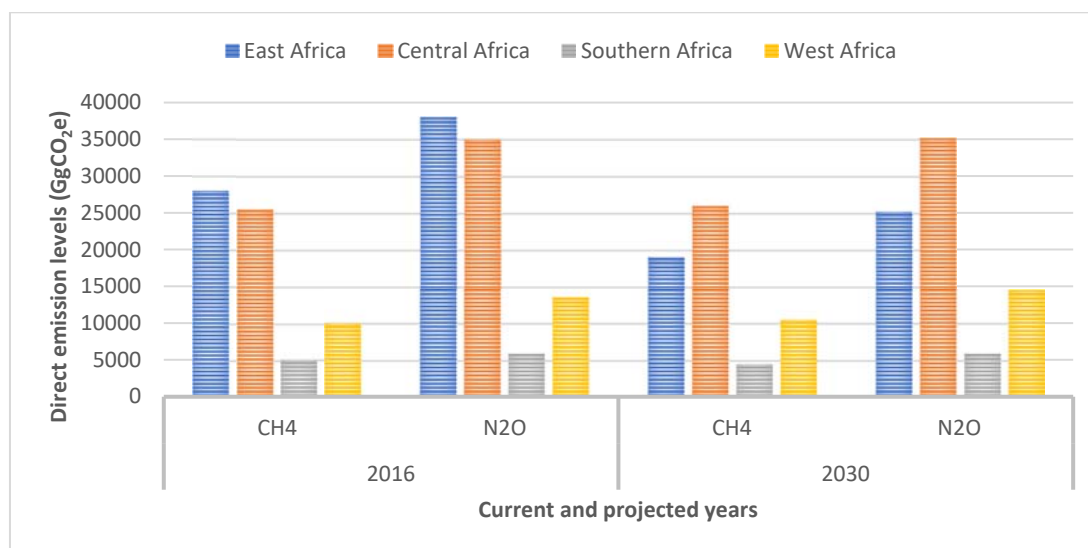


Fig. 13: 2016 and 2030 emission levels from SSA savannah burning [12]

III. SMALLHOLDER FARMERS' KNOWLEDGE ON DAIRY FARMING GHGs EMISSIONS IN SSA

Although different African governments including Rwanda have put an emphasis on setting up strategic development policies that facilitate the mitigation of agricultural GHG emissions among other polluting sectors, supporting smallholder dairy farmers to implement these mitigation measures will require interventions at several levels in feed supply chains [95]. Wu et al., (2018) [96] stipulates that farmers' perception of climate change is positively correlated with adaptive behaviour. Farmers need to know what climate change is and how their activities contribute to increase greenhouse gases emissions. The understanding of the farmers' perception of climate change and its influencing factors is a prerequisite for the formulation of climate change mitigation and adaptation policies [97].

Using Bayesian hierarchical techniques, Ng'ombe et al., (2020) [98] highlighted the drivers of awareness of climate change and its risks to agriculture among smallholder farmers in Zambia. The findings from this study concluded that 77% of smallholder farmers are aware of climate change and its impacts on agriculture. Radio, Televisions and access to extension services were the major paths of knowledge sharing. However, it is unclear whether the farmers who were involved in the study are aware specifically on how their respective farming activities contribute to Global warming and strategies in place for mitigation.

In Botswana, Mogomotsi et al., (2020) [99] used empirical data gathered from farming households to analyse the perceptions of smallholder farmers regarding climate change. The study revealed that there was a direct relationship between the farmers' adaptation strategies and education. The major constraints that most farmers were facing are: insufficient financial resources and lack of adequate skills to cope with climate change. Government subsidies and continuous trainings were proposed as remedials for sustainable farming activities.

Other similar studies were conducted in Ethiopia [100]–[103], Nigeria [104]–[106], South Africa [107], [108], etc. The common denominator of these studies is that many smallholder farmers are aware of climate change but its adaptability is hindered by lack of information, insufficient funds, among others.

Therefore, the farmers' capacity to implement climate change measures may be stifled due to lack of understanding of how exactly emissions are generated from livestock farming [109], [110]. Successful implementation of mitigation and adaptation measures is determined through farmers' awareness of the issue and their perceptions of risks that it may bring. While knowledge is seen as an important first step in the adoption process [111] on one hand, Niles et al., (2016) [112] found that education is a positive predictor for the likelihood of mitigation measures on the other hand.

