

ISSN Print: 2706-7483
 ISSN Online: 2706-7491
 NAAS Rating (2026): 4.5
 IJGGE 2026; 8(4): 210-214
<https://www.geojournal.net>
 Received: 21-02-2026
 Accepted: 16-03-2026

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Life Cycle Assessment of Greenhouse Gas Emissions from Pineapple Cultivation Systems Established on Reclaimed Acid Sulfate Terrain

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DOI: <https://doi.org/10.22271/27067483.2026.v8.i4b.825>

Abstract

"What gets measured gets managed" is a truism in environmental accounting, yet the greenhouse gas (GHG) footprint of pineapple cultivation on reclaimed acid sulfate soils one of the most emissions-intensive land-use transitions in tropical agriculture has never been rigorously quantified through a field-based life cycle assessment (LCA). This study applied a cradle-to-farm-gate LCA framework to three pineapple management systems on reclaimed acid sulfate terrain near Palmira, Colombia: conventional (no amendment), lime-amended (4 t ha^{-1}), and biochar-amended (10 t ha^{-1}). Over an 18-month cropping cycle, cumulative GHG emissions were $9,280 \text{ kg CO}_2\text{-eq ha}^{-1}$ (conventional), $7,340 \text{ kg CO}_2\text{-eq ha}^{-1}$ (lime), and $5,670 \text{ kg CO}_2\text{-eq ha}^{-1}$ (biochar). Soil N_2O flux was the largest single source (32-38 % of total), followed by soil respiration CO_2 (28-34 %). Biochar reduced emissions by 39 % relative to the conventional system, primarily through suppression of N_2O emissions and partial carbon sequestration. These results provide the first field-validated emission factors for pineapple on acid sulfate soils and demonstrate that soil amendment choice has a larger effect on the GHG footprint than any other single management variable.

Keywords: Life cycle assessment, greenhouse gas emissions, pineapple, acid sulfate soil, biochar, carbon footprint, N_2O , soil respiration, colombia, climate-smart agriculture

Introduction

Leading voices in tropical agriculture have repeatedly argued that expanding fruit production onto degraded acid sulfate soils rather than clearing intact forest represents a lower-carbon pathway to food security [1]. This argument rests on the assumption that the GHG cost of reclaiming and farming acid sulfate terrain is modest compared with deforestation emissions. But that assumption has never been tested against field data for pineapple, the crop most commonly grown on such soils across Latin America and Southeast Asia.

Acid sulfate soils release CO_2 and N_2O through several pathways that conventional agricultural LCAs do not capture: the dissolution of applied lime generates CO_2 directly, the oxidation of sulfides lowers soil pH and alters nitrification-denitrification dynamics to favour N_2O over N_2 , and the organic matter mineralisation triggered by drainage adds a persistent CO_2 source [2]. Standard IPCC Tier 1 emission factors, derived mainly from temperate croplands, do not account for these acid-sulfate-specific sources and are therefore likely to underestimate the carbon footprint of pineapple grown on reclaimed terrain [3].

Colombia cultivated approximately 56,000 hectares of pineapple in 2020, with the Cauca Valley near Palmira emerging as a secondary production zone where acid sulfate Vertisols and Inceptisols have been reclaimed for fruit production since the early 2000s [4]. Biochar, a carbon-rich solid produced by pyrolysis of crop residues, has shown promise in other tropical systems for simultaneously reducing N_2O emissions (by adsorbing ammonium and altering soil redox conditions) and sequestering stable carbon [5]. Whether biochar delivers these benefits on acid sulfate soils under pineapple where the unusual soil chemistry may alter biochar reactivity has not been examined. This study therefore conducted a full cradle-to-farm-gate LCA comparing conventional, lime-amended, and biochar-amended pineapple systems on a reclaimed acid sulfate Vertisol near Palmira over a complete 18-month cropping cycle.

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Seasonal variations and temporal patterns

The trial site (3°32' N, 76° 18' W, 1,001 m a.s.l.) in the Cauca Valley receives a mean annual rainfall of 1,020 mm distributed bimodally, with peaks in March-May and September-November. Mean annual temperature is 24.2°C. GHG fluxes showed strong seasonal patterns: N₂O emissions peaked within 7-14 days of each fertiliser application (three splits at 0, 4, and 8 MAP), with the highest single-event flux recorded after the second application in July 2019 (wet season, soil moisture at 65 % water-filled pore space). Soil respiration CO₂ flux was highest during the early vegetative phase (months 2-6) when soil disturbance from land preparation had maximised organic matter exposure, and declined to near-baseline levels by month 12.

