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Spatial analysis of human fecal waste in rural Oromia, Ethiopia: biomethane and nutrient recovery potential

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Sanitation remains a critical development and public-health challenge, particularly in rural Ethiopia, where only 7% of the population has access to safely managed sanitation. This study models the spatial distribution and resource-recovery potential of human feces in rural Oromia, integrating high-resolution population data with experimentally validated methane yields and nutrient contents. Model-based estimates suggest annual feces production of ∼2 million tonnes, corresponding to ∼27.9 PJ of biomethane energy and 7309 t N, 2206 t P, and 4511 t K—equivalent to over 2.6 billion Birr in synthetic fertilizer. Resource potential is spatially uneven, with northeastern and central highlands offering the greatest opportunities for biogas and nutrient recovery. Biogas digesters are best suited to livestock-rich highlands, urine-diverting dry toilets to peri-urban areas, and composting or container-based systems to low-income, nutrient-depleted communities. Adoption, however, is hindered by socio-cultural perceptions, financial constraints, and institutional gaps. Coordinated action across health, water-energy, agriculture, environmental protection, and infrastructure sectors—supported by strong regulation, targeted financing, community engagement, and public-private partnerships—is essential for scaling. With context-specific deployment and institutional support, resource- oriented sanitation technologies can convert human waste into a circular resource that enhances rural energy access, soil fertility, and environmental sustainability; improves public health; and advances progress toward the UN's Sustainable Development Goals.

Environmental significance

This study highlights the environmental benefits of utilizing human fecal waste in rural Oromia to produce biomethane and recover essential nutrients. By spatially analyzing waste distribution and recovery potential, it demonstrates a sustainable approach to waste management that reduces emissions of methane—a potent greenhouse gas—while promoting renewable energy production and soil health restoration through nutrient recycling. This integrated biomethane and nutrient recovery strategy supports environmental sustainability, climate change mitigation, and improved agricultural productivity in resource-limited rural communities. Such interventions contribute to the circular bioeconomy, waste reduction, and enhanced local livelihood resilience. This study highlights the key environmental advantages of biomethane production and nutrient recovery from waste, informed by recent understanding of their role in renewable energy, greenhouse gas mitigation, and soil fertility improvement.

Introduction

Sanitation remains one of the most critical global development and public-health challenges. Around 4.2 billion people worldwide rely on on-site sanitation systems, many of which lack effective containment, treatment, and resource recovery, resulting in significant health risks, environmental pollution, and missed opportunities for energy and nutrient recovery.[1]

Ethiopia's reduction in open defecation — from 82% to 29% during the Millennium Development Goal period — represents one of the largest declines globally. However, only 7% of households currently have access to safely managed sanitation services, while 70–80% rely on unimproved latrines or basic pit systems.[2–4] These systems often fail to safely isolate, treat, or dispose of fecal waste, leading to environmental contamination and high burdens of diarrheal and sanitation-related diseases.[2,5–8]

The sanitation crisis is especially pronounced in rural Ethiopia, where 77.5% of the population resides.[9] Rural communities face intertwined challenges: inadequate sanitation infrastructure, energy poverty, and low agricultural productivity.[10,11] Residential cooking accounts for about 80% of total energy consumption, dominated by biomass fuels that produce hazardous indoor air pollution. Children in

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households using biomass fuels are 2.6–3.89 times more likely to suffer acute respiratory infections, while women experience anemia, respiratory symptoms, and reduced lung function.[12–17]

Rural Oromia, Ethiopia's largest region, has large household sizes and high fertility rates,[18–21] generating significant quantities of human waste — a resource that remains largely underutilized.[22–24] Biogas systems could address both sanitation and energy deficits, yet only 0.3% of households have access to biogas, and 60% of these systems are non-functional due to technical limitations, lack of maintenance, and institutional gaps.[25–28] Where adopted, biogas reduces firewood use by 45% and charcoal use by 50.9%.[29,30]

Recent experimental research has strengthened the evidence base for fecal-to-energy conversions. A laboratory study found that fresh human feces yields around 0.39 m^3 CH_4 per kg of fresh matter (14.16 MJ kg^{-1}), equivalent to approximately 28.71 m^3 of methane per person per year.[22] Human feces show higher energy content than wood biomass and are comparable to wood biochar or bituminous coal.[153–155] Complementary technical research on anaerobic membrane-based treatment and thickening of fecal sludge demonstrates practical pathways to improve feedstock quality and digestion performance, which can increase biogas yields and enable more compact treatment systems suitable for peri-rural deployment.[31,32] Additional studies demonstrate significant nutrient content (N, P, K) in digested feces, reinforcing the potential for bio-fertilizer production.[33–37]