Most of farmers recognize climate change through factors such as droughts, frost, floods, extreme temperatures and seasons' variations frequently occurring nowadays in most of SSA countries. However, the level of farmers' knowledge on the causes of their occurrences is still uncertain since only few researches on smallholder farmers' perceptions regarding climate change have been conducted [113]–[115]. Therefore, Farmers' capacity to implement mitigation and adaptation measures needs both personal cognitive motivation and societal support such as subsidies, trainings, etc [26], [116], [117]. Access to extensions services, fields visit and other forms of training and information sharing (radio, TV, etc) have demonstrated positive impacts for raising climate change awareness among farmers such as in Ethiopia [118], Zambia [98] and other regions of the world. Lack of appropriate information regarding interaction between farmers activities and climate change is not only in SSA's smallholder farming but also in other parts of the worlds as witnessed by some Germany's farmers [117], Brazil [119], etc.

The livelihood of many people in developing countries depends on smallholder farming systems [8]. Lack of knowledge and limited access to technology are major concerns raised by many researchers on the cause of increase in GHG emissions in smallholder farmers of SSA [78], [120]. Smallholder farmers in Sub-Sahara Africa depend upon inorganic farm inputs. As a consequence of increase in inorganic farm inputs consumption, vast quantities of gases and effluents are discharged that may change the climate composition of the atmosphere. Unfortunately, many livestock farmers in Africa are unaware of their contribution to climate change. For example the majority of smallholder dairy farmers (around 62%) in Ethiopia think that livestock do not contribute to global warming while 16% of them had no idea at all about animal GHG emissions [57]. This is a common issue which is found in many farmers of agricultural sector. Recent study conducted by Jantke et al., (2020) [117] and Ndambi et al., (2019) [78] revealed that farmers in livestock keeping and crop-cultivating farms were lacking sufficient information on GHG emissions in order to plan mitigation measures. Agricultural magazines were proposed as tool for disseminating knowledge on GHG emission and mitigation measures.

Smallholder farmers in Africa could take advantage of carbon markets and other climate change mitigation financing mechanisms to get training and support for managing agricultural land more sustainably, which would improve the yield and resilience of their agricultural systems. Carbon projects that reduce emissions of greenhouse gases such as carbon dioxide and methane can earn farmers 'carbon credits' for sale in the global carbon market [121]. Producing food for community consumption is the major duty for smallholder farmers but also, they should ensure that the environment is preserved by adopting waste recycling, reduce air, soil and water pollution. However limited access to financial assistance (credit, etc) may affect the successful implementation of good agricultural practices [122], [123]. Weakness is transferring feed technologies and too many top-down approaches are also highlighted as barriers to sustainable smallholder farming systems [124].

IV. STRATEGIES TO REDUCE GHGs EMISSIONS IN SMALLHOLDER DAIRY FARMING

Currently GHG emissions in smallholder farming of SSA are on a rise and are expected to grow rapidly due to agricultural expansion resulting from increased food demand of growing population (both livestock and crop production) and use of fossil fuel [27], [30]. As the demand of dairy products expected to be tripled by 2050 in SSA [27], significant GHG emissions which will impact the climate are unavoidable in case the livestock management practices are kept as they are today. For sustaining smallholder dairy farming and minimizing GHG emissions of livestock production for global warming control, strategies to reduce the CF of smallholder dairy products in SSA are necessary. In most of smallholder dairy farms of SSA, significant GHGs production is resulted from feed production, enteric methane (also known as enteric fermentation) and manure management. That is why proposed strategies to be adopted by smallholder farmers will mainly focus on the aforementioned three GHGs sources.

