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Greenhouse gas emissions in maize agroecosystems of Sub-Saharan Africa: evidence synthesis and mitigation insights

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Maize-based agroecosystems dominate food production across much of Sub-Saharan Africa (SSA) and are central to regional food security. At the same time, agricultural soils are important sources of greenhouse gas (GHG) emissions, particularly nitrous oxide (N₂O), carbon dioxide (CO₂) and methane (CH₄), raising concerns about the climate impacts of maize intensification. Although a broad body of agronomic research in SSA has examined soil carbon dynamics, nitrogen cycling and productivity trade-offs, evidence based on field-measured GHG fluxes from maize systems remains limited. This review synthesises experimental, field-based studies that quantify CO₂, N₂O and CH₄ emissions from maize agroecosystems in SSA to characterise emission levels, identify key emission drivers and assess the mitigation potential of various management strategies. A PRISMA-guided systematic mapping and narrative synthesis was conducted using Web of Science and Scopus databases. Twenty-one field-based studies met the inclusion criteria and were analysed using bibliometric and thematic approaches. Across the reviewed studies, GHG emissions from maize systems in SSA were generally lower than those reported from high-input systems elsewhere, attributed to low nitrogen inputs and prevailing environmental conditions. Nitrogen management and soil moisture consistently emerged as dominant controls of N₂O emissions, which typically contributed most to overall global warming potential. Carbon dioxide fluxes were strongly influenced by tillage practices and residue management, while soils commonly acted as net sinks for CH₄, with episodic emissions during prolonged wet conditions. Evidence on conservation agriculture components points to context-dependent mitigation potential, with trade-offs among CO₂, N₂O and CH₄ varying by soil type, climate and management intensity. The review highlights the need for long-term, multi-site field experiments, particularly in underrepresented regions, to support the development of context-specific, climate-smart maize production strategies in SSA.

KEYWORDS

conservation agriculture, conventional tillage, greenhouse gas emissions, maize, nitrous oxide, Sub-Saharan Africa, yield-scaled emissions

1 Introduction

Agriculture is a major contributor to global GHG emissions, with cropland soils representing a dominant source of N₂O and an important regulator of CO₂ and CH₄ fluxes (Brouziyne et al., 2023). In SSA, maize (*Zea mays* L.) is the most widely cultivated staple crop and central to food security and rural livelihoods for a large proportion of the population (ten Berge et al., 2019; Erenstein et al., 2022). Maize production in the region is dominated by smallholder systems characterised by low external inputs, high climate variability, and strong dependence on soil fertility and rainfall (Macharia et al., 2020; Musafiri et al., 2020b; Githongo et al., 2022; Tabe-Ojong, 2023). As population growth and food demand intensify, improving maize productivity while limiting environmental externalities—particularly GHG emissions—has become a central challenge for sustainable maize intensification in SSA.

Empirical research explicitly quantifying GHG emissions from maize-based systems in SSA has expanded over the past two decades, particularly in East and Southern Africa. Field-based studies from countries such as Kenya, Tanzania, Ethiopia, South Africa, and Zimbabwe have measured CO₂, N₂O, and CH₄ fluxes under a range of management practices, including varying nitrogen (N) input levels, tillage intensity, residue management, crop rotation, and intercropping. Beyond studies that directly measure GHG fluxes, a much broader body of research across SSA has examined processes and outcomes that are closely linked to emissions and mitigation potential in maize-based systems. These include investigations of soil organic carbon sequestration (McNair Bostick et al., 2007; Gram et al., 2020; Sundberg et al., 2020; Abdalla et al., 2021; Zheng et al., 2023), nitrogen budgets and loss pathways (Chikowo et al., 2006; Gram et al., 2020), fertiliser response curves (Lemarpe et al., 2021; Maertens et al., 2023; Zheng et al., 2023), yield gaps (Bellarby et al., 2014; Rusere et al., 2022; Maertens et al., 2023), and trade-offs associated with agricultural intensification (Bellarby et al., 2014; Zheng et al., 2023). Numerous studies have assessed integrated soil fertility management, organic and inorganic nutrient inputs, agroforestry systems, improved fallows, and climate-smart agricultural practices, often using modelling approaches and other process-based frameworks (Ellis-Jones and Tengberg, 2000; Pyle and Mirza, 2007; Roobroeck et al., 2019; Macharia et al., 2021; Rusere et al., 2022; Zizinga et al., 2022). While many of these studies do not report field-measured GHG emissions from maize plots, they provide critical indirect insights into the biophysical mechanisms controlling emissions, including nitrogen availability, carbon inputs, soil aeration, and water dynamics.

Conservation agriculture (CA), based on the principles of minimal soil disturbance, permanent soil cover, and crop diversification, has been widely promoted in SSA as a climate-smart approach to enhance productivity, resilience, and environmental sustainability (Kimaro et al., 2014; Kimaro et al., 2016a; Kulagowski et al., 2021). Evidence from SSA and other regions suggests that CA practices can increase soil organic carbon stocks and reduce CO₂ emissions, while their effects on N₂O and

CH₄ are more variable and strongly context dependent (Soler et al., 2011; Kimaro et al., 2016b; Nyambo et al., 2020; Muzangwa et al., 2021). In SSA, several studies have evaluated individual CA components—such as reduced tillage (Centre and Centre, 2008; Hickman et al., 2015a; Tongwane et al., 2016; Vilakazi et al., 2021; Tully et al., 2023), residue retention, and legume integration (Millar et al., 2004; Nyamadzawo et al., 2017; Muzangwa et al., 2021; Mirzaei et al., 2022; Tully et al., 2023)—and have reported mixed effects on GHG emissions, contingent on factors such as soil texture, residue quality, nitrogen inputs and rainfall regime. However, the magnitude and consistency of reported mitigation benefits remain unclear.