Ethiopian soils suffer from severe nutrient depletion — 122 kg N, 13 kg P, and 82 kg K per hectare annually — while over 37% of children are stunted due to malnutrition.[156,157] Resource-oriented toilet systems (ROTS) thus offer a dual solution for sanitation, energy and soil fertility.[38–41] However, adoption remains low due to cost, lack of demand, cultural attitudes, leadership gaps, and limited space.[38,42] Despite 40% of households expressing interest in ROTS, only 7% show readiness and willingness to pay for adoption.[39]

Current sanitation practices also have climate implications. Methane and nitrous oxide emissions from non-sewered systems represent a significant share of sanitation-sector greenhouse gases.[43,44] Container-based sanitation in Nairobi produces 15.72 kg CO_2-eq per-capita annually,[45] while emissions from sanitation chains in Kampala may constitute more than half of city-level emissions.[46] Non-sewered sanitation systems globally contribute an estimated 4.7% of anthropogenic methane emissions.[43] Off-site composting can reduce sanitation methane emissions by 13–44%.[47] Comparative studies of fecal sludge management demonstrate the importance of integrating diagnostics, treatment selection, and disposal planning to limit environmental releases and public health threats while enabling resource recovery.[32,48–51]

Despite growing evidence, substantial knowledge gaps remain regarding the spatial distribution, quantity, and resource-recovery potential of fecal waste in rural Oromia. Previous studies have not integrated high-resolution population data, experimental methane yields, and nutrient content data that reflect local diets.[52–54] GIS and remote sensing have been proven effective for identifying optimal waste-management sites and improving sanitation planning in rural contexts.[52–55]

This study addresses this critical gap by conducting a high-resolution spatial analysis of fecal waste generation and resource-recovery potential in rural Oromia. By integrating population data with experimentally validated biomethane yields and nutrient contents, the study identifies hotspots with the greatest potential for communal biogas systems and targeted bio-fertilizer application. The findings offer evidence for policy-makers and development practitioners to transform waste from an environmental liability into an energy and agricultural resource, contributing to circular sanitation, climate mitigation, energy access, and sustainable agriculture goals simultaneously.

Methods

Study area and context

The Oromia region—Ethiopia's largest and most populous state—provides diverse environmental conditions that make spatially targeted resource-recovery planning essential. The quantity and quality of human feces, and thus its biomethane and nutrient recovery potential, vary with socioeconomic, dietary, geographic, and climatic factors. Rural diets dominated by high-fiber, low-protein staples such as teff, maize, and legumes generate high fecal volume but lower methane yield and nitrogen content.[25,26] Socioeconomic constraints—including poverty affecting over 24% of residents and limited access to improved sanitation and clean energy—underscore the need for integrated waste-to-energy strategies.[56,57] Oromia's climatic gradient, from cool highlands to arid lowlands, influences decomposition rates and biogas feasibility, with warmer zones offering more favorable anaerobic digestion conditions. Given that up to 80% of rural Ethiopian households rely on biomass fuels for cooking, expanding biogas systems is an urgent priority.[12,58]

Study design and data sources

This study applies a spatial variability analysis to estimate the potential for nutrient recovery (nitrogen, phosphorus, and potassium) and biomethane production from human feces in Ethiopia's Oromia region. Using a geographic information system (GIS), we integrate multiple datasets to map the distribution of human waste and its suitability for bio-fertilizer and biogas production.