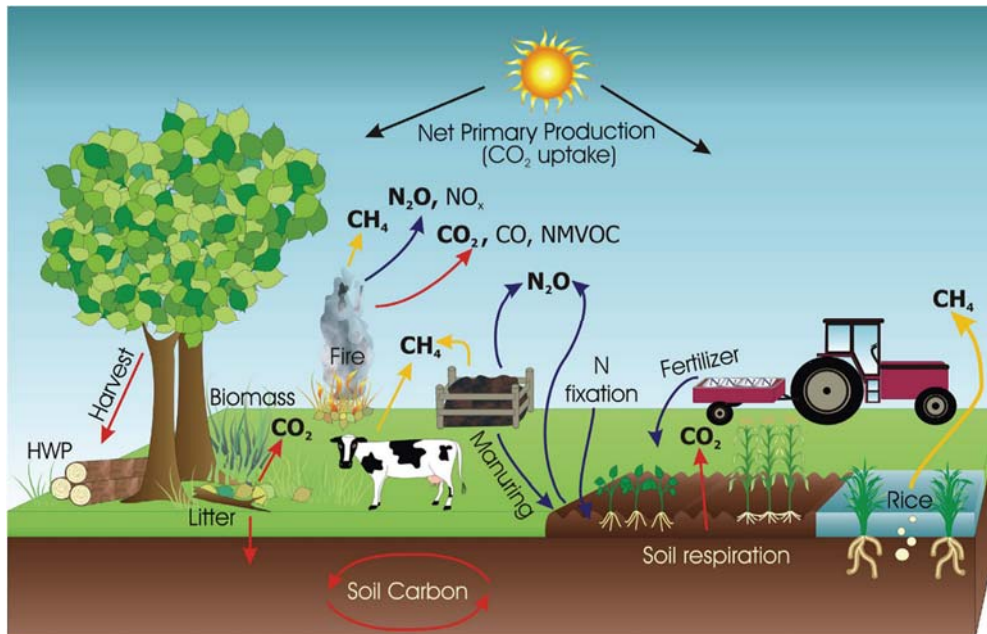


Fig. 14: The major GHGs emission sources, removals and processes in agriculture

Source: [125]

Literature shows that methane and nitrous oxide loss do not only accelerate the climate change but also exacerbates the livestock productivity [63]. Enteric fermentation and manure GHG emissions (dominated by CH_4 and N_2O) can be reduced significantly if there is change in livestock feeds types, selection of livestock that produces fewer emissions and biotechnological solutions such as vaccinations or the introduction of microorganisms to the animals that reduce enteric fermentation [30]. By providing animals with greener, more nutritious forage, enteric fermentation can be lowered relative to weight gain, reducing methane emissions [126]. Feeds of high quality pass the rumen faster, which reduces anaerobic fermentation and methanogenesis due to post ruminal digestion and, thus, results in lower production of CH_4 [127]. However, increased protein content in diets may cause higher N excretion leading to potential trade-offs between CH_4 and N_2O emissions.

The study conducted by Brandt et al., (2018) [128] focusing on the contribution of sectoral (dairy production) climate change mitigation options to Kenya national targets revealed that improving forage quality by increasing the use of Napier grass and supplementing dairy concentrates, reduced emission intensities by 26%–31%. Furthermore, the above authors concluded that covering manure heaps may reduce emissions from manure management by 68%. Emission of methane gas from livestock do not only harm the atmosphere but also is a form of feed energy loss which would have been used by the animal in milk and meat production.

On the other hand, milk production sector of Tanzania which is 97% dominated by traditional/small scale dairy farmers; produce 70% of the national milk. In this country 97% of the total GHG emissions come from traditional dairy systems with improved

systems contributing only 3% of all dairy emissions. Average emissions from traditional systems range between 20.3 to 28.8 kg CO₂ eq./kg FPCM while in improved systems they range from 1.9 to 2.2 kg CO₂ eq./kg FPCM [129].

