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Review Article

Nitrous Oxide Emissions from Smallholders' Cropping Systems in Sub-Saharan Africa

Shaankua E. Lemarpe,[1] **Collins M. Musafiri**,[1,2] **Joseph M. Macharia**,[3] **Milka N. Kiboi**,[2] **Onesmus K. Ng'etich**,[1] **Chris A. Shisanya**,[3] **Jeremiah Okeyo**,[1] **Elizabeth A. Okwuosa**,[4] and **Felix K. Ngetich**[2,5]

[1]*Department of Water and Agricultural Resource Management, University of Embu, P.O. Box 6-60100, Embu, Kenya*
[2]*Cortile Scientific Co. Ltd., P.O. BOX 34991-00100, Nairobi, Kenya*
[3]*Kenyatta University, Department of Geography, P.O. Box 43844-00100, Nairobi, Kenya*
[4]*Kenya Agricultural and Livestock Research Organization (KALRO), Muguga, P.O. BOX 30148–00100, Nairobi, Kenya*
[5]*Department of Plant, Animal and Food Sciences (PAFS),*
Jaramogi Oginga Odinga University of Science and Technology (JOOUST), P.O. Box 210–40601, Bondo, Kenya

Correspondence should be addressed to Felix K. Ngetich; felixngetich@gmail.com

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Increased concentration of atmospheric nitrous oxide (N_2O), a potent greenhouse gas (GHG), is of great concern due to its impact on ozone layer depletion leading to climate change. Ozone layer depletion allows penetration of ultraviolet radiations, which are hazardous to human health. Climate change culminates in reduced food productivity. Limited empirical studies have been conducted in Sub-Saharan Africa (SSA) to quantify and understand the dynamics of soil N_2O fluxes from smallholder cropping systems. The available literature on soil N_2O fluxes in SSA is limited; hence, there is a pressing need to consolidate it to ease mitigation targeting and policy formulation initiatives. We reviewed the state of N_2O emissions from selected cropping systems, drivers that significantly influence N_2O emissions, and probable soil N_2O emissions mitigation options from 30 studies in SSA cropping systems have been elucidated here. The review outcome indicates that coffee, tea, maize, and vegetables emit N_2O ranging from 1 to 1.9, 0.4 to 3.9, 0.1 to 4.26, and 48 to 113.4 kg N_2O-N ha^{-1} yr^{-1}, respectively. The yield-scaled and N_2O emissions factors ranged between 0.08 and 67 g N_2O-N kg^{-1} and 0.01 and 4.1%, respectively, across cropping systems. Soil characteristics, farm management practices, and climatic and environmental conditions were significant drivers influencing N_2O emissions across SSA cropping systems. We found that site-specific soil N_2O emissions mitigation measures are required due to high variations in N_2O drivers across SSA. We conclude that appropriate fertilizer and organic input management combined with improved soil management practices are potential approaches in N_2O emissions mitigation in SSA. We recommend that (i) while formulating soil N_2O emissions mitigation approaches, in SSA, policymakers should consider site-specific targeting approaches, and (ii) more empirical studies need to be conducted in diverse agroecological zones of SSA to qualify various mitigation options on N_2O emissions, yield-scaled N_2O emissions, and N_2O emission factors which are essential in improving national and regional GHG inventories.

1. Introduction

Nitrous oxide (N_2O), a potent greenhouse gas (GHG) with a global warming potential (GWP) of 265 compared to carbon dioxide (CO_2), has attracted much attention globally [1]. Its global concentration in the atmosphere has been rising (estimated at ~331.1 ppb) and contributes about 6% of the GHG-caused global warming effect [2]. Increased N_2O concentration has increased average atmospheric temperature causing global warming, associated with unreliable precipitation and droughts [3]. Prolonged droughts result in crop failures while unpredictable rainfall inconveniences cropping calendar, especially planting schedule for rainfed smallholder farming, prompting food insecurity [4]. Besides its adverse effects on climate variability, N_2O is also associated with stratospheric ozone layer depletion and acid rain formation [5, 6]. Assessment of agricultural contribution to soil N_2O fluxes is essential for climate change mitigation.

Agriculture is a significant source of anthropogenic nitrous oxide (N_2O) emissions, contributing about 60% of global N_2O emissions predominantly from N fertilizers, animal manure, and crop residues left in fields [7, 8]. In SSA, agriculture covers about 12.6% of total cultivated land, dominated by smallholder farmers who produce crops depending on resource availability [9]. Over 95% of agricultural land in SSA is rainfed, nonmechanized, and under small-scale farming with inherent low fertility due to continuous farming with limited use of external soil inputs Altieri and Koohafkan[10] which could have a direct effect on the amounts of soil N_2O emitted [11]. These agricultural soils in SSA contribute between 6% and 19% of total global anthropogenic N_2O emissions [12, 13]. However, literature on the contribution of different cropping systems on soil N_2O fluxes in SSA is limited.

Different cropping systems exist across various regions in SSA. The common crops grown in West Africa, Southern Africa, and Central Africa are cassava, yams, and cereals such as maize and sorghum [14]. With perennial cropping systems, maize is common in Eastern and part of Southern Africa [15]. Different dynamics across cropping systems contribute differently to N_2O emissions [14, 16]. For instance, cereal-legume intercropping contribute to N_2O emissions through the addition of more NH_4^+ and NO_3^- into soils from mineralization of organic matter [17, 18]. Additionally, farmers in SSA integrate livestock and crops leading to a trade-off between manure and crop residues, a dynamic that influences N cycling (including N_2O) in soils [19, 20]. However, most smallholder farmers in SSA rarely retain crop residues on fields as sources of nutrients but instead use them as animal feeds and as fuel for cooking [21].