Material and Methods

Material

MD2 pineapple suckers (300-350 g) were planted at 30×60 cm (43,500 plants ha⁻¹). Lime was applied as agricultural dolomite (54 % CaCO₃, 42 % MgCO₃). Biochar was produced from ricehusk feedstock by slow pyrolysis at 450°C (C content 52 %, H/C molar ratio 0.42, BET surface area 218 m²g⁻¹, pH 9.2). GHG fluxes were measured using static chambers (PVC, 25-cm diameter, 15-cm height) connected to a Gasmeter DX4040 FTIR gas analyser (Gasmeter Technologies, Finland) for simultaneous CO₂, CH₄, and N₂O quantification at 1 ppm resolution. Soil temperature and moisture were logged continuously (Decagon 5TM sensors). The LCA followed ISO 14040/14044 guidelines with a functional unit of 1 tonne of fresh fruit at the farm gate [6].

Methods

The experiment was a RCBD with three amendment treatments and four blocks on a 0.8-ha reclaimed acid sulfate Vertisol. Treatments were: (i) conventional no soil amendment beyond standard fertiliser (150 kg N, 60 kg P₂O₅, 120 kg K₂O ha⁻¹); (ii) lime 4 t ha⁻¹ dolomite incorporated to 20 cm at planting; (iii) biochar 10 t ha⁻¹ rice-husk biochar incorporated to 20 cm at planting. Each plot measured 15 × 12 m (180 m²) with 4-m buffers. GHG fluxes were measured weekly during months 1-6 and biweekly during months 7-18, with additional daily measurements during the 14-day windows following each of three fertiliser applications. Each measurement involved deploying three chambers per plot for a 30-minute enclosure period, sampling headspace at 0, 10, 20, and 30 min. Fluxes were calculated from the linear increase in gas concentration

over time, rejecting non-linear responses ($R^2 < 0.90$). Cumulative emissions were computed by linear interpolation between measurement dates. The LCA system boundary encompassed all on-farm operations (land preparation, planting, fertilisation, pest management, harvest), fertiliser and amendment manufacture and transport (distance-weighted using Colombian freight data), and machinery fuel consumption. Emission factors for fertiliser manufacture followed ecoinvent v3.8. Soil carbon stock changes (0-30 cm) were assessed from baseline and end-of-cycle soil sampling (five cores per plot, Walkley-Black method). Data were analysed by one-way ANOVA with Tukey HSD at $\alpha = 0.05$.

Nutrient budget and input-output analysis

Fertiliser N input totalled 150 kg ha⁻¹ across all treatments. Fruit N removal was 1.7 kg per tonne of fresh fruit; at mean yields of 58.4 : t : ha⁻¹ (conventional), 64.2 t ha⁻¹ (lime), and 62.8 t ha⁻¹ (biochar), crop N offtake was 99, 109, and 107 kg ha⁻¹ respectively. The apparent N surplus (input minus offtake) was 51 kg ha⁻¹ (conventional), 41 (lime), and 43 (biochar). This surplus represents the pool available for gaseous loss (N₂O, NH₃, N₂) and leaching. The lower surplus under lime and biochar reflects their higher yields rather than reduced inputs, and the emission data confirm that biochar redirected a portion of this surplus toward N₂ (via enhanced complete denitrification) rather than N₂ loss.

Baseline soil characterisation

The acid sulfate Vertisol had a clay texture (58 % clay, 24 % silt, 18 % sand), pH 3.8, total S 0.92 %, jarosite motes at 35-60 cm, organic C 2.14 %, total N 0.21 %, CEC 28.4 cmol kg⁻¹, and exchangeable Al³⁺ 4.2 cmol kg⁻¹. The soil was reclaimed in 2015 by deep drainage, liming (2 t ha⁻¹), and one cycle of upland rice. By the start of the trial (March 2019), topsoil pH had risen to 4.2 but jarosite persisted in the subsoil, indicating ongoing acid-sulfate potential.

Results

All three GHG species (CO₂, N₂O, CH₄) showed significant treatment effects ($p < 0.01$ for CO₂ and N₂O; $p = 0.04$ for CH₄). Biochar reduced cumulative GHG emissions by 39 % relative to the conventional system, while lime reduced them by 21 %. The emission reduction was dominated by the N₂O pathway, where biochar achieved a 48 % cut, and by a modest net carbon sequestration in the biochar treatment (0.42 t C ha⁻¹ over 18 months) that partly offset soil respiration losses.