On the other side most of GHG emissions from livestock manure are emitted in storage and in anaerobic treatment. Generally most of strategies to reduce GHG emissions in manure involve the use of anaerobic digesters (biogas production), covering manure storage facility (pit, etc), shortening storage duration, improving timing and application of manure, using a solids separator, and changing the animal diets [26]. Anaerobic digestion is a biochemical process which take place under anaerobic conditions (without oxygen) using bacterial action to convert organic waste (manure in this case) into combustible gas known as biogas [130]. Biogas is composed of CH₄ (60%) and CO₂ (35–40%) [131]. This gas is used as fuel for cooking (as it generates heat) and generating electricity for home use. It is helpful in reducing GHG emissions and reduction of deforestation in SSA [132]. However, the production of this gas has a higher initial investment; a challenge of many smallholder dairy farmers in SSA. This is why governments should put in place subsidies for encouraging such farmers to adopt biogas production. Summarized mitigation strategies are summarized in the **Table 9** below:

Table 9: Summary of selected strategies that smallholder dairy farmers can adopt to mitigate GHG emissions in SSA

Strategy	Practice	Procedure/Aim	Potential for CH ₄ and/or N ₂ O reduction	Technology availability/feasibility for smallholder dairying	References
Feed production		Avoid applying fertilizers (manure) during wet periods (seasons) or before major rainfall events for allowing nitrogen to reach the targeted crop efficiently	This practice optimizes biomass production and reduces GHG emissions from soil	Feasible and practical	[87]
		Improvement of forage digestibility (Grinding/milling and pelleting of forages)	20-40% reduction in CH ₄ per unit of diet	Feasible but may require high initial investment for pelleting equipment	[63], [68], [133]–[135]
Feeding (nutrition)	Forage selection and processing	Improving pasture quality by adopting forages with lower fibre and rich in soluble carbohydrates (increasing to more than 50% /adopting legumes or grain forage such as corn, wheat, etc). In other words, adoption of concentrate diets	8-25% reduction in CH ₄	Despite the challenge of land holding sizes this strategy is feasible and practical for farmers with pasture land.	[68], [133], [134]
		Cassava products such as roots (chopped), leaves and peels are used by several livestock farmers in developing countries such as Mozambique as an alternative source of carbohydrate and protein. This can be used as livestock feed where grains such as maize is limited	When cassava feed is mixed with biochar and nitrate, the reduction in enteric methane is by 22% and 29%, respectively	Feasible and practical	[136]–[138]

Feed additives/supplements	Dietary oils (lipid addition to feeds)	Studies have indicated that for every 1% of oil mixed with the diet (6% maximum), there will be a reduction in CH₄ between 3.6-25%. Introduce lipids/oils rich in medium chain fatty acids (such as sun flower oil) in feeds when fat contained in pasture is lower (i.e dry/summer periods)	Feasible and practical but may require subsidies from government for availing such oils	[139]–[141]
	Additives (such as ionophores, tannins, etc)	24-30% reduction in CH₄ when 33 ppm ionophore such as monensin is included in forage diets. One the other hand when used as forage diets or feed additives; plants which contain tannins can reduce enteric methane up to 20%. Feeds containing tannins also reduces N excretion, increases N retention, and shifts N excretion from urine to faeces.	Feasible and practical but may require external subsidies as motivation	[26], [133], [142]–[145]
	Regular removal of manure/slurry to an outside storage facility	This practice can reduce emissions from CH ₄ and N ₂ O by 55% and 41% respectively	Feasible and do not require high initial investment	[146]

Manure management	Manure collection, storage and use	Separation of solids from liquid manure (use of solids separator)	This practice has a potential of reducing GHG emissions up to 30%	Feasible but may require moderate initial investment for gravity or mechanical separation system (e.g filters, centrifuges, etc)	[6], [87]
		Anaerobic digestion (Biogas production)	This process mainly produces CH ₄ and CO ₂ which are collected for generating heat for cooking and/or power for lighting. Biogas production is reported to reduce up to 30% of GHGs emissions associated with inadequate manure storage	Feasible but may require high initial investment for installing digestors and accessories. This is why local governments are encouraged to subsidise this equipment to poor smallholder farmers	[23], [147]
Animal management	Improved fertility in dairy animals (Animal breeding/ Artificial insemination)	Genetic selection of efficient and productive breeds (cattle, goats, other milky livestock) with low emissions and high productivity. Dairy cattle such as Bos taurus and crossbreeding have shown improved performance and reduction in CH ₄ emissions specifically in tropical production systems	This practice can reduce emissions from CH ₄ and N ₂ O by 10-24% and 9-17% respectively	Feasible in the long term but currently not practical in most countries in Sub-Saharan Africa because of lack of genetic selection programmes	[26], [87], [134], [148], [149]
		Adopting nitrification inhibitors & vaccination	This practice can reduce nitrous oxide losses by up to 40%	Feasible and practical with the support of stakeholders	[150]