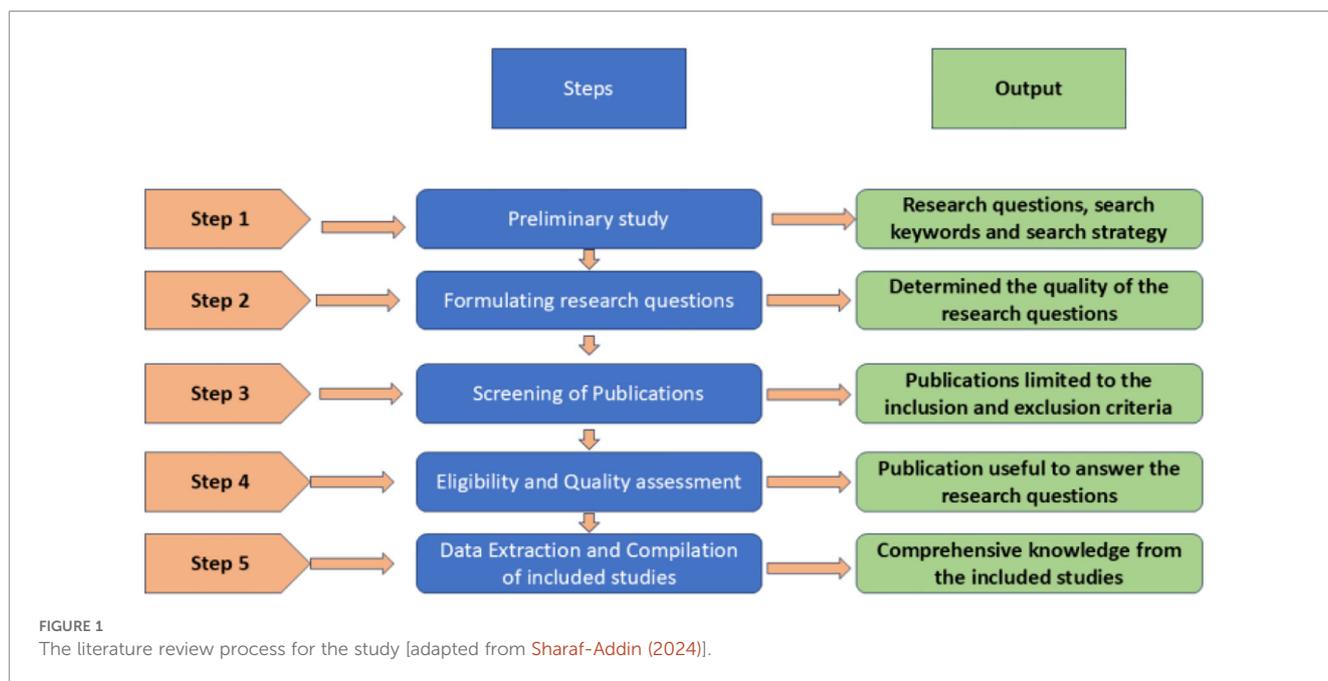
This review examines the existing literature on GHG emissions from maize agroecosystems in SSA and evaluates the impact of various mitigation strategies on these emissions. By identifying research gaps and synthesising current knowledge, the review aims to provide an understanding of current emissions levels, influencing factors, and insights into the mitigation strategies implemented in the region. A comprehensive understanding of the interactions among maize production, mitigation practices, and GHG dynamics will support the development of sustainable agricultural systems in SSA and help address the interconnected challenges of food security and environmental sustainability.

2 Methodology

This study followed PRISMA guidelines to conduct a systematic review of GHG emissions from maize agroecosystems in SSA. The review focussed specifically on experimental, field-based studies that directly quantified soil–atmosphere fluxes of CO₂, N₂O, and/or CH₄ from maize production systems. This narrow scope was adopted to ensure comparability of emission estimates and to synthesise evidence derived from direct measurements, while recognising that a broader body of agronomic and modelling literature relevant to mitigation processes exists outside these criteria. The review was guided by three research questions: (i) What are the reported magnitudes of GHG emissions from maize systems in SSA? (ii) What environmental and management factors influence emission dynamics? and (iii) What mitigation strategies have been evaluated, and what trade-offs do they present in terms of emissions and productivity? The review process adapted the methodology outlined by Sharaf-Addin (2024) (Figure 1). The initial step involved identifying relevant keywords and developing a search strategy to capture studies that effectively address the research questions. The keywords were then refined and combined in various ways to generate the most relevant articles on GHG emissions in maize agroecosystems within the SSA region.

2.1 Literature search strategy

A literature search was conducted on 22 March 2025 using the Web of Science and Scopus databases. Searches were performed



across titles, abstracts, and author keywords and used a structured Boolean strategy with three keyword blocks. The first block captured maize systems using the terms “maize” OR “corn” OR “Zea mays”. The second block captured GHG-related studies using “greenhouse gas” OR “GHG” OR “emission” OR “flux*” OR “nitrous oxide” OR “N₂O” OR “methane” OR “CH₄” OR “carbon dioxide” OR “CO₂”. The third block restricted retrieval to Sub-Saharan Africa by including regional terms (“sub-Saharan Africa”, “SSA”, and East/West/Central/Southern Africa**) and the names of Sub-Saharan African countries (e.g., Malawi, Kenya, Uganda, Tanzania, Zambia, Zimbabwe, Nigeria, Ghana, Ethiopia, South Africa, among others). The three blocks were combined using AND (maize terms AND GHG terms AND SSA terms), while synonymous terms within each block were combined using OR, to ensure that retrieved records contained maize-related terms and at least one GHG/emissions term alongside a Sub-Saharan Africa location term.

2.2 Inclusion and exclusion criteria

Records retrieved from the database searches were screened and studies were included if they were peer-reviewed, field-based experiments conducted in Sub-Saharan Africa under maize-based cropping systems and reported quantitative soil–atmosphere greenhouse gas fluxes of CO₂, N₂O and/or CH₄. Studies were excluded if they were conducted outside Sub-Saharan Africa, did not involve maize (*Zea mays*) systems, or did not report quantitative GHG emissions/flux data. We also excluded studies based on laboratory incubations, modelling/simulation, life-cycle assessment, or other indirect estimation approaches without field flux measurements relevant to maize systems. The full inclusion and exclusion criteria are summarised in Table 1.

2.3 Study screening and selection

The study selection process followed PRISMA 2020 reporting guidelines. All records retrieved from Web of Science and Scopus were exported to Mendeley desktop for reference management and

TABLE 1 Criteria for inclusion and exclusion.