The feces production estimate of 73 kg per person per year is grounded in global physiological ranges (0.15–0.4 kg per day);[59] Ethiopia's high-fiber, plant-based diets—dominated by cereals, legumes, and enset—which increase fecal bulk;[60] and regional research recommending 70–75 kg per year for rural populations.[24,61,62] Regional validation from sub-Saharan Africa (65–80 kg per year) further validate this value.[59,63–67] The 73 kg per year figure offers a conservative and context-appropriate basis for resource-recovery planning and aligns with global guidance on safe fecal waste management.[24,68–70]

Biomethane and nutrient recovery estimates explicitly distinguish nutrient concentrations from total annual per-capita yields. The selected methane yield of 28.71 m^3 CH_4 per person per year is derived from experimental anaerobic digestion of feces from rural Ethiopian households[22] and falls within the 23–30 m^3 per person per year range reported in earlier studies.[25,71] A broader *meta*-analysis of methane yields from non-sewered sanitation systems[43] similarly shows mean values clustering around 28 m^3 per person per year when conservative excreta production estimates (12 g TS per person per day) are applied. The methane yield and nutrient content values used here rely on experimentally validated measurements, ensuring realistic projections for fecal-based resource recovery. Selecting 28.71 m^3 per person per year avoids optimistic overestimation while remaining consistent with local fecal production rates and volatile solids content, providing a robust foundation for fecal sludge management and biogas planning (see Table 1).

In contrast, a study[86] reported a combined theoretical energy potential of 8568 GJ per year from food waste and human excreta at Jimma University, without isolating methane yields specifically from feces. The estimates were based on aggregated institutional waste streams, making them less directly comparable to rural household conditions. For nutrient recovery, Donacho *et al.*[22] measured per-kilogram concentrations of 3.71 g N, 1.12 g P, and 2.29 g K, whereas Tucho and Okoth[86] reported the annual per-capita totals of 4 kg N, 0.6 kg P, and 0.96 kg K. These differences reflect distinct methodological approaches: Donacho *et al.* quantified nutrient content per unit mass of feces, while Tucho and Okoth derive aggregated yearly outputs from a controlled institutional setting characterized by consistent diets and high excreta collection efficiency.

To provide realistic estimates for decentralized rural environments, this study adopts a methane potential of 28.71 m^3 per person per year and uses experimentally measured nutrient concentrations (g kg^{-1}) converted to annual totals (t per year). Monetary valuation of recoverable nutrients was performed by converting modeled N, P, and K quantities into equivalent amounts of urea, DAP, and muriate of potash using standard nutrient content factors, and applying average import prices of approximately 536 USD/tonne (urea), 702 USD/tonne (DAP), and 443 USD/tonne (potash).[87,88]

To estimate the rural population of Oromia's districts (*woredas*), highly disaggregated population data were integrated into a GIS. Total population grids were combined with a settlement typology to distinguish rural from urban areas. Two datasets were used:

(I) GHS-POP R2023A — Multitemporal Global Population Grid:[89]

Scope and resolution: Global population estimates (1975–2030) at 100 m resolution.

Method: Census counts are dasymetrically redistributed using built-up extents from Sentinel-2, Landsat, and elevation data, yielding standardized 100 m raster estimates of population per cell, see 90.

(II) GHS-SMOD R2023A —Degree of Urbanisation Classification:[91]

Scope and resolution: Global settlement typology (urban centres, clusters, rural areas) at 1 km resolution.

Method: Combines GHS-POP density with built-up surfaces from Sentinel-2 and Landsat to implement UN Stage I DoU criteria, see 90.

The Global Administrative Areas dataset (GADM, 2022) supported spatial aggregation and cartographic outputs. Data acquisition and raster processing were conducted in Google Earth Engine (GEE), with final analyses and mapping completed in QGIS 3.40.

Geospatial analysis for rural population identification

GHS-POP and GHS-SMOD grids for Oromia (reference year 2020) were accessed in GEE. Rural populations were isolated by masking out the following urban areas: GHS-SMOD classes 30 (Urban Centre), 23 (Dense Urban Cluster), and 22 (Semi-Dense Urban Cluster) were reclassified to 0, while all other classes

Table 1 Literature data from 14 studies on anaerobic digestion with human feces as substrate[a]