V. GAPS IN EXISTING LITERATURE AND NEW RESEARCH DIRECTIONS

Despite its significant contribution to SSA's milk market (i.e more than 70% of milk production), researches concerning the SDF sector need to be increased mainly focusing on how it can reduce its GHG emissions as one of main agricultural contributors on the continent in particular. The current knowledge is only limited to the effects of climate change/variability on smallholder dairy farmers and farmers' adaptation, Farmers' perceptions of climate change and adaptation. The smallholder farmers' knowledge on dairy farming GHGs emissions in SSA need further researches to better get a clear picture on the level of understanding among farmers and their willingness of reducing their emissions.

Research works on dissemination of best practices information in mitigating GHG emissions to farmers on regular and timely basis, field study (visiting role model farmers/ Establish partnership between farms) towards improved awareness in SDF need further investigations.

Another gap is the lack of updated data on the development situation of smallholder dairy farming systems. An extensive review revealed that more data are needed to better quantify GHG emissions from smallholder farmers in SSA's dairy sector. Most of countries in this region implement agricultural development policies and strategies in isolation without taking into account climate change mitigation objectives. The role of public private partnership is not clear concerning this matter.

Furthermore, the role of private stakeholders in bringing the cost-effective technologies supporting GHG mitigations (such as biogas digestors, grass cutting machine, devices for monitoring the levels of CH₄ emissions, etc) is not clear as well.

VI. CONCLUSION

The rapidly increase of smallholder dairy farming activities in SSA need priority and more attention as far as the world in general and Africa particularly seeks to mitigate agricultural GHG emissions hence addresses climate change issues. Between 1994-2014 a mean GHGs emissions annual increase ranging from 2.9% to 3.1% was observed from Africa's agricultural sector; with enteric fermentation alone contributing more than half of the total GHGs emissions. Compared to other parts of the world, Africa emits highest GHGs per unit of milk and meat production. SSA alone emits 9tCO₂e per ton of milk; the highest in the world while North America and Europe emit only 1.9tCO₂e and 1.6tCO₂e per ton of milk respectively. It is a result of inadequate livestock's feed and low productivity from Smallholder farming systems.

Several best practices have been developed over the years for mitigating GHG emissions in SSA. These strategies differ in cost, practicability, level of reducing emissions and acceptability level by farmers. Therefore, their adoption will depend on the desired animal performance and affordability to implement the strategy. Among them three of the most promising strategies in curbing the carbon footprint of SDF: livestock diet manipulation (additives such as lipids, cereals, grass grinding, etc), breeding (genetic selection) and anaerobic manure storage for biogas production. These practices are considered as the most effective approaches of directly reducing enteric methane and nitrous oxide emissions in ruminants. Despite their significant role in addressing GHG emissions and improving farm efficiency some strategies in place are costly to implement (such as digesters for biogas production); therefore, governments should avail incentives and subsidies for their adaption. The support from governments and various stakeholders is also highly needed in terms of capacity building (training) and extension services so that SDF addresses its increasing GHG emissions for sustainability. Furthermore, communication between dairy farmers and researchers should be enhanced so that findings are implemented timely and feedback provided adequately.

In addition to that, to better understand past, present and future trends in GHG emissions of smallholder dairy farming in SSA region, governments, research institutions and other stakeholders need to integrate their collaboration in publishing, reporting and making available updated data concerning the development situation of smallholder dairy farming in respective countries and design development policies of this sub sector for achieving food security without significant increase in GHG emissions.

This study also recommends the use of hand-held laser methane detectors (LMD) by group of smallholder farmers (for sharing its cost) for checking the level CH₄ emissions once the proposed mitigations strategies have been implemented. This technological practice can help farmers as well environmentalists to better evaluate their progress towards reduction of GHG emissions. More research work is required to better understand the smallholder dairy farmers' awareness towards GHG emissions and existing cost-effective mitigating strategies. By taking into account the highlighted mitigating strategies, smallholder dairy farmers in SSA can simultaneously contribute to a reduction in GHGs and improve the farm efficiency.

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