Nitrogen undergoes a complex biogeochemical process (Figure 1). First, atmospheric nitrogen is biologically fixed by leguminous plants associated with rhizobia bacteria and nitrogenase enzymes [22]. Second, human-induced activities such as the production of fertilizer, sewage, farm produce, and manure application also account for N addition into the soil, which is later released as N_2O emissions (Figure 1). Further, high N accumulation in the soil is associated with environmental problems such as ammonia volatilization and leaching, also indirect losses of N from soils. Net N_2O emissions result from complex biogeochemical processes that take place in soils [23]. Nitrification occurs during aerobic conditions and oxidizes ammonium (NH_4^+) to nitrate (NO_3^-) and nitrite (NO_2) [24]. Additionally, denitrification occurs in oxygen-limited situations and reduces NO_3^- and NO_2^- to N_2O and nitrogen gas (N_2) [25]. These processes are aided by the availability of three significant microorganisms: ammonia-oxidizing bacteria (AOA), ammonia-oxidizing archaea (AOA), and nitrite-oxidizing bacteria (NOB) [26]. Nitrous oxide emissions can also occur through nitrate reduction to ammonium and codenitrification [27]. Other nonbiological processes involved in N_2O emissions are chemodenitrification and hydroxylamine decomposition, although they release negligible N_2O emissions [28]. These processes are influenced by soil moisture, temperature, C/N ratio, oxygen concentration, organic carbon, and soil nitrogen availability [11].

Developing countries are obligated to report their Nationally Determined Contributions (NDCs) and climate change mitigation options to the United Nations Framework Convention on Climate Change (UNFCCC) [29, 30]. Further, as captured in the Paris Climate Agreement of 2015, countries agreed to limit global temperature increase below 1.5°C by reducing GHG emissions [31]. To achieve this, most SSA countries consider agriculture a potential mitigation option to reduce GHG emissions [32]. However, there are uncertainties in national GHG inventories in SSA countries. A vast data gap arising from countries in the region has limited, or none whatsoever, empirical studies from existing cropping systems. It is imperative to note that only a few studies in SSA (approximately 30 published studies) have attempted to quantify N_2O emissions based on different cropping systems (Figure 2).

Consequently, most of the countries in SSA have continuously used Intergovernmental Panel on Climate Change (IPCC) Tier 1 emission factors (EFs), which tend to overestimate GHG emissions in the region [21, 32, 33]. Therefore, in this paper, we reviewed the state of N_2O emissions from selected cropping systems, drivers that significantly influence N_2O emissions, and probable soil N_2O emissions mitigation options in SSA cropping systems. We hypothesized that, in SSA, (i) there are significant variations in N_2O emissions across different cropping systems, (ii) environmental factors, climatic conditions, farm management practices, and soil properties directly influence N_2O dynamics, and (iii) combination of inorganic and organic fertilizer application serves as best mitigation options for N_2O emissions compared to sole application of either organic or inorganic fertilizer.

2. Methodology

Our literature review surveyed peer-reviewed papers on N_2O fluxes from Sub-Saharan Africa cropping systems published until December 2020. To include as many published studies as possible, we used search terms such as “nitrous oxide,” “Sub-Saharan Africa,” “cropping systems,” “greenhouse gas emission,” “nitrous oxide yield-scaled emissions,” “nitrous oxide emission factors,” and “mitigation measures” in Web of Science and Google Scholar. Thirty (30) peer-reviewed papers were selected according to the following exclusion-inclusion criteria:

(1) The study measured nitrous oxide fluxes in situ in Sub-Saharan Africa.

(2) The static chamber method was used in nitrous oxide measurements.

(3) Nitrous oxide measurements were conducted from a specified period.

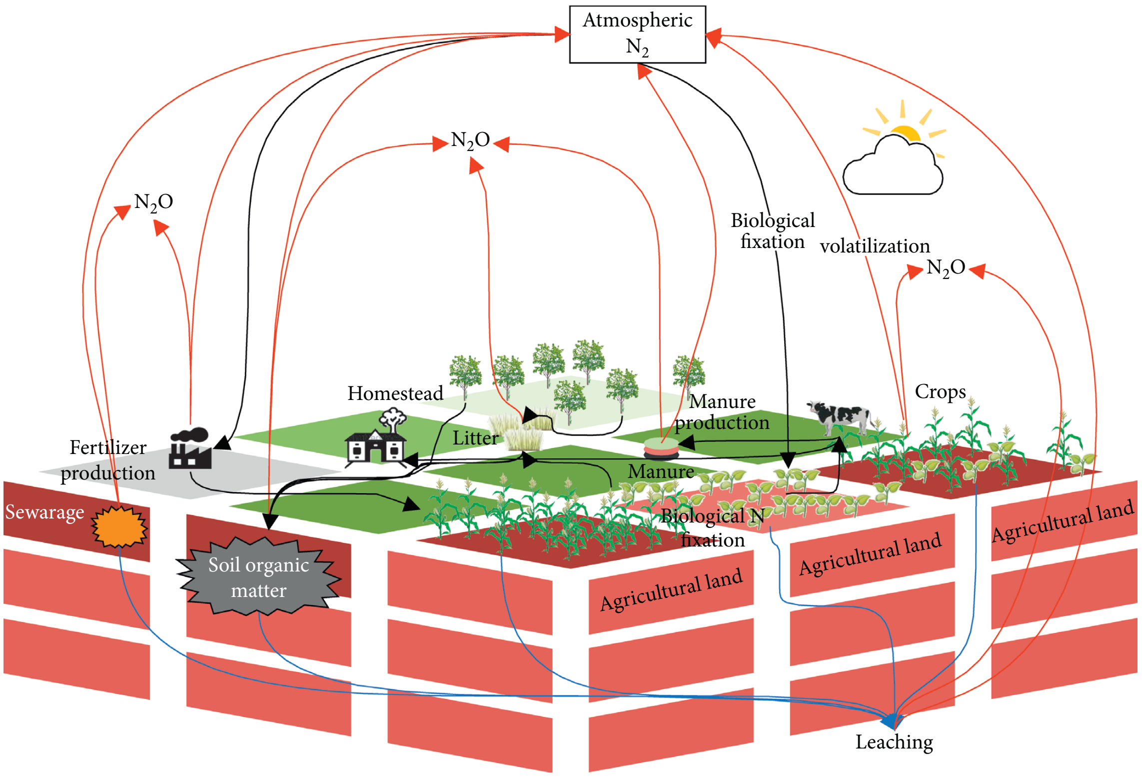

Figure 1: Nitrogen transformation processes in soil. The arrows in red show N_2O emissions, ones in black are N_2O sources, and blue ones are N losses.