SN	Studies	TS (g L^{-1})	VS (g L^{-1})	VS/TS (%)	MP (L/gVS)	W	Constant (K)	CH_4 density at STP (kg m^{-3})	CH_4 yield (kg per year)	CH_4 yield (m^3 per year)
1	72	15.5	10.1	0.652	0.122	12	7300	0.716	7	10
2	73	NR	4.5	—	0.124	12	7300	0.716	—	—
3	74	3.45	2.85	0.826	0.16	12	7300	0.716	12	16
4	75	219.5	179	0.815	0.177	12	7300	0.716	13	18
5	76	4.5	2.83	0.629	0.22	12	7300	0.716	12	17
6	77	67	52.6	0.785	0.243	12	7300	0.716	17	23
7	78	245	201	0.820	0.271	12	7300	0.716	19	27
8	79	12	8.54	0.712	0.299	12	7300	0.716	19	26
9	80	145.6	128	0.879	0.327	12	7300	0.716	25	35
10	81	67.1	55.3	0.824	0.36	12	7300	0.716	26	36
11	82	47.94	35.48	0.740	0.402	12	7300	0.716	26	36
12	83	3.2	2.6	0.813	0.449	12	7300	0.716	32	45
13	84	150	130.5	0.870	0.471	12	7300	0.716	36	50
14	85	4.4	3.8	0.864	0.3	12	7300	0.716	23	32
	Pooled mean	—	—	—	—	—	—	—	—	28

[a] Notes: 1 TS = total solids, VS = volatile solids, MP = methane potential, W = daily fecal solid production, 2 W (12 g TS per person per day) represents a low-end conservative estimate of fecal solid production, appropriate for rural or low-income settings with lower dietary protein/energy intake. 3 Constant (K = 7300) converts daily volatile solids and methane production to annual methane emissions (grams per year), encapsulating chemical conversion and unit scaling. 4 CH_4 density at STP = 0.716 kg m^{-3}. 5 “NR” = Not reported; “–” indicates data unavailable or not applicable.

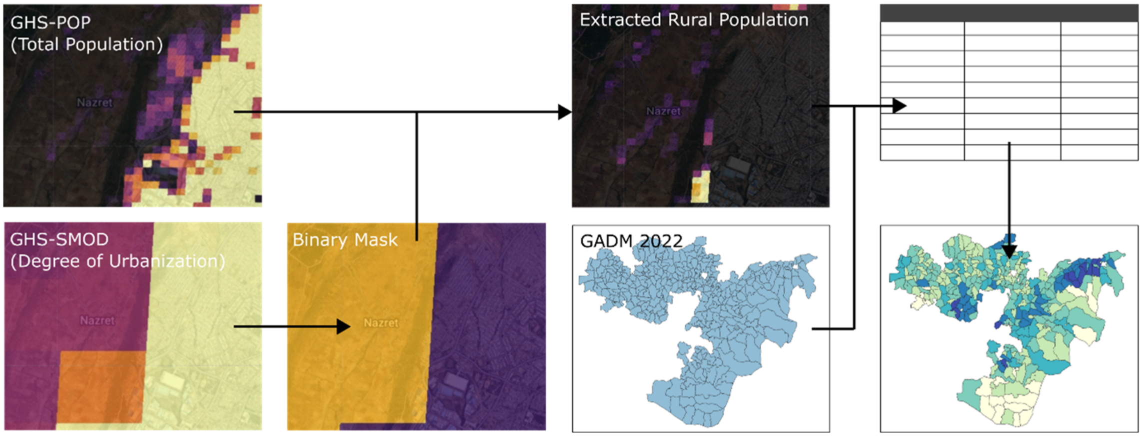

Fig. 1 Flowchart illustrating the geospatial analysis of fecal production in rural communities of Oromia, Ethiopia, based on spatially explicit demographic raster data, urbanization classification, and zonal statistics at the district (woreda) level, 2025.

were set to 1. Multiplying this binary mask with GHS-POP removed urban populations and preserved rural cells.

Non-zero pixel values were then aggregated using Reducer.sum with the GADM 2022 boundaries as the reference geometry. The resulting woreda-level rural population estimates were exported as tables and further analyzed in Excel to compute feces production as well as methane and nutrient recovery potentials. Quality control was performed by comparing derived figures with available local census data; see Fig. 1.

Data processing and mapping

All calculations of total feces production, biomethane yield, and nutrient recovery were performed in Microsoft Excel using rural population estimates from GHS-POP 2023A and GHS-SMOD 2023A, combined with per-capita feces production (73 kg per person per year) and experimentally derived values for methane (28.71 m^3 CH_4 per person per year) and nutrients 3.71 g N kg^{-1} (0.27 t per year), 1.12 g P kg^{-1} (0.082 t per year), and 2.29 g K kg^{-1} (0.167 t per year) per person.[22]

Results were mapped in QGIS 3.40 using Oromia's georeferenced administrative boundaries. Raster analysis and binary classification isolated rural populations, while thematic maps employed inverse distance weighting (IDW) interpolation to visualize spatial gradients in feces production, biomethane yield, and nutrient recovery.