Inclusion criteria	Exclusion criteria
<ul style="list-style-type: none"> Study design: Experimental, field-based study (on-farm or research station) in which maize management treatments were applied and compared. 	<ul style="list-style-type: none"> Not field-based: laboratory based (e.g. soil cores), pot trials, or purely observational studies without an experimental field component.
<ul style="list-style-type: none"> Geography: Conducted in Sub-Saharan Africa (SSA) (study site located within SSA). 	<ul style="list-style-type: none"> Conducted outside SSA, or location not in SSA.
<ul style="list-style-type: none"> Cropping system: Includes maize (<i>Zea mays</i>) as a main crop (sole maize, maize-based rotation, or maize intercrop with maize plot-level results). 	<ul style="list-style-type: none"> Non-maize systems crops only), or maize not separable (no maize plot-level data).
<ul style="list-style-type: none"> Outcome: Reports quantitative soil–atmosphere GHG fluxes/emissions for at least one gas (CO₂, N₂O, and/or CH₄) measured in the field (Using static chamber method) Publication type: Peer-reviewed journal article. Relevance: Addresses GHG emissions from maize systems in relation to management and/or environmental drivers (e.g., N inputs, tillage, residue management, rotations/intercropping). 	<ul style="list-style-type: none"> No quantitative soil–atmosphere GHG flux/emission data (e.g., qualitative discussion only, SOC stock change only, yield-only, nutrient balances only, proxy indicators). Reviews, editorials, conference abstracts, theses/reports (if excluded), and non-peer-reviewed sources. Studies focussed on life cycle assessment/carbon footprint of inputs or supply chains (e.g., fertiliser manufacture, transport, processing) without field flux measurements

duplicate removal prior to screening. The remaining records were screened in two stages: (i) title and abstract screening to exclude clearly irrelevant studies, followed by (ii) full-text assessment to confirm eligibility against the predefined inclusion and exclusion criteria (Table 1). During full-text screening, reasons for exclusion were recorded (e.g., conducted outside SSA, non-maize systems, non-field approaches such as modelling or laboratory incubations, or absence of quantitative GHG flux/emission data). The number of records retained at each stage—identification, screening, eligibility, and inclusion—is summarised in the PRISMA flow diagram (Figure 2).

2.4 Data extraction and synthesis

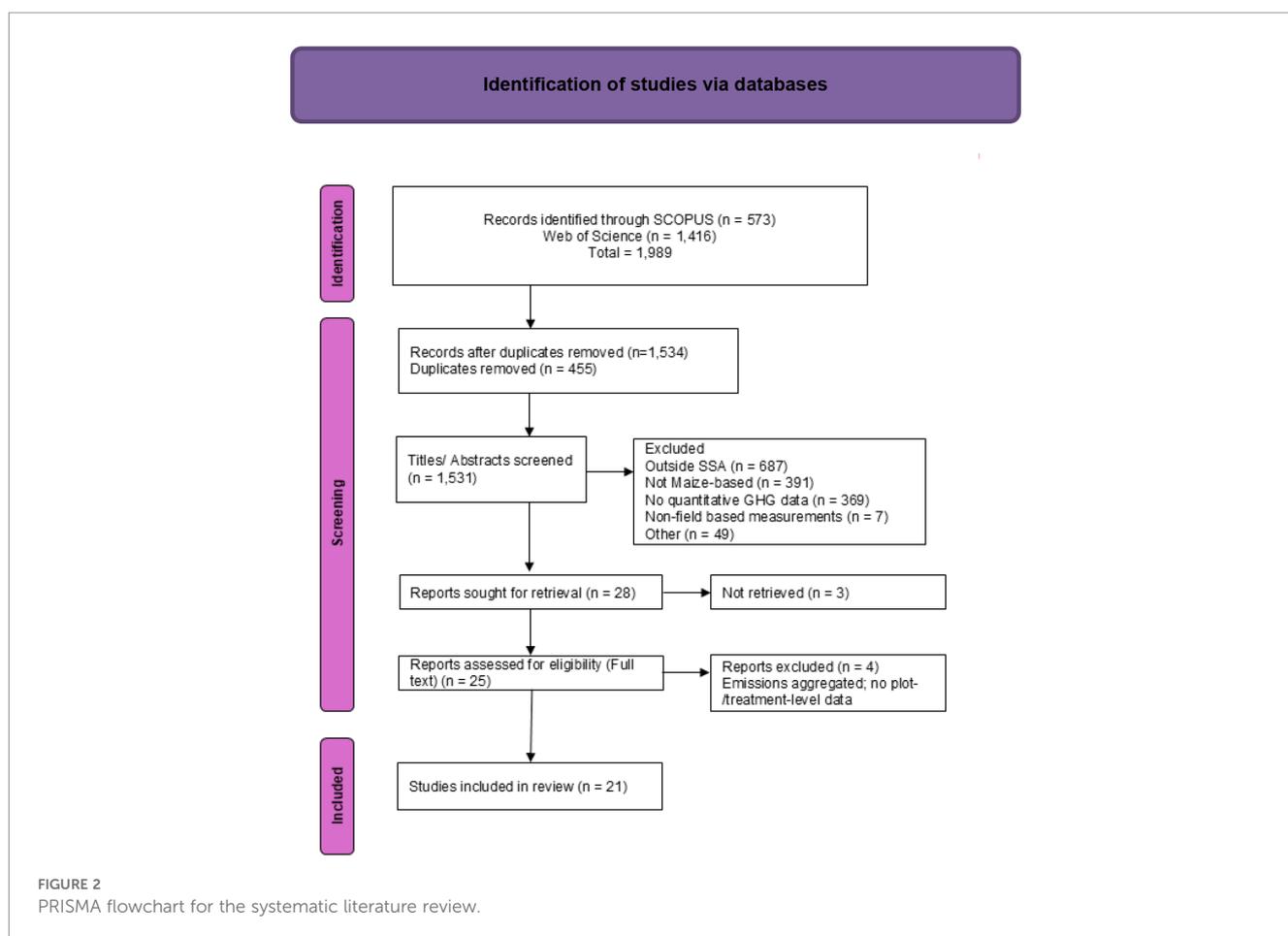
For each eligible study, data were extracted into a structured spreadsheet using a predefined extraction template. Extracted fields included bibliographic details (authors, year, journal and DOI), study setting (country/region, site description and climate/rainfall regime where reported), experimental design and measurement approach and agronomic management (cropping system, tillage/residue management, crop diversification such as rotations or intercropping, and fertiliser and/or organic amendment inputs including rates and forms). Greenhouse gas outcomes were extracted as reported (CO_2 , N_2O and/or CH_4 fluxes