(4) The study reported nitrous oxide fluxes and either yield, N_2O emission factors, yield-scaled emission, or mitigation potential.

(5) Soil properties, cropping system, soil fertility management, experimental durations were clearly described.

A qualitative analysis was implemented to assess nitrous oxide fluxes, N2O emission factors, yield-scaled N_2O emission factors, and mitigation potential. This included reporting the data observed from different cropping systems in Sub-Saharan Africa.

3. Soil N_2O Emissions from Cropping Systems in Sub-Saharan Africa

3.1. Maize Cropping System. Most of the soil N_2O quantification experiments carried out in SSA are under maize cropping systems (Table 1). This is because maize is considered an important food and source of cash for most rural families in the region [60]. Millar et al. [50] reported N_2O (N_2O-N) emissions ranging between 0.1 and 4.1 kg ha^{-1} from maize cropping systems in Kenya under improved-fallow agroforestry systems (Table 1). While investigating the effects of organic and mineral fertilizers in Zimbabwe, Mapanda et al. [52] reported N_2O emissions ranging between 0.1 and 0.5 kg ha^{-1}. Moreover, while evaluating the effects of clearing savannah woodland for maize cropping in Zimbabwe, Mapanda et al. [38] reported 0.8 to 2.5 kg N_2O-N ha^{-1} (Table 1). Hickman et al. [41] studied the relationship between N inputs and N_2O emissions from maize cropping systems in Kenya and reported N_2O-N fluxes ranging between 0.1 and 0.3 kg ha^{-1} yr^{-1} (Table 1). Further, with no fertilizer or manure application, Rosenstock et al. [42] reported N_2O emissions from maize cropping systems as 0.9 kg ha^{-1} yr^{-1} in Kolero, Tanzania (Table 1).

Pelster et al. [1] reported that maize cropping systems with low fertilizer inputs (<25 kg N ha^{-1}) were responsible for N_2O fluxes ranging between −0.1 and 1.8 kg ha^{-1} yr^{-1} in Kenya, attributing observed N_2O fluxes to dry soil which limits anaerobic condition for denitrification (Table 1). While investigating N_2O emissions from different inorganic fertilizer rates and their combination with an organic fertilizer in Zimbabwe under maize cropping systems, Nyamadzawo et al. [53] reported N_2O emissions ranging from 0.3 to 0.5 kg ha^{-1} yr^{-1}. Additionally, while studying the contribution of different soil fertility technologies towards the national GHG budget in the central highlands of Kenya, Macharia et al. [28] reported 0.13 to 1.22 kg N_2O-N ha^{-1} yr^{-1} across treatments. Similarly, Musafiri et al. [48] also reported N_2O emissions ranging from 0.21 to 0.38 kg N_2O-N ha^{-1} yr^{-1} under the maize cropping system. Hence, we note that maize cropping systems emit less N_2O emissions than the global average, probably due to soil degradation and soil N mining alongside inadequate nutrient replenishment from external inputs [61].

Figure 2: Map showing the location of reviewed N_2O related studies in Sub-Saharan countries. Basemap sources: National Geographic, Esri, Garmin, HERE, UNEP, WCMC, USGS, NASA, ESA, MERI, NRCAN, GEBCO, NOAA, and increment P Corp.

3.2. Cereal-Legume Intercropping/Rotation System. Legume-cereal intercropping is a farming practice that acts as an N source through atmospheric N fixation [62]. However, the addition of N in the soils can come at the cost of increased N_2O emissions if supply exceeds plant demand [41]. For example, Millar et al. [50] recorded 4.1 $kg\,ha^{-1}$ N_2O emissions from a maize-bean intercropping system in Kenya following the incorporation of *Sesbania* and *Macroptilium.* These fluxes were the highest recorded in SSA, which could be attributed to residue application with 60% more N content above the normal threshold (1.7% to 1.8%) [63]. From a short-term experiment in Western Kenya, Baggs et al. [9], working on effects of tillage and residue quality on GHG emissions under an improved-fallow agroforestry system, showed that maize (*Zea mays*) intercropped with beans (*Phaseolus vulgaris*) emits 0.2 to 0.6 $kg\,N_2O\ ha^{-1}$. Rotation of millet and beans in Mali accounted for N_2O emissions that ranged from 0.9 to 1.5 $kg\,ha^{-1}\,yr^{-1}$ [64]. Ortiz-Gonzalo et al. [43] showed that maize (*Zea mays*) intercropped with beans (*Phaseolus vulgaris*) in central highlands of Kenya emitted N_2O in the range of 0.18 to 0.27 $kg\,ha^{-1}$. Inorganically fertilized maize crops intercropped with lablab *(L. purpureus)* and Crotalaria *(C. juncea)* in Ethiopia emitted between 0.17 and 0.33 $kg\,N_2O$-N $ha^{-1}\,yr^{-1}$ [47]. Intercropping or rotating cereals with legumes provides synergies in managing soil nutrients in the field and may result in relatively lower N_2O emissions.

3.3. Coffee Cropping System. Coffee is among the critical annual cash crops grown in SSA. In Kenya, Ortiz-Gonzalo et al. [43] reported N_2O emissions that ranged between 1 and 1.9 $kg\,N_2O$-N $ha^{-1}\,yr^{-1}$ from coffee cropping system following fertilizer application of 85 $kg\,N\,ha^{-1}$ (Table 1). In Tanzania, Gütlein et al. [65] established that coffee cropping systems accounted for 0.35 $kg\,N_2O$-N $ha^{-1}\,yr^{-1}$. Soil N_2O emissions from coffee cropping systems in SSA are at a lower range, probably due to a decline in soil fertility in SSA's soil and little nutrient supply from both organics and inorganics [65].

TABLE 1: In situ empirical studies on N_2O emissions from different cropping systems in Sub-Saharan Africa.