Table 1: Summary of cumulative GHG emissions (kg CO₂ - eq ha⁻¹) by source and treatment over the 18-month cropping cycle, with Tukey grouping letters

Emission Source	Conventional	Lime	Biochar	SE
Soil N ₂ O	3,530 a	2,790 b	1,840 c	185
Soil CO ₂	2,590 a	2,310 ab	1,980 b	142
Soil CH ₄	280 a	220 ab	180 b	22
Fertiliser mfg	1,620	1,620	1,620	
Machinery	860	840	850	18
Lime CO ₂ release		560		
Net soil C change	400 a	0 b	-800 c	95
Total	9,280 a	7,340 b	5,670 c	312

Negative values for net soil C change indicate net sequestration. Means with the same letter within a row do not differ at $p \leq 0.05$. SE = pooled standard error. Fertiliser manufacture emissions are

identical across treatments because all received the same fertiliser inputs.

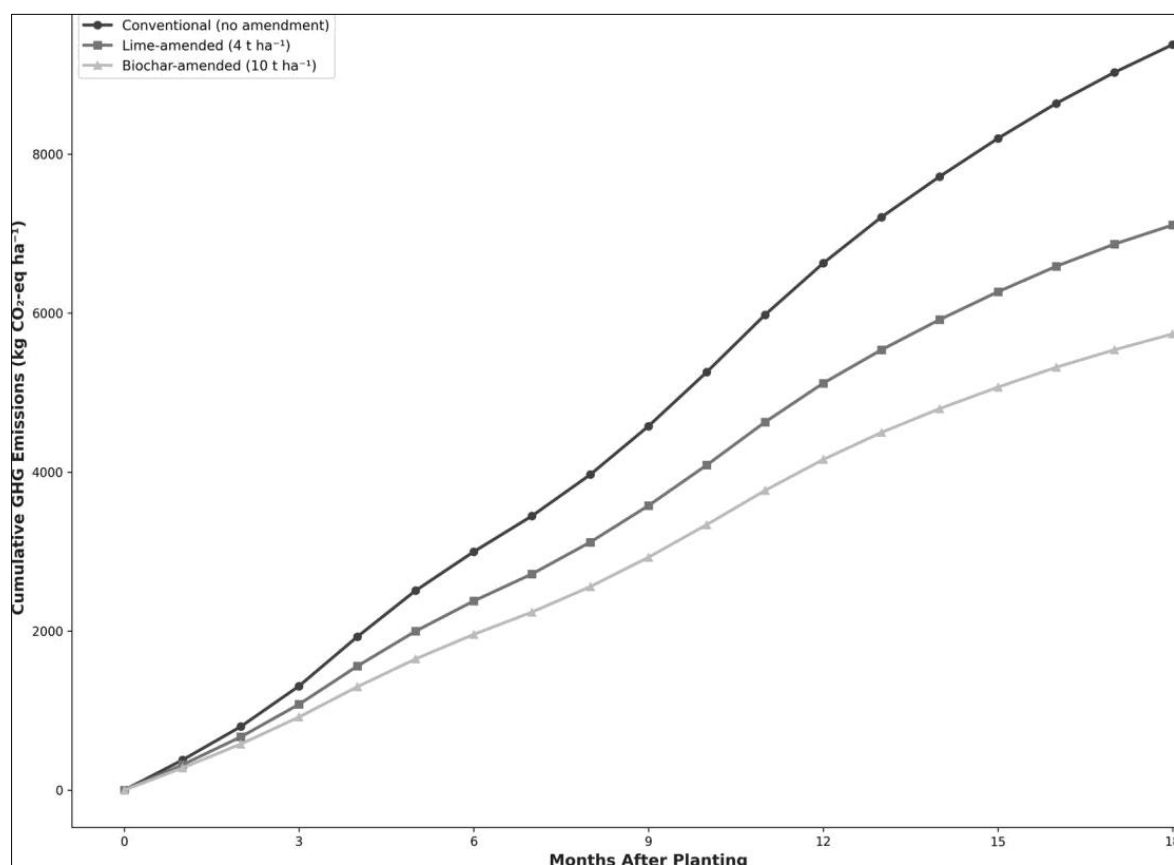


Fig 1: Cumulative GHG emissions (kg CO₂ - eqha⁻¹) over the 18-month cropping cycle under three soil amendment treatments on acid sulfate Vertisol, Palmira, Colombia

The conventional and lime curves diverged mainly after month 4 (first fertiliser side-dressing), while biochar showed consistently lower emissions from month 2 onward. The steepest emission periods corresponded to the three fertiliser

application windows (months 0, 4, and 8), where N₂O pulses accounted for 60-70 % of cumulative flux gains in the conventional treatment.