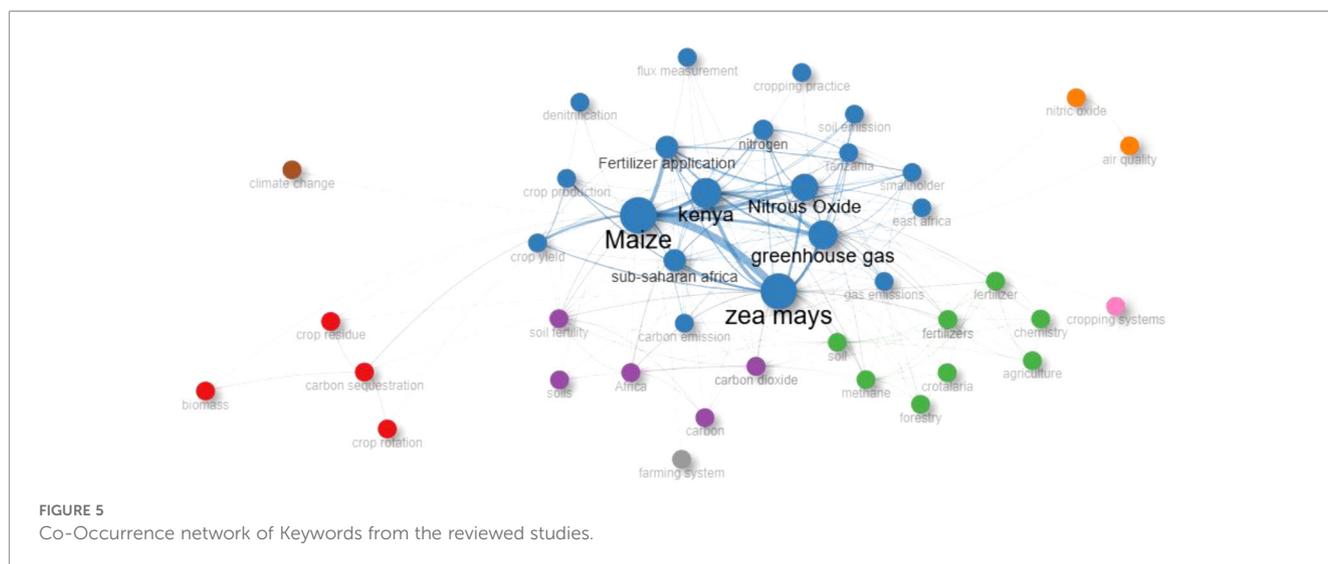
and, where provided, cumulative or seasonal emissions), together with the units and reporting period. Bibliometric analyses of the retrieved literature were conducted in RStudio using Biblioshiny (bibliometrix) to summarise publication trends, dominant research themes, keyword co-occurrence networks, and the geographical distribution of studies. Findings were synthesised using systematic mapping and narrative synthesis, grouping results by gas type (CO_2 , N_2O , CH_4), management category (e.g., nitrogen inputs, tillage intensity, residue retention, crop diversification), and environmental context (e.g., rainfall seasonality, soil moisture status and temperature where reported). Emission responses were interpreted in relation to management-driven mechanisms (particularly nitrogen availability and residue/organic matter inputs) and site conditions known to influence GHG production and transport, with attention to context dependence and trade-offs between mitigation potential and productivity.

3 Results and discussion

3.1 Search outcomes and study selection

The literature search identified 1,989 records from Web of Science ($n = 1,416$) and Scopus ($n = 573$). After merging records





appears as a secondary theme, typically associated with soil moisture conditions and more complex or diversified production systems, such as agroforestry. This reflects the predominantly aerobic conditions of upland maize systems in SSA, where CH_4 emissions are generally low but may become important under specific hydrological conditions (Musafiri et al., 2020b).

3.4 Characteristics of GHG emissions from maize agroecosystems in SSA

Across the reviewed studies, maize-based agroecosystems in SSA exhibited distinct GHG emission characteristics shaped by low external inputs, strong seasonal climatic variability, and site-specific soil properties. Although CO_2 , N_2O , and CH_4 were all reported, their relative contributions to overall climate impact differed substantially, with N_2O consistently dominating the global warming potential of maize systems (Table 2). Carbon dioxide emissions represented the largest absolute fluxes among the measured gases and were closely associated with soil respiration processes (Macharia et al., 2020; Musafiri et al., 2020b; Nyambo et al., 2020). Across studies, CO_2 fluxes displayed pronounced temporal variability, with emission peaks commonly occurring following rainfall events that stimulated microbial activity and root respiration (Maccarthy et al., 2018). Tillage intensity and residue management further influenced CO_2 dynamics, with higher emissions generally reported under conventional tillage and residue incorporation compared with reduced or no-tillage systems (Kimaro et al., 2016a; Nyambo et al., 2020; Muzangwa et al., 2021). Importantly, several studies reported increases in soil organic carbon under reduced disturbance and residue retention, indicating that short-term CO_2 emission pulses do not necessarily imply long-term carbon losses. Nitrous oxide was the most frequently measured greenhouse gas and emerged as the primary contributor to climate forcing in maize systems across SSA. Emission dynamics were strongly regulated by nitrogen availability and soil moisture, with pronounced N_2O pulses following fertiliser application and during wetting events after dry periods (Hickman et al., 2014;

Zheng et al., 2019; Musafiri et al., 2020a). Across studies, N_2O responses to increasing nitrogen inputs were often nonlinear, with disproportionately large emission increases observed beyond certain fertiliser thresholds (Hickman et al., 2017; Zheng et al., 2019). Despite this sensitivity, absolute N_2O emissions reported in SSA were generally lower than those observed in high-input maize systems elsewhere, reflecting lower fertiliser use and nutrient-limited conditions typical of smallholder production systems (Leitner et al., 2020). For instance, N_2O emissions from maize farming systems in Michigan, USA, were found to be ten times higher than those in SSA and in Peru, maize-legume rotations receiving 100 kg N/ha had an emission factor of 1.53%, while a maize chop-and-mulch system in Brazil reported an emission factor of 2.3% (Pauw et al., 2018). Methane fluxes on the other hand, were assessed less frequently, consistent with the predominantly aerobic conditions of upland maize systems. Where measured, soils commonly functioned as net CH_4 sinks, particularly during dry periods. Episodic CH_4 emissions were observed under prolonged soil saturation, when anaerobic microsites favoured methanogenic activity and reduced CH_4 oxidation (Kimaro et al., 2016b; Ortiz-Gonzalo et al., 2018; Macharia et al., 2020; Musafiri et al., 2020a; Kibet et al., 2022; Mosongo et al., 2022). These findings indicate that CH_4 dynamics in maize systems are highly sensitive to short-term hydrological conditions and may become increasingly variable under changing rainfall regimes.