Cropping systems	Country	Sampling frequency	Sampling duration	Soil type	N_2O fluxes	N_2O EFs (%)	N_2O YSE (g N_2O kg^{-1} grain)	References
Annual emissions								
Sorghum, peanut, and groundnut	Burkina Faso	1–3 per week	Jun–Sep 2006	Sandy	0.19–0.67 kg ha^{-1} yr^{-1}	*	*	Brummer et al. [34]
Millet-legume intercrop	Mali	Monthly	Jan 2004–Feb 2005	Alfisol	0.9–1.5 kg ha^{-1} yr^{-1}	4.1	*	Dick et al. [35]
Vegetable	Niger	Twice a day for 6 days	Apr 2006–Feb 2007	Sandy	48–92 kg ha^{-1} yr^{-1}	*	*	Predotova et al. [36]
Vegetable	Zimbabwe	Twice a day	Mar 2008–Mar 2009	Clay	80.5–113.4 kg ha^{-1} yr^{-1}	3–4		Lompo et al. [37]
Maize	Zimbabwe	During raining season	Jun 2006–May 2009	Clay/loam	0.8–2.5 kg ha^{-1} yr^{-1}			Mapanda et al. [38]
Fruit	Zimbabwe	2 days–2 weeks	2011–2013	Sandy loam	2.5–112 kg ha^{-1}	*	2.1–14	Nyamadzawo et al. [39]
Maize	Kenya	Daily to weekly	99 days	Clay	0.16–0.81 kg ha^{-1} yr^{-1}	*	*	Hickman et al. [40]
Maize	Kenya	Daily to weekly	March 2011–July 2011	Sandy-clay	0.1–0.3 kg ha^{-1} yr^{-1}	0.11	0.27–0.8	Hickman et al. [41]
Tea, vegetable, and maize	Kenya	Weekly	Jan–Dec 2013	Sand-clay	0.4–3.9 kg ha^{-1} yr^{-1}	0.4–0.8	*	Rosenstock et al. [42]
Maize, beans, and sorghum	Kenya	Weekly	Aug 2013–Aug 2014	Nitisols	-0.1–1.8 kg ha^{-1} yr^{-1}	*	1.1–67	Pelster et al. [1]
Maize, bean, and coffee	Kenya	1-2 times a week	Feb 2015 –Feb 2016	Nitisols	1–1.9 kg ha^{-1} yr^{-1}	<1	0.08–0.15	Ortiz-Gonzalo et al. [43]
Tea	Kenya	1-2 times per week	Aug 2015–July 2016	Humic nitisols	0.6–2.34 kg ha^{-1} yr^{-1}	*	*	Wanyama et al. [44]
Maize	Ghana	Daily during fertilization, then weekly	Aug 2013–Aug 2014	Ferric luvisol	1.22–4.29 kg ha^{-1} yr^{-1}	0.1–0.55	0.39–1.24	Atakora et al. [45]
Maize	Tanzania	Weekly to monthly	Dec 2015–Nov 2017	Alfisol/ andisol	0.26–2.24 kg ha^{-1} yr^{-1}	0.1–1.3	0.18	Zheng et al. [46]
Maize-legumes (lablab/ Crotalaria	Ethiopia	Weekly	107–123 days	Clay-loam	0.17–0.33 kg ha^{-1} yr^{-1}	0.2–0.25		Raji and Dörsch [47]
Maize	Kenya	Weekly	Feb 2017–Feb 2018	Sandy loam	0.13–1.22 kg ha^{-1} yr^{-1}	0.2–0.9	0.5–2.2	Macharia et al. [28]
Maize	Kenya	Weekly	March 2018–March 2019	Humic nitisols	0.21–0.38 kg ha^{-1} yr^{-1}	0.05–1.4	0.024–0.028	Musafiri et. [48]
Seasonal fluxes								
Maize	Zimbabwe	Weekly	Dec 2000–Feb 2001	Sandy loam	0.1–0.3 kg ha^{-1}	0.2	*	Chikowo et al. [49]
Maize	Kenya	1-2 times per week	84 days	Sandy-clay	0.1–4.1 kg ha^{-1}	*	*	Millar et al. [50]
Maize	Kenya	Weekly	Feb–June 2002	Silt-clay-loam	0.2–0.6 kg ha^{-1}	*	*	Baggs et al. [18]

Table 1: Continued.

Cropping systems	Country	Sampling frequency	Sampling duration	Soil type	N_2O fluxes	N_2O EFs (%)	N_2O YSE (g N_2O kg^{-1} grain)	References
Soybeans and maize	Madagascar	Weekly	Nov 2006–Apr 2007	Ferralsol	0.3 kg ha^{-1}	0.46–0.47	*	Chapuis-Lardy et al. [51]
Maize	Zimbabwe	Once every two months	Jan 2006–May 2009	Clay and sandy loam	0.1–0.5 kg ha^{-1}	*	0.02–3.93	Mapanda et al. [52]
Maize	Zimbabwe		2008/2009 growing season	Sandy loam	0.26–0.52 kg ha^{-1}	*	0.22–0.68	Nyamadzawo et al. [53]
Vegetable	Kenya	1–3 days per week	Sept 2015–July 2016	Humic nitisols	0.4–3.0 kg ha^{-1}	0.0–2.6	*	Kurgat et al. [54]
Coffee, maize-beans	Kenya	1–3 days per week	Feb 2015–Feb 2016	Nitisols	0.18–1.9 kg ha^{-1}			Ortiz-Gonzalo et al. [43]
Maize-beans	Nigeria	1–3 days to 2 weeks	21 days	Short duration Ferric lixisol	0.1–0.3 kg N ha^{-1}/day	1		Roing et al. [55]
Maize	Kenya	3 times per month	4 weeks	Humic nitisols	1.3–12 μg m^{-2} h^{-1}	*	*	Kimetu et al. [56]
Vegetables	Zimbabwe	Biweekly	Sept 2007–Nov 2008	Loamy sandy	2.5–18.8 g N_2O–N h^{-1}	0.3–1.0	*	Masaka et al. [57]
Banana-coffee	Uganda	4-5 times per month	May 2018–June 2018	Sandy-clay loam	3.7–6.7 μg m^{-2} h^{-1}		*	Fatumah et al. [58]
Amaranth	Benin/ Nigeria	Daily during planting and then after 2 weeks	21 days	Haplic lixisols/ plethnic plinthosols	24.8–279.5 mgN/kg soil			Olaleye et al. [59]

N/B. All measurements were carried out using static chambers. *no value reported.