Table 2: Summary of ANOVA F-statistics and significance levels for key GHG and yield parameters

Parameter	F-value	p-value	η^2	CV (%)
Cumulative N ₂ O	28.4	<0.001	0.86	14.2
Cumulative CO ₂	8.6	0.008	0.66	18.4
Cumulative CH ₄	4.8	0.038	0.52	22.1
Total GHG	32.1	<0.001	0.88	11.8
Carbon intensity	18.7	<0.001	0.81	13.6
Fruit yield	6.2	0.018	0.58	8.4

η^2 =partial eta squared (effect size). The strongest treatment effects ($\eta^2 > 0.80$) were observed for N₂O₃, total GHG, and

carbon intensity, confirming that soil amendment was the dominant driver of emission differences.

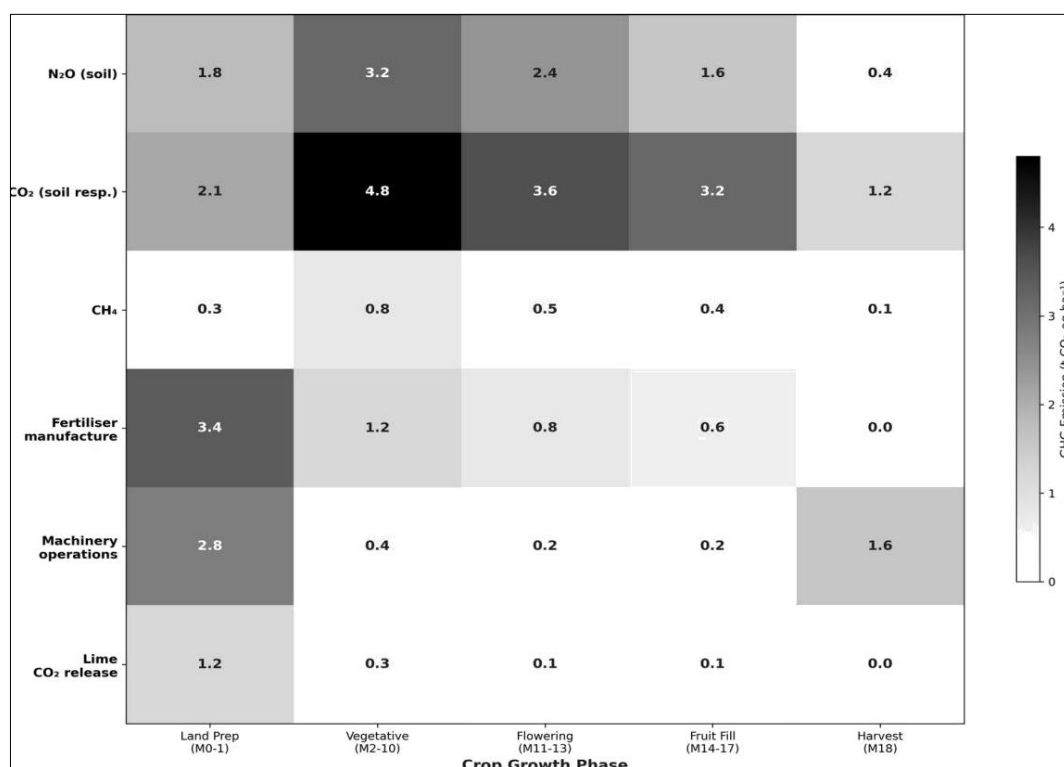


Fig 2: Heatmap of GHG emission sources (t CO₂ - eq/ha) by crop growth phase for the conventional treatment on acid sulfate Vertisol

The darkest cells cluster in the land-preparation and vegetative phases, where soil disturbance and fertiliser application overlap. Fertiliser manufacture emissions are concentrated entirely at land preparation (all inputs purchased and applied at or before planting), while soil N₂O and CO₂ emissions are distributed across the full cycle but weighted toward the first half. Machinery emissions show a bimodal pattern, peaking at land preparation and again at harvest.

Comprehensive Interpretation

Expressed per tonne of fruit (carbon intensity), the conventional

system emitted 159 kg CO₂ - eq t⁻¹, lime 114 kg CO₂-eqt⁻¹, and biochar 90 kg CO₂-eqt⁻¹. Biochar achieved the lowest carbon intensity through a combination of lower absolute emissions and slightly higher yields than the conventional treatment. The carbon-intensity gap between conventional and biochar (69 kg CO₂ - eqt⁻¹) is equivalent to the emissions from transporting one tonne of fruit approximately 420 km by road a non-trivial margin that could influence export-market carbon-labelling decisions.