Hotspot areas were overlaid with Köppen–Geiger climate zones, 1991–2020,[92] poverty prevalence using the Relative Wealth Index,[93] and agriculture typology based on the FAO Agricultural Typology dataset[94] to assess the practical applicability of ROTS technologies. Soil nutrient potential was integrated using the Africa SoilGrids Nutrient Clusters dataset at 30 m resolution.[95] Data were reprojected to EPSG:4326 and clipped to the Oromia boundary for alignment across layers. Model reliability was verified using out-of-bag accuracy (∼65%) and visual assessment of cluster separation.

The final suitability map combined wealth, agriculture, climate, soil, and road-proximity layers in a GIS-based overlay model. Nested conditional statements and slope-based masking ensured geotechnical feasibility. Outputs were classified, symbolized, and polygonized to inform planning, stakeholder engagement, and decision-making for targeted biogas and bio-fertilizer interventions. These spatial analyses provide a robust evidence base linking biophysical resource potential to practical implementation strategies, supporting SDG-aligned sanitation and energy planning in Oromia.

Results

Overview of spatial distribution

A GIS-based spatial analysis was conducted to evaluate human fecal resource generation and its potential for nutrient recovery and biogas production across Oromia. Administrative units were mapped for five key variables: human feces (kt per year), biomethane (Bio-CH_4, million m^3 per year), nitrogen (t per year), phosphorus (t per year), and potassium (t per year). Consistent color scales facilitated direct spatial comparisons and highlighted regional heterogeneity.

Resource distribution is highly uneven. High-value clusters occur primarily in northeastern, central, and southwestern districts, corresponding to areas of higher rural population density, while southern, northern, eastern, and some south-western districts show lower values for all variables. These spatial patterns, clearly visualized in classification maps, provide critical guidance for identifying hotspots and low-potential zones, enabling targeted interventions in resource recovery and decentralized biogas and bio-fertilizer planning.

Population estimate

Oromia's rural population is estimated at 27 million, representing 61% of the region's total population. The highest rural population is found in the East Hararghe zone (3.36 million), while the Borena zone has the lowest (364 846). This demographic variation is a primary driver of the spatial patterns observed in resource generation; see Fig. 2.

Human feces production

The analysis revealed that rural areas in the Oromia region of Ethiopia generate approximately 2 million tonnes of human feces

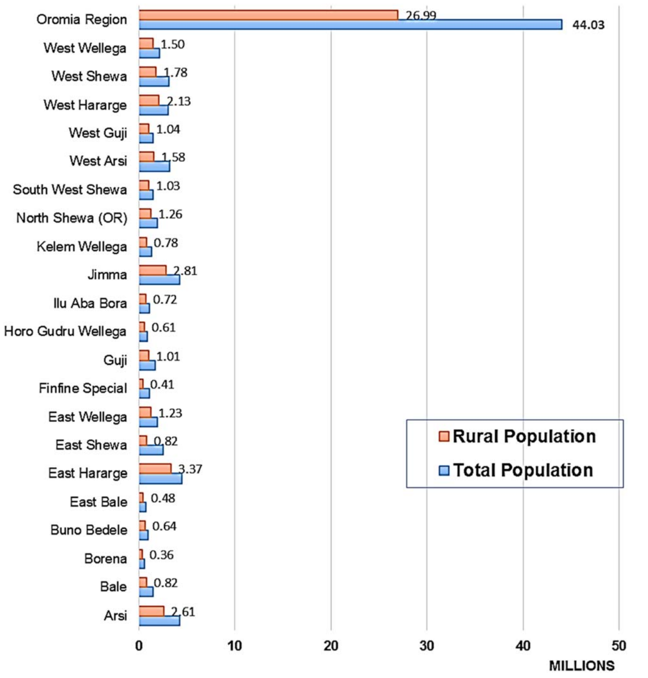

Fig. 2 Total population *versus* rural population of the Oromia region as derived from geospatial analysis based on population raster data (GHS-POP 2023A) and raster data on the degree of urbanization (GHS-SMOD 2023A) *via* Google Earth Engine, 2025.

annually. The spatial analysis highlights marked disparities across the region, with the lowest production class (≤2 kt per year) predominantly observed in the southern and southwestern parts of the study area; several contiguous administrative units fall into this category. Intermediate production classes (2–4.8, 4.8–10.7, and 10.7–15.4 kt per year) were distributed throughout the central and western regions. The highest production class (15.4–24.9 kt per year) was concentrated in the northeastern administrative units, forming a distinct cluster. Notably, the maximum value class (≤24.9 kt per year) was observed in several adjacent units in the northeast, indicating a regional hotspot for fecal resource generation; see Map A.