3.4. Tea Cropping System. Tea cropping systems are precious and primarily found in agroecological zones that receive high rainfall amounts. Rosenstock et al. [42] showed that tea cropping systems in western Kenya emitted N_2O fluxes that ranged between 0.4 and 0.7 kg N_2O–N ha^{-1}. Tea cropping systems in Kenya emitted between 1.2 and 1.4 kg N_2O-N ha^{-1} yr^{-1} [44]. Emissions of N_2O for tea cropping systems were also at a lower range attributed to low inherent soil fertility status with little or no replenishment with soil amendments.

3.5. Vegetable Cropping System. Due to high amounts of organic or inorganic fertilization, vegetable cropping systems produce the highest N_2O emissions across different cropping systems in SSA. For instance, vegetable cropping systems in Niger had N_2O emissions ranging between 48 and 92 kg ha^{-1} yr^{-1} [36]. Peri-urban vegetable gardens in Burkina Faso emitted N_2O emissions that ranged from 80.5 to 113.4 kg ha^{-1} yr^{-1} [37]. Cumulative annual vegetable N_2O fluxes in Kaptumo, Kenya, were found to be 0.9 kg N_2O-N ha^{-1} yr^{-1} [42]. Similarly, in Kenya, indigenous vegetables produced 0.4 to 3.0 kg N_2O-N ha^{-1} [54]. While comparing GHG emissions in two ecoregions of SSA, Benin (rain forest) and Nigeria (dry savannah), in a short experiment performed under controlled conditions under local amaranth (*Amaranthus cruentus*), Olaleye et al. [59] reported N_2O emissions ranging from 0.01 to 0.02 and 0.06 to 0.3 kg N kg^{-1} of soil day^{-1}, respectively. There was a high variation of N_2O emissions (0.01 to 113 kg N ha^{-1} yr^{-1}) for vegetable cropping systems. The variation was attributed to high N input (25 to 750 kg N ha^{-1}) in vegetable gardens.

3.6. N_2O Emissions from Organic and Inorganic Fertilizer Use. Organic resources in SSA improve soil fertility and overall soil health and increase crop yields [66]. However, the addition of organic resources may contribute to increased soil N_2O emissions [66]. Some of the organic inputs used in SSA include animal manure, *Tithonia diversifolia*, numerous leguminous plants, crop residues, and some herb trees such as *Lantana Camara* [25, 67, 68]. A couple of studies have quantified organic resources' effects on N_2O emissions in SSA across cropping systems. The addition of *Tithonia diversifolia* increased N_2O emissions, especially during the first weeks of application, as shown by Kimetu et al. [56], implying that organic matter decomposes rapidly in soil. Green manure quickly releases nutrients to the soil immediately after addition since they contain easily decomposable organic matter for microorganism consumption as substrates [69]. The use of cattle manure as a treatment in tomatoes production planted in a wetland in Zimbabwe led to 0.01 to 0.06 kg N_2O-N ha^{-1} emissions [70]. Higher N_2O fluxes of 43 μg N_2O-N $m^{-2}h^{-1}$ were observed in Central Highlands of Kenya under manure treatment compared with 3 μg N_2O-Nm^{-2} h^{-1} under no external inputs [43]. While investigating GHGs emissions from maize cropping systems under different soil fertility management, Macharia et al. [28] showed that plots treated with animal manure had 1.22 kg N_2O-N $ha^{-1}yr^{-1}$, ninefold higher than the control treatment.

Nitrogen-based inorganic fertilizer application significantly affects the amount of soil N_2O emissions. Hickman et al. [40] showed that plots treated with 200 kg N ha^{-1} registered 24% more N_2O emissions than plots that received no fertilizer. In a maize-based study by Nyamadzawo et al. [53] in Zimbabwe, the use of inorganic fertilizers emitted 0.35 to 0.52 kg N_2O-N ha^{-1} compared to control that emitted 0.32 kg N_2O-N ha^{-1}. Ortiz-Gonzalo et al. [43] reported 65% of total N_2O emissions in fertilized plots than unfertilized plots under cereal-legume and coffee cropping systems in Kenya. For instance, a higher fertilizer rate of more than 100 kg N $ha^{-1}yr^{-1}$ emitted 3.49 to 4.29 kg N_2O-N ha^{-1}. In comparison, fertilizer rates below 100 kg N $ha^{-1}yr^{-1}$ recorded 1.22 and 1.79 kg N_2O-N ha^{-1} in Ghana under maize cropping systems [45], while in Iringa and Mbeya sites in Tanzania, inorganic fertilizer plots planted with maize crops emitted between 0.14 to 0.44 kg and 0.18 to 0.72 kg N_2O-N ha^{-1}, respectively [46]. Further, from Macharia et al. [28], inorganic fertilized plots under maize cropping systems emitted 10% more N_2O emissions than control plots in the Central Highlands of Kenya. In comparison, Musafiri et al. [48] in the same region reported 98% more N_2O emissions from inorganic fertilizer treatment than the control treatment. The above studies show that an increase in N application results in higher N_2O emissions regardless of fertilizer type and cropping system.