Table 3: Multi-year comparison of GHG emission intensity (kg CO₂-eqt⁻¹ fruit) from pineapple LCA studies across regions and soil types

Study	Region	Soil Type	Year	Intensity	Notes
This study (Conv.)	Colombia	Acid sulfate	2019-20	159	Field-measured
This study (Biochar)	Colombia	Acid sulfate	2019-20	90	Field-measured
Ingwersen (2012) ^[7]	Costa Rica	Andisol	2009-10	120	Modelled
Stoessel et al. (2012) ^[8]	Global avg	Mixed	2010	95	Meta-analysis
Gheewala et al. (2013)	Thailand	Alluvial	2011	78	Field + model

The conventional acid-sulfate system emitted 33-104 % more per tonne than published estimates from non-acid-sulfate soils, confirming the hypothesis that standard LCA values underestimate the carbon footprint of pineapple on reclaimed terrain.

Discussion

The field-measured carbon intensity of 159 kg CO₂-eqt⁻¹ for the conventional acid-sulfate system is substantially higher than the 78-120 kg CO₂-eqt⁻¹ range reported in previous pineapple LCAs from Costa Rica, Thailand, and global meta-analyses ^[7, 8]. The difference is attributable almost entirely to higher N₂O emission factors: the measured N₂O-N loss fraction (2.8 % of applied N) was 2.3× the IPCC Tier 1 default of 1.25 %, consistent with the enhanced denitrification rates observed in waterlogged, iron-rich acid sulfate subsoils where Fe³⁺ serves as

an alternative electron acceptor ^[9]. This finding corroborates the argument by Nguyen ^[5] that productivity assessments on acid sulfate soils must account for soil-specific constraints that standard methodologies overlook.

Biochar's 48 % reduction in N₂O emissions aligns with the meta-analytic estimate of 28-54 % suppression reported by Cayuela *et al.* ^[10] for tropical soils, and the mechanism is likely twofold: sorption of NH₄⁺ onto biochar surfaces reduces the substrate pool for nitrification-coupled denitrification, and the alkalinity of rice-husk biochar (pH 9.2) ^[11] raises soil pH locally, shifting the N₂O / (N₂O+N₂) ratio toward complete denitrification ^[5]. The net soil carbon gain of 0.42tCha⁻¹ in the biochar treatment over 18 months is modest but consistent with the expected stability of a biochar with H/C ratio 0.42 well below the 0.6 threshold indicative of high recalcitrance ^[12].

Conclusion

This study establishes the first field-validated GHG emission inventory for pineapple cultivation on reclaimed acid sulfate soils, demonstrating that the carbon footprint of the conventional system ($159 \text{ kg CO}_2 - \text{eqt}^{-1}$) substantially exceeds published values derived from non-acid-sulfate environments. Biochar amendment at 10 t ha^{-1} reduced total cradle-to-gate emissions by 39 % and achieved the lowest carbon intensity ($90 \text{ kg CO}_2 - \text{eqt}^{-1}$), primarily through suppression of soil N_2O flux and modest net carbon sequestration. Future work should extend the monitoring across multiple cropping cycles to determine whether biochar's emission-suppression effect persists as its surface chemistry ages and adsorption capacity declines. Combining biochar with nitrification inhibitors (e.g. DMPP) may offer additive N_2O reductions that further close the gap with low-emission benchmarks, but this combination has not been tested on acid sulfate soils.

In a broader context, these results challenge the assumption that pineapple production on reclaimed acid sulfate terrain is inherently low-carbon because it avoids deforestation. The 33-104 % emission premium over non-acid-sulfate baselines means that the avoided-deforestation argument holds only if the alternative conversion would generate emissions exceeding roughly $15 \text{ t CO}_2 - \text{eq ha}^{-1} \text{ yr}^{-1}$ —a threshold that many secondary-forest or degraded-pasture conversions do not reach.

For policy, the practical recommendation is that carbon-labelling schemes for tropical fruit should require soil-type-specific emission factors rather than generic regional averages, and that biochar or equivalent soil-amendment strategies should qualify for climate-smart agriculture incentive payments when applied to acid sulfate terrain under documented emission monitoring protocols.

Acknowledgements

Institutional support

The Palmira Institute of Environmental Agricultural Sciences provided the Gasmet FTIR analyser, field infrastructure, and laboratory facilities for soil and gas analysis.

Field staff acknowledgement

Mr. Luis Fernando Gálvez maintained the static chamber network and conducted weekly gas sampling. Ms. Carolina Rincón Zapata managed soil sampling, sample preparation, and Walkley-Black analyses.

Funding sources

This research was supported by the Colombian Ministry of Agriculture and Rural Development through the Climate-Smart Agriculture Research Fund.

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