3.5 Management drivers of GHG emissions in maize systems

3.5.1 Mineral N inputs and fertiliser management

Across the reviewed studies, nitrogen management consistently emerged as the dominant driver of GHG emissions from maize-based systems in SSA, particularly for N_2O . Fertilised treatments generally exhibited higher N_2O emissions than unfertilised controls, reflecting increased substrate availability for nitrification and denitrification (Table 2). Field experiments in western Kenya, for example, demonstrated clear increases in N_2O fluxes following

TABLE 2 GHG emissions studies in SSA.

Publication (Location)	Soil type	Crop management/ Treatment	Fertilisation rate (kg N ha ⁻¹)	CO ₂ emissions (Mg CO ₂ -C ha ⁻¹ yr ⁻¹)	N ₂ O emissions (kg N ha ⁻¹ yr ⁻¹)	CH ₄ emissions (kg CH ₄ -C ha ⁻¹ yr ⁻¹)
(Hickman et al., 2015b) (Ethiopia)	Andosols	No N Control Fertilised maize monocrop Crotalaria intercropping at 3 weeks Crotalaria intercropping at 6 weeks Lablab intercropping at 3 weeks Lablab intercropping at 6 weeks	0 64 64 64 64 64		0.10 - 1.20 0.18 - 2.06 0.15 - 3.00 0.18 - 2.12 0.17 - 5.49 0.13 - 0.94	
(Maccarthy et al., 2018) (Kenya)	Humic Nitisol	No N Control Inorganic fertiliser Animal manure Animal manure+inorganic fertiliser	0 120 120 60 + 60	4.63 - 4.98 6.33 - 6.82 5.55 - 5.89 5.90 - 6.07	0.20 - 0.22 0.36 - 0.40 0.26 - 0.28 0.30 - 0.32	-2.74 - 2.06 -1.67 - 1.59 -2.26 - -2.10 -1.72 - -1.52
(Zheng et al., 2019) (Iringa and Mbeya, Tanzania)	Haplustalfs	No N Control Moderate N input Optimal N input High N input Inorganic fertiliser and stover Inorganic fertiliser and stover	0 50 100 150 50 + Stover 2Mg C ha ⁻¹ 150 + Stover 2Mg C ha ⁻¹		0.14 - 0.30 0.26 - 0.51 0.30 - 0.58 0.34 - 0.73 0.37 - 0.88 0.55 - 2.38	
(Tegha et al., 2024) (Tanzania)		Conventional cultivation Reduced tillage + surface mulch Reduced tillage + mulch + legume cover crop Reduced tillage + mulch + nitrogen fertiliser Reduced tillage + mulch + woody legumes	100 100 100 100 100	3.92 - 5.74 4.01 - 5.66 4.63 - 6.41 4.47 - 6.04 3.75 - 7.18	0.33 - 0.59 0.32 - 0.54 0.59 - 0.73 0.41 - 0.63 0.49 - 1.22	-2.07 - 3.65 -3.42 - 10.74 0.87 - 7.38 -3.95 - 1.33 -1.52 - 0.16
(Kibet et al., 2022) (Kenya)	Ferralsol	Maize monocrop	125	5.95 - 7.07	0.93 - 1.89	-1.31 - - 0.79
(Musafiri et al., 2020b) (Kenya)	Humic Nitisol	No N Control Tithnia green manure Inorganic fertiliser	0 60 60		0.64 1.10 0.11	
(Chikowo et al., 2007) (South Africa)	Haplic Cambisol	No Till Conventional Tillage Residues removed Residues retained Biochar incorporation Maize-Fallow-Maize rotation Maize - Oat - Maize rotation Maize - Vetch - Maize rotation	90 90 90 90 90 90 90 90			
(Fatumah et al., 2021) (Ghana)	Ferric Acrisol	Conventional Tillage and stover	0	3.29 - 7.71		
(Nyambo et al., 2020) (South Africa)	Eutric Cambisol	Conventional tillage No Till Residues removed Residue retained Biochar incorporation Maize -Wheat-Maize rotation	90 90 90 90 90 90	1.25 - 18.70 1.06 - 15.41 7.03 - 11.85 8.78 - 9.92 6.73 - 9.76 13.62 - 14.38 12.49 - 13.24		

(Continued)

TABLE 2 Continued

Publication (Location)	Soil type	Crop management/ Treatment	Fertilisation rate (kg N ha ⁻¹)	CO ₂ emissions (Mg CO ₂ -C ha ⁻¹ yr ⁻¹)	N ₂ O emissions (kg N ha ⁻¹ yr ⁻¹)	CH ₄ emissions (kg CH ₄ -C ha ⁻¹ yr ⁻¹)
		Maize – Wheat-Soy bean Maize – Fallow-Maize Maize-Fallow-Soy bean	90 90	11.3 10.97		
(Vilakazi et al., 2021) (South Africa)	Ferralsol	Conventional Tillage Control Conventional Tillage Conventional Tillage No Till Control No Till No Till	0 120 240 0 120 240	2.84 – 3.24	0.07 – 0.09 0.05 – 0.34	
(Hickman et al., 2014) (Kenya)	Humic Nitisols	No N Control Moderate N input Intermediate N input Optimal N input High N input	0 50 75 100 200		0.71 – 0.98 0.67 – 0.80 0.62 – 0.63 0.58 – 0.62 0.81 – 1.39	
(Macharia et al., 2020) (Kenya)	Xanthic Ferralsol	No N Control Inorganic fertiliser Goat manure Goat manure+inorganic fertiliser	0 120 120 60 + 60	1.32 – 1.47 1.80 – 2.02 3.46 – 3.69 2.54 – 2.87	0.05 – 0.21 0.26 – 0.52 1.10 – 1.34 0.39 – 0.87	-0.17 - -0.05 -1.12–0.60 -0.12 - -{-}-0.06 -1.22 - -0.84
(Sommer et al., 2016) (Kenya)	Acric Ferralsol	Farmyard manure+maize stover+Maize-legume rotation Farmyard manure +continuous maize Maize stover+continuous maize	30 0 90		5.3 – 8.7 3.0 – 4.0 3.3 – 3.4	
(Mosongo et al., 2022) (Kenya)	Chromic Vertisol	No N Control Maize with mineral fertiliser Irrigated Maize Irrigated Maize and Manure Maize intercropped with legumes	0 100 0 40 0	4.1 – 5.0 4.1 – 5.5	≤2.0 0.25 – 2.45 0.72 – 2.68	-1.8 – 0.0 -1.83 – 0.33
(Macharia et al., 2021) (Kenya)	Xanthic Ferralsols	No N control Inorganic Fertiliser Goat manure Fertiliser + Goat manure	0 120 120 60 + 60	1.31 – 1.46 1.79 – 2.01 3.46 – 3.69 2.52 – 2.87	0.05 – 0.21 0.26 – 0.52 1.09 – 1.34 0.39 – 0.87	
(Nyamadzawo et al., 2017) (Zimbabwe)	Haplic Lixisol	No N control Inorganic Fertiliser Inorganic Fertiliser Fertiliser + Manure	0 60 120 60 + 60		0.32 0.52 0.41 0.35	
(Chikowo et al., 2006) (Zimbabwe)	Lixisol	Sole Maize	0		0.39	
(Ortiz-Gonzalo et al., 2018) (Kenya)	Nitisols	Fertilised planting rows Unfertilized inter-rows	100 0	5.57 – 9.24 4.83 – 5.81	0.56 – 0.64 0.10 – 0.22	-2.84 - -2.78 -4.41 - - 3.38
(Tully et al., 2023) (Kenya and Tanzania)	Eutric Ferralsols & Ferric Acrisols	No N Control Moderate N input Intermediate N input Optimum N input High N input	0 50 75 100 150		0.02 – 1.40 0.04 – 3.60 0.03 – 3.30 0.04 – 1.90 0.03 – 3.50	