Nevertheless, contrasting results on N_2O emissions in SSA on the use of organic and inorganic inputs have been reported. Dick et al. [35] reported less N_2O emissions in plots treated with both organic and inorganic fertilizer (0.9 kg N_2O-N ha^{-1}) than plots treated with sole manure (1.5 kg N_2O-N ha^{-1}) in semiarid areas of Mali. Similarly, increasing N input through the combination of inorganic fertilizer (60 kg N_2O-N ha^{-1}) and manure (97.5 kg N ha^{-1}) increases N_2O emissions by 22 times more than control plots under rape fruits in Zimbabwe [39]. Positive N balance was reported in the combination of organic and inorganic fertilizer during maize growth in western Kenya compared with sole inorganic fertilizer application [71]. However, Nyamadzawo et al. [53] found that sole manure application reduces N_2O emissions by 16% compared to sole inorganic and integrated application, which increases N_2O emissions by 28 and 9%, respectively in reference to control in Zimbabwe. The combination of inorganic and organic fertilizer as reported by [43] in two farms were 3- and 5-fold higher than unfertilized maize and coffee cropping systems, respectively, in Thara farm while in Kahau farm, fertilized plot registered 2- and 6-fold higher N_2O emissions than unfertilized plots for coffee and maize plots, respectively. The combination of inorganic fertilizer and maize stover treatments (150 kg N ha^{-1} each) had significantly higher N_2O emissions (0.55 to 2.2 kg N ha^{-1}) compared to sole fertilizer application at the same rate (0.34 to 0.72 kg N ha^{-1}) in Tanzania [46]. A combination of organic and inorganic manure increased N_2O emissions five-fold compared to control under maize cropping systems in Central Highland Kenya [21]. Additionally, Musafiri et al. [48] reported 1.5 times more N_2O in inorganic plots than in control. The above studies found that a combination of organic and inorganic fertilizer provides mixed results concerning N_2O emissions. It is worth noting that a combination of organic and inorganic fertilizers can only lower N_2O emissions when organic manure with a low C/N ratio and inorganic fertilizer with high N levels are combined.

4. Yield-Scaled N_2O Emissions (YSE) and Nitrous Oxide Emissions Factors (EFs)

4.1. Yield-Scaled N_2O Emissions (YSE). Farm management activities for cropping systems should improve soil fertility, agronomic productivity, and environmental sustainability. Yield-scaled emissions (YSE) relate to N_2O emissions and crop yields expressed as emissions per unit yield that can be used to assess management impact [72]. The amount of N_2O emitted determines the amount of YSE. Therefore, the YSE parameter provides an entry point to evaluate the ability of management to mitigate N_2O emissions without compromising productivity [72]. Limited studies have attempted to determine YSE on different cropping systems based on inorganic and organic fertilizer applications in SSA. The YSE reported in a few studies ranges between 0.02 and 67.7 g N_2O-N kg^{-1}. For instance, Mapanda et al. [52] reported YSE emissions ranging from 0.02 to 3.93 g N2O-N kg–1 in Zimbabwe under maize cropping systems. Nyamadzawo et al. [53] reported YSE of 0.26 g N_2O–N kg^{-1} yield from integrated fertilizer management for maize cropping systems in Zimbabwe. Pelster et al. [1] reported YSE between 1.1 and 67 g N_2O-N kg^{-1} aboveground uptake in maize cropping systems in Eastern Africa. Findings from a maize cropping system in Ghana by Atakora et al. [45] showed that N fertilization above 100 kg N $ha^{-1}yr^{-1}$ led to 1.24 g N_2O kg^{-1} grain, while N fertilization below 100 kg ha^{-1} yr^{-1} resulted in less than 0.6 g N_2O kg^{-1} grain. In the central highlands of Kenya, Macharia et al. [28] reported YSE ranging from 0.5 to 2.2 g N_2O-N kg–^{1} grain yield under manure and a combination of manure and inorganic fertilizer, respectively. Similarly, Musafiri et al. [48] reported YSE ranging from 0.024 to 0.028 g N_2O–N kg^{-1} grain yield from sole manure and inorganic fertilizer, respectively, in Central Highland of Kenya. Yield-scaled emissions reported in most SSA farming systems may be associated with existing climate variability and soil fertility decline, which could have lowered crop yield, which determines YSE other than higher N_2O emissions.

4.2. Nitrous Oxide Emissions Factors (EFs). Limited studies in SSA notwithstanding, most of the derived EFs were below 1% and ranged between 0.1 and 0.9% across cropping systems in SSA [9, 28, 41, 46, 48, 49, 57]. However, there were a few instances where EFs exceeded 1% from maize, vegetable cropping systems, and soil laboratory incubation studies [35, 37]. In Mali, for instance, Dick et al. [35] reported the highest EFs for maize cropping of 4.1%, attributed to field management interferences where higher fluxes of N_2O were noted even before applying fertilizer. For maize cropping systems in Kenya, N_2O EFs ranged from 0.01 to 0.9% (e.g., Baggs et al. [18], Hickman et al. [41], Macharia et al., [28] and Musafiri et al. [48]) while in Zimbabwe, it was below 0.2% [49]. Similarly, in Tanzania, EFs ranged between 0.13 and 0.42% [46]. Rosenstock et al. [42] showed that tea cropping EFs were below 1% in Kenya. The N_2O emission factors from vegetable cropping systems in Zimbabwe ranged from 0.3 to 4% and were attributed to high fertilizer application [37, 70]. The EFs mentioned above are largely below IPCC tier 1 defaults, suggesting that default EFs on SSA's GHG emissions estimations may overestimate it, resulting in incorrect targeting of adaptation and mitigation measures. These findings may also show that "umbrella" recommendation of adaptation and mitigation measures may not accurately be applicable in a different place with different climatic, environmental, and farm management practices.

5. Drivers of Soil N_2O Emissions in SSA

Studies across SSA have documented varied soil N_2O emissions under different environmental, climatic, and soil conditions and farm management practices [1, 9, 28, 45, 53, 73]. Environmental factors (land use land cover changes), soil properties (bulk density, temperature, moisture, pH, type, organic carbon, and nitrogen), and climatic factors (temperature and precipitation) may significantly influence soil N_2O fluxes. Similarly, farm management practices, including fertilizer application (rates, time, type, and method), tillage, crop type, and residue management, may also influence N_2O emissions. It is noteworthy that these factors do not occur singly, but their interactive effects determine whether the soil is a net sink or source of N_2O emissions [42].