(Continued)

TABLE 2 Continued

Publication (Location)	Soil type	Crop management/ Treatment	Fertilisation rate (kg N ha ⁻¹)	CO ₂ emissions (Mg CO ₂ -C ha ⁻¹ yr ⁻¹)	N ₂ O emissions (kg N ha ⁻¹ yr ⁻¹)	CH ₄ emissions (kg CH ₄ -C ha ⁻¹ yr ⁻¹)
(Hickman et al., 2015b) (Kenya)	Humic Nitisols	No N Control, Moderate N input &	0, 50 &75		0.62 – 0.71	
		Intermediate N input	100		0.17 – 0.71	
		Optimum N input	150		0.25 – 0.29	
		High N input	200		0.81	
		Very high N Input				
(Fatumah et al., 2021) (Uganda)	Lixic Ferralsols	Maize-Beans intercrop (mulched -NT)				
		Maize-Beans intercrop (Non-mulched + Reduced Tillage)		6.34	0.72	0.002
		Maize-Beans intercrop + compost and reduced tillage)		8.59	0.80	-0.006
		Sole Maize (Mulched – NT)		7.47	0.55	-0.010
		Sole Maize (Non-mulched + Tillage)		8.23	0.86	0.001
		Sole Maize (Mulched – NT)		11.75	1.22	-0.008
		Sole Maize (Non-mulched + Tillage)		9.67	0.55	-0.013

mineral fertiliser application, with pronounced emission pulses occurring shortly after fertilisation and during subsequent rainfall events (Hickman et al., 2014; Hickman et al., 2017). Similar patterns were reported in Tanzania and Ethiopia, where fertiliser-induced N₂O emissions were strongly modulated by soil moisture dynamics (Raji and Dörsch, 2020; Tully et al., 2023). Although average fertiliser application rates in SSA remain comparatively low, several studies reported nonlinear emission responses at higher N inputs. In maize systems receiving more than approximately 100 kg N ha⁻¹, N₂O emissions increased disproportionately, particularly under wet soil conditions (Raji and Dörsch, 2020). Long-term experiments in Kenya showed that N₂O fluxes nearly doubled when fertiliser rates increased from moderate to high levels, without corresponding yield gains (Hickman et al., 2014; Zheng et al., 2019; Tully et al., 2023). In contrast, split fertiliser applications improved synchrony between nitrogen availability and crop demand, reducing peak N₂O emissions while maintaining or increasing maize yields (Raji and Dörsch, 2020). These findings indicate that fertiliser management strategies that optimise timing and placement can substantially influence emission intensity, even under low-input systems.

3.5.2 Organic amendments and integrated nutrient management

The use of organic amendments, including animal manure and crop residues, modified GHG emission dynamics relative to mineral fertilisers by altering the timing and duration of nitrogen release. Across studies, organic N sources were associated with delayed and more prolonged N₂O emission peaks, reflecting gradual mineralisation processes (Mapanda et al., 2012; Macharia et al., 2021). For instance, field trials in Kenya reported that manure-amended maize plots exhibited N₂O emission peaks several days after application, in contrast to the rapid emission responses

observed following mineral fertiliser use (Kimetu et al., 2006; Nyamadzawo et al., 2017; Musafiri et al., 2020a; Vilakazi et al., 2021). Integrated nutrient management approaches combining organic and inorganic inputs produced variable emission outcomes depending on soil texture, carbon availability, and moisture conditions (Zheng et al., 2019). In coarse-textured, well-drained soils with low organic carbon, Macharia et al (Macharia et al., 2021). reported increased N₂O emissions following manure incorporation. The rise in emissions was attributed to enhanced microbial denitrification driven by the additional organic carbon, particularly during wetting events. Conversely, in fine-textured soils with higher carbon content, Musafiri et al (Musafiri et al., 2020b). found no significant emission increases after manure application. The quality of organic amendments further influenced emission outcomes. Manure from smallholder systems in SSA typically has a high C:N ratio and low nitrogen content compared to that in developed regions. Nyamadzawo et al (Nyamadzawo et al., 2017). demonstrated this in a comparative study between Zimbabwe and China, where low-quality manure (1.2–1.4% N, dry basis) in Zimbabwe resulted in significantly lower N₂O emissions than the high-quality manure used in China. Importantly, integrated nutrient management consistently improved maize yields relative to sole mineral fertilisation, and yield-scaled emissions often indicated comparable or improved environmental performance.