5.1. Effects of Soil Temperature and Elevation on N_2O Emissions in SSA. Soil temperature significantly influences soil N_2O fluxes by increasing microbial activities responsible for N_2O emissions in soil [27]. Nitrous oxide emissions increase with an increase in soil temperature due to advanced decomposition rates of organic matter [58]. An increase in N_2O emissions with rising temperature can be associated with increased nitrogen mineralization, hence higher availability of nitrogen lost as N_2O fluxes [27]. However, denitrifying bacteria are susceptible to soil temperature and operate best at an optimum temperature of 30°C, beyond which activities go down, thus lowering N_2O emissions [74]. Various studies in SSA, such as Mapanda et al. [52] in Zimbabwe, Lompo et al. [37] in Burkina Faso, Rosenstock et al. [42] in Kenya, and Atakora et al. [45] in Ghana, have reported a significant positive correlation between soil temperature and nitrous oxide emissions.

Atmospheric temperature also influences N_2O emissions. For instance, Fatumah et al. [58] reported higher N_2O emissions in higher altitudes (1200–1300 m above sea level (asl)) characterized with low temperatures as compared to low altitudes (1100 to 1200 m and 900 to 1100 m asl) with higher temperature in Uganda. Further, in Kenya, higher soil N_2O emissions were observed in Kaptumo with an elevation of 2000 m asl than Kolero with an elevation of 1250 m asl [42]. Notably, higher elevations recorded greater soil C and N, resulting in high N_2O fluxes. However, atmospheric temperature decreases with increasing elevation; therefore, it may influence soil microbial activities responsible for N_2O emissions.

5.2. Effects of Soil Moisture Content on N_2O Emissions in SSA. Soil moisture is a crucial driver of N_2O fluxes as it determines oxygen and organic substrates' availability [24]. Several studies have shown that increased soil moisture content, especially at the onset of a season, results in increased microbial activities causing enhanced soil N_2O emissions [28, 43, 44, 58, 64]. Increased N_2O emissions following the beginning of precipitation can be attributed to improved soil CN mineralization and decomposition due to Birch's birch effect [75]. Sufficient anaerobic microsites for the denitrification process increase N_2O emissions [12]. It also increases bacterial growth and other activities, thereby increasing respiration rates and soil aeration. Soil moisture increases nutrients' transport to soil microbes responsible for the denitrification process. For instance, in a study by Rabenarivo et al. [76] in Madagascar, an increase in soil moisture from 40% to 90% amplified N_2O fluxes by about 46%. In Kenya, Macharia et al. [28] observed that a difference of 32% in rainfall amounts between long rains and short rains seasons of 2017 resulted in a variance of four to six times more N_2O emissions across treatments. Soil moisture influences N_2O emissions by activating microbial activities that lead to denitrification and nitrification processes.

5.3. Effects of Soil Properties on N_2O Emissions in SSA. Soil physicochemical properties play a crucial role in N_2O dynamics by controlling soil carbon and nitrogen availability [77]. Soil texture influences water holding capacity and gas diffusivity rate and, therefore, regulates oxygen availability, enhancing microbial activities [12]. Course soil texture emits less N_2O emissions than fine texture due to the high accumulation of oxygen that limits denitrification rates, which is an ideal process for N_2O emissions production [78]. On the other hand, clayey soil microsites pores contribute to N_2O emissions production by enhancing anaerobic conditions favorable for denitrification. Studies have documented that adding inorganic fertilizers on fine-textured soil and organic fertilizer on coarse-textured soil significantly increases N_2O oxide emissions [28, 52, 53]. Concerning soil type, coarse-textured soils are generally C deficient, while fine-textured soil is generally N deficient [79]. The application of organic fertilizer on coarse-textured soil supplies mineralizable C hence stimulating N_2O emissions in carbon-limited soils, while applying inorganic fertilizer in fine soil supply N, providing substrate for microbial community, thus increasing N_2O emissions.

Soil bulk density influences N_2O fluxes by regulating oxygen diffusion into soils, which is essential for nitrification [12]. It limits soil aeration, which enhances the production of N_2 into the atmosphere through diffusion. Wanyama et al. [44] found a negative correlation between bulk density and soil N_2O fluxes, implying that increased bulk density and higher soil compaction result in lower N_2O emissions.

Soil pH significantly affects N_2O emissions as it controls bacterial activities, nutrient availability, and soil structure. Nitrification–denitrification microbes are pH-sensitive; hence, their alteration determines N_2O emissions. Low soil pH may alter functions of N_2O reductase enzymes, which are responsible for reducing N_2O/N_2 ratio and, therefore, may lead to higher N_2O emissions [80]. Under acidic soils, an increase in soil pH leads to less N_2O emissions though N_2O emissions increase with a decrease in pH under alkaline soil [81]. The manure application may also contribute to an increase in soil pH, resulting in lower N_2O emissions [43]. However, Macharia et al. [28] found higher N_2O emissions in manure-treated plots despite having the highest pH. Consequently, caution should be taken during continuous fertilizer application since it may promote soil acidification and encourage N_2O emissions.

Soil N_2O emissions can significantly be influenced by soil C, N, and C/N ratio [58]. The C/N ratio can predict whether mineralization or immobilization takes place. Use of crop residue with a high C/N ratio results in prolonged decomposition of organic matter. Consequently, a combination of low-quality crop residue with high-quality manure may offset N loss by balancing C/N, therefore, reducing immobilization. Low soil organic carbon limits denitrification and microbial activity resulting in lower N_2O emissions [42]. Studies have reported a positive correlation between inorganic nitrogen (NO_3-N, $NH_4{}^+$-N, and IN) and N_2O fluxes [1, 28, 44, 50]. Both soil C and N influence N_2O fluxes; therefore, the soil C/N ratio is an essential predictor of N_2O emissions. For instance, Wanyama et al. [44] documented a negative correlation between soil C/N ratio and N_2O fluxes which was attributed to a potential decrease in N mineralization with an increase in C : N ratio.

6. Soil N_2O Emissions' Mitigation Options in SSA

Given the diversity of soil N_2O fluxes drivers in SSA, no single mitigation option is applicable across all agroecological conditions. Therefore, a targeted approach specific to an agroecological zone is necessary for recommending different SSA interventions. For instance, soil type-soil fertility management targeting is an appropriate mechanism in evaluating N_2O emissions mitigation. Organic manure, which is readily available in most SSA households (e.g., Macharia et al. [67] and Nganga et al. [68]) may provide an essential entry point in mitigating N_2O emissions in SSA. Manure enriches soils with mineralizable C and N, thus improving soil fertility, general soil health, and crop yields but may come at the cost of more N_2O emissions [21]. However, with most of the landmass in SSA being arid and semiarid (ASALs) (45–55%), there is a need to achieve a nexus between crop production and N_2O emissions [82]. Therefore, N_2O yield-scaled emissions, which compare N_2O emissions and crop yields, can be used to assess the suitability of effective mitigation options.

6.1. Integrated Soil Fertility Management (ISFM). Integrated soil fertility management is an agricultural practice that combines locally available organic resources, improved germplasm, and mineral fertilizers to enhance nutrients and water efficiency to increase crop production [66, 83]. Combining manure and inorganic fertilizers has increased agricultural productivity while mitigating N_2O emissions in sandy loam (moderate texture) soils in Zimbabwe by increasing mineralizable C [53]. Sommer et al. [71] also found that integrated soil fertility management practices can improve N balance and contribute to environmental sustainability better than either sole inorganic fertilizer or organic fertilizer application. Crop residue retention can increase agricultural productivity with lower N_2O emissions compared with inorganic fertilizers [84]. Integrated soil fertility management contributes to the mitigation of N_2O emissions by improving soil health and crop productivity, increasing yield, and reducing YSEs.

6.2. Cereal-Legume Intercropping. Cereal-legume intercropping enhances soil and crop productivity through nitrogen fixation and soil conservation. Leguminous crops have a low C/N ratio than cereal crops [85]. This implies that combining both cereals and legumes in the field may reduce N's immobilization in soil and increase the availability of N and better synchronization by plant. Therefore, cereal-legume intercrop/rotation targeting might be an essential entry point in mitigating soil N_2O fluxes among smallholder farming systems in SSA. For instance, cereal-legume intercropping or rotation might enhance soil N_2O mitigation. Dick et al. [35] found significantly low soil N_2O fluxes under cereal-legume rotation cropping in Mali. According to Frimpong et al. [73], cowpea-maize intercrop emitted lower N_2O emissions than cowpea alone. The use of cereal-legume rotation improves nitrogen fixation, thus reducing the need for inorganic fertilizer [86], which, if applied, could lead to more N_2O fluxes. The cereal-legume in SSA can fix approximately 15 to 210 $\mathrm{kg\,N\,ha^{-1}}$ [87], thus improving soil fertility. This implies that the use of legumes, intercropped, or rotation may reduce N mining of maize crops currently ranging between 14 and 110 $\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$ in SSA [88]. In addition to reducing N_2O emissions and improving soil fertility, farmers practicing cereal-legume intercropping spread risk of crop failure in climate variability, hence increasing their economic plausibility and nutritional security [89].

6.3. Fertilizer Application Management. Fertilizer application management is very crucial for plant growth and N cycle in soil. Effective N fertilizer management in farm needs to consider N's amount required by plants and N supplied. This is because N application to soils might significantly influence N_2O emissions in SSA [41]. For instance, even though Hickman et al. [40] observed no significant difference in N_2O fluxes between fertilizer application rates in Western Kenya, emissions increased with an increased fertilizer application rate. This implies that applying the right amount of N to soil could significantly mitigate N_2O emissions instead of countries' specific blanket fertilizer application recommendations.

Further, the determination of site-specific fertilizer type can be essential in mitigating N_2O emissions. The use of nitrogen inhibitors and split application can also be necessary for reducing N_2O emissions from smallholder cropping systems in SSA. Finally, Nafi et al. [90] documented that microdosing (fertilizer application at the root) lowered N losses. Therefore, establishing site-specific 4Rs of fertilizer application (right time, right rate, right place, and right type) is requisite for mitigating N_2O emissions in SSA.

6.4. Reduce/No-Tillage Option. Soil disturbance through tillage could significantly increase N_2O emissions by altering soil physical properties such as bulk density. Tillage method targeting can offer bases for N_2O fluxes mitigation among smallholder cropping systems in SSA. For instance, Chikowo et al. [49] and Baggs et al. [18] documented lower N_2O emissions under no-tillage than tilled farms. Since conservation tillage (no-tillage or minimum tillage) increases agricultural productivity and lowers N_2O emissions, their adoption among smallholder farmers in SSA could mitigate the effects of N_2O emissions.

7. Conclusion

A better understanding of soil N_2O emissions, YSE, and EFs from different cropping systems in SSA is essential in promoting agricultural sustainability and climate change mitigation. The finding from the SSA studies agrees with our hypothesis that N2O emissions significantly differ across cropping systems. However, N_2O emissions remained relatively low compared to global averages, except for vegetable cropping systems mainly due to inherently low soil fertility due to continuous farming with limited replenishment with external inputs. We found out that better nutrient management through the combination of organic and inorganic fertilizers could provide a viable option in mitigating N_2O emissions in SSA. Our review also reveals that SSA's EFs are lower than IPCC Tier 1 default EFs meaning that the use of default EFs may overestimate soil N_2O emissions and lead to inaccurate targeting of climate change adaptation and mitigation measures in SSA. However, a few exceptional cases, mainly from vegetable production and applied more fertilizers comparatively, documented more than 1% in SSA. Our review identified environmental, climatic, and soil properties as critical drivers that significantly influence N_2O fluxes dynamics in SSA. Our study revealed that "umbrella" (universal) recommendations for climate change mitigation measures might not be effective across SSA cropping systems based on their diversity. Therefore, devising site-specific mitigation interventions could be a plausible entry point to mitigate N_2O emissions. We singled out options for targeting N_2O emissions mitigation in SSA: integrated soil fertility management; cereal-legume intercropping; reduced/no-tillage; and improved fertilizer application management. We recommend establishing more empirical studies in area with varying agro-ecological zones and soil types in SSA to qualify various mitigation options on N_2O emissions, yield-scaled N_2O emissions, and N_2O emission factors, which are essential in improving national and regional GHG inventories.

Data Availability

The data supporting the findings of the study are available upon request from the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

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