3.5.3 Tillage practices

Tillage intensity influenced GHG emissions through its effects on soil structure, aeration, and organic matter decomposition. Conventional tillage was generally associated with higher CO₂ emissions due to enhanced microbial decomposition of soil organic matter following soil disturbance. For example, studies from the Eastern Cape Province of South Africa reported 26.3% higher CO₂ fluxes under conventional tillage compared with no-

tillage systems, particularly following rainfall events that stimulated microbial activity (Maccarthy et al., 2018; Macharia et al., 2021; Muzangwa et al., 2021). Reduced and no-tillage practices promoted soil carbon retention in surface layers and often reduced CO₂ emissions over time. However, their effects on N₂O emissions were more variable. In some cases, no-tillage systems exhibited higher N₂O fluxes during wet periods, as observed in maize trials in South Africa and Tanzania, where increased soil moisture and reduced aeration promoted denitrification (Table 2). When evaluated using global warming potential or yield-scaled emission metrics, reduced tillage systems generally outperformed conventional tillage, indicating net mitigation benefits despite occasional increases in individual gas fluxes (Kimaro et al., 2016a; Atakora et al., 2019; Vilakazi et al., 2021; Tegha et al., 2024).

3.5.4 Residue management

Residue management affected GHG emissions by modifying soil microclimate, moisture retention, and substrate availability for microbial processes. Residue retention generally increased soil moisture and reduced temperature fluctuations, creating favourable conditions for both microbial activity and carbon sequestration (Musafiri et al., 2020a; Muzangwa et al., 2021; Vilakazi et al., 2021). Studies from South Africa and Tanzania reported higher short-term CO₂ and N₂O emissions under residue-retained plots, particularly when residues were combined with mineral fertiliser (Table 2). Emission responses were strongly influenced by residue quality. In Tanzanian maize systems, the incorporation of maize stover with nitrogen fertiliser increased N₂O emission factors, particularly under high water-filled pore space conditions. In contrast, studies using low-quality residues typical of SSA systems, characterised by high carbon-to-nitrogen ratios, reported reduced N₂O emissions due to microbial nitrogen immobilisation and more complete denitrification to N₂ (Chikowo et al., 2007; Ortiz-Gonzalo et al., 2018; Zheng et al., 2019). Residues converted to biochar and applied to maize fields generally improved yields and reduced overall GHG emissions, although CO₂ fluxes were higher than in non-biochar controls in Nyambo et al (Nyambo et al., 2020); however, the overall mitigation benefit remained evident when emissions were evaluated on a yield-scaled basis. Despite short-term increases in CO₂ and, in some cases, N₂O, residue retention consistently increased soil organic carbon stocks, suggesting long-term mitigation potential when assessed over extended time horizons.

3.5.5 Crop diversification and rotations

Crop diversification through intercropping and rotation influenced GHG emissions by altering nitrogen inputs and soil biological activity. Legume intercropping systems often increased N₂O emissions due to the addition of biologically fixed nitrogen, although emission magnitude varied by species and management (Kimetu et al., 2006). For example, field studies in Ethiopia reported higher N₂O emissions under maize-lablab intercropping compared with maize monocropping, while delayed intercropping significantly reduced emission intensity (Nyambo et al., 2020). Additionally, emission responses also varied with legume species.

For example, Lablab purpureus generated higher N₂O emissions due to its high biomass and nitrogen fixation potential, whereas *Crotalaria juncea* was associated with lower emissions (Raji and Dörsch, 2019). In contrast, crop rotations incorporating legumes generally improved yields and reduced emissions compared with continuous maize systems. Long-term experiments in South Africa demonstrated lower CO₂ emissions and improved soil carbon status under maize-legume rotations relative to continuous cereal systems (Muzangwa et al., 2021). These findings suggest that rotational diversification may offer more stable mitigation benefits than intercropping in certain agroecological contexts, particularly when combined with optimised nitrogen management.

3.6 Conservation agriculture and mitigation trade-offs in maize systems

Conservation agriculture, based on the principles of reduced soil disturbance, permanent soil cover, and crop diversification, is widely promoted in SSA as a climate-smart approach capable of enhancing productivity while reducing GHG emissions (Kimaro et al., 2016a). Evidence from the reviewed studies indicates that CA practices can influence emission dynamics through multiple interacting pathways, but their mitigation outcomes are strongly context dependent and often involve trade-offs among different gases and management objectives (Kimaro et al., 2016a; Nyambo et al., 2020; Muzangwa et al., 2021; Vilakazi et al., 2021). Across studies, reduced or no-tillage systems consistently improved soil organic carbon retention and reduced CO₂ emissions relative to conventional tillage, particularly over longer time frames. Field experiments in South Africa and Tanzania, for example, reported lower CO₂ fluxes and higher soil carbon stocks under reduced tillage, reflecting reduced soil disturbance and slower organic matter decomposition (Kimaro et al., 2016b; Nyambo et al., 2020; Muzangwa et al., 2021). However, these benefits were not uniform across all conditions. In wetter environments or during prolonged rainfall periods, reduced tillage occasionally increased N₂O emissions due to higher soil moisture and the formation of anaerobic microsites that favoured denitrification (Nyambo et al., 2020). These findings highlight a key trade-off in CA systems, where practices that promote carbon sequestration may simultaneously increase short-term N₂O losses under certain environmental conditions. Residue retention, another core CA principle, further illustrates these trade-offs. Retaining crop residues generally enhanced soil moisture conservation and contributed to long-term soil carbon accumulation, but several studies reported short-term increases in CO₂ and N₂O emissions following residue addition, particularly when residues were combined with nitrogen fertiliser. For example, maize stover retention in Tanzanian systems (Centre and Centre, 2008) increased N₂O emissions during wet periods, while low-quality residues with high carbon-to-nitrogen ratios in other SSA systems promoted nitrogen immobilisation and reduced N₂O losses. These contrasting outcomes highlight the importance of residue quality, soil texture, and fertiliser management in determining emission responses. Crop

diversification through rotations or intercropping influenced CA mitigation outcomes by altering nitrogen inputs and residue dynamics. While legume intercropping increased N₂O emissions in some studies due to biological nitrogen fixation, rotational systems incorporating legumes generally improved yields and reduced overall emissions compared with continuous maize monocropping. Long-term rotation trials in southern Africa demonstrated lower global warming potential and improved yield-scaled emissions under diversified systems, suggesting that rotation-based diversification may offer more consistent mitigation benefits than intercropping alone. Importantly, when mitigation outcomes were evaluated using yield-scaled metrics rather than absolute emissions, CA systems frequently performed better than conventional systems. Studies in Tanzania and South Africa showed that although absolute N₂O emissions were sometimes higher under CA practices, improved yields and soil carbon sequestration resulted in lower emission intensity per unit of grain produced (Chikowo et al., 2007; Atakora et al., 2019; Zheng et al., 2019; Fatumah et al., 2021; Tegha et al., 2024; Alasinrin et al., 2025). This finding emphasises that assessments of CA mitigation potential should account for productivity outcomes alongside emission measurements. Overall, the reviewed evidence indicates that CA holds significant potential to contribute to GHG mitigation in maize-based systems of SSA, but its effectiveness depends on the specific combination of practices implemented and their alignment with local soil and climatic conditions. Rather than delivering uniform emission reductions, CA practices influence emissions through complex interactions that require site-specific management and long-term evaluation. These insights reinforce the need to assess CA systems holistically, integrating emissions, soil carbon dynamics, and productivity to identify context-appropriate climate-smart strategies.

3.7 Evidence gaps and synthesis priorities for maize GHG research in SSA

Despite the growing body of research on GHG emissions from maize-based systems in SSA, important evidence gaps and synthesis challenges remain. These gaps do not reflect a lack of agronomic or environmental research in the region, but rather the fragmented nature of existing studies, which differ widely in spatial coverage, experimental duration, measurement scope, and methodological approaches. A key limitation of the current evidence base is the strong geographic concentration of field-based GHG studies in a small number of countries, particularly in East and Southern Africa. Large maize-producing regions in West and Central Africa remain underrepresented in experimental emission measurements, limiting the ability to generalise findings across the region's diverse agroecological zones. Expanding field-based measurements to these underrepresented regions would substantially improve regional emission estimates and mitigation assessments. Temporal limitations also constrain synthesis. Most studies are short-term, often spanning one to three growing seasons, and therefore capture only a limited range of climatic variability. Given the strong

influence of rainfall, soil moisture, and temperature on emission dynamics, longer-term experiments are required to assess interannual variability and the persistence of mitigation outcomes under changing climate conditions. While individual components of conservation agriculture have demonstrated mitigation potential, their combined and long-term effects remain insufficiently quantified across diverse SSA environments. Addressing these gaps will require coordinated, multi-site, long-term experiments that integrate biophysical measurements with productivity and soil health indicators. Such efforts are essential for developing context-specific, climate-smart maize production strategies that balance food security and greenhouse gas mitigation objectives in Sub-Saharan Africa.

4 Potential limitations of the review

While this review provides valuable insights into GHG emissions from maize-based systems in SSA, several limitations should be acknowledged. The synthesis was restricted to published field-based experimental studies reporting direct GHG measurements, which may have excluded a broader body of agronomic, modelling, and soil carbon research that offers complementary insights into mitigation-relevant processes; such studies were therefore considered only for contextual interpretation. In addition, the spatial coverage of the reviewed studies was uneven, with research concentrated in a limited number of countries, potentially limiting representation of the full diversity of agroecological conditions, management practices, and socio-economic contexts across the region. Furthermore, the reviewed literature primarily reflects smallholder farming systems, which dominate maize production in SSA, while the contributions of more intensive systems—although present to a lesser extent—were not explicitly captured. Despite these limitations, the review provides a robust synthesis of available evidence and identifies key priorities for future research. Addressing these gaps through more geographically inclusive, methodologically integrated, and long-term studies will be essential for improving understanding of GHG emission dynamics and supporting the development of context-specific mitigation strategies for SSA.

5 Conclusion and recommendation

This review synthesised field-based experimental evidence on GHG emissions from maize-based agroecosystems in SSA, with emphasis on emission characteristics, key management drivers, and the mitigation potential of conservation-oriented practices. The reviewed studies collectively indicate that GHG emissions from maize systems in SSA are generally lower than those reported in high-input systems elsewhere, largely reflecting low nitrogen inputs and prevailing environmental conditions. Across systems, N₂O consistently emerged as the dominant contributor to climate forcing, while CO₂ and CH₄ fluxes were strongly regulated by soil disturbance, residue management, and hydrological conditions. Management

practices exerted a strong influence on emission dynamics, but their effects were highly context dependent. Nitrogen input rate and timing were the primary determinants of N₂O emissions, with nonlinear emission responses observed at higher fertiliser levels. Reduced tillage and residue retention promoted soil carbon accumulation and often reduced CO₂ emissions, although short-term increases in N₂O were reported under wet conditions. Crop diversification, particularly through rotations incorporating legumes, generally improved productivity and reduced emissions relative to continuous maize monocropping, while intercropping outcomes varied with species, timing, and nitrogen management. When evaluated using yield-scaled metrics, conservation agricultural practices frequently demonstrated improved environmental performance despite occasional increases in absolute emissions. Although conservation agriculture shows clear potential to contribute to climate-change mitigation in maize systems of SSA, its effectiveness depends on the specific combination of practices implemented and their alignment with local soil and climatic conditions. Rather than delivering uniform emission reductions, conservation agriculture influences GHG emissions through interacting biophysical processes that require site-specific management and long-term evaluation. Several synthesis priorities emerge from this review. Future research should expand field-based GHG measurements to underrepresented regions, particularly West and Central Africa, and prioritise long-term, multi-site experiments capable of capturing climatic variability. Greater integration of multiple greenhouse gases, soil carbon dynamics, and productivity outcomes within the same experimental frameworks is needed to enable robust assessment of trade-offs and mitigation potential. Explicit consideration of environmental drivers—such as soil texture, moisture, and pH—will further improve the transferability of management recommendations. Advancing climate-smart maize production in SSA will require coordinated research efforts that integrate biophysical measurements with agronomic performance and soil health indicators. Such evidence is essential to support the development of context-specific mitigation strategies that balance food security, resilience, and greenhouse gas reduction objectives across the region.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

CM: Data curation, Conceptualization, Writing – review & editing, Validation, Writing – original draft, Methodology, Formal analysis. OO: Validation, Writing – review & editing,

Formal analysis, Supervision, Visualization, Methodology, Writing – original draft, Conceptualization. JD: Validation, Supervision, Writing – review & editing, Methodology, Investigation. RL: Supervision, Writing – review & editing, Investigation, Project administration, Visualization, Data curation. PN: Supervision, Writing – review & editing. JC: Writing – review & editing, Supervision. AL-L: Resources, Supervision, Validation, Writing – review & editing. LC: Resources, Conceptualization, Writing – review & editing, Project administration, Supervision.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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