Biogas methane (Bio-CH_4) potential

Annual human feces production translates to an estimated 775 million cubic meters of methane per year. With an energy conversion factor of 36 MJ per cubic meter, this equates to an energy potential of approximately 27.89 petajoules per year—enough to meet a substantial share of rural household cooking energy demands if properly harnessed. Human feces production exhibited marked spatial variability across the administrative units.

The spatial pattern of biogas methane potential closely mirrored that of human feces production, as expected due to the direct relationship between the two variables. The lowest class (≤0.8 million m^3 per year) was found mainly in the southern and southwestern administrative units. The highest class (≤9.8 million m^3 per year) was concentrated in the northeastern region, overlapping with the areas of highest fecal production. Intermediate classes were dispersed throughout the central and western portions of the study area; see Map A (Fig. 3).

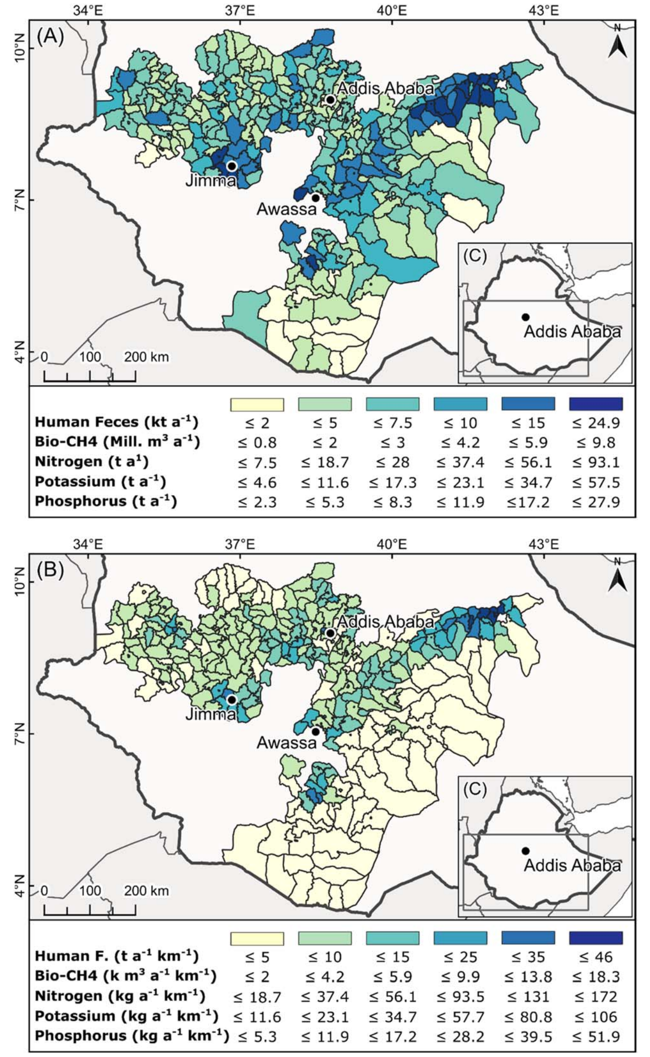

Fig. 3 Spatial distribution of annual human faecal production, biogas potential, and nutrient recovery: (map A) absolute figures per district (Woreda); (map B) values normalized by km^{2-} (map C) overview map indicating the spatial extent of maps A and B, 2025.

Nutrient content distribution (nitrogen, phosphorus, and potassium—NPK)

The total annual recoveries for the region are estimated at 7309 tonnes of nitrogen, 2206 tonnes of phosphorus, and 4511 tonnes of potassium. These quantities are significant given Ethiopia's reliance on imported synthetic fertilizers, highlighting the potential for locally sourced, circular nutrient solutions.

From a nutrient recovery perspective, the analysis estimates annual recoveries of 7309 tonnes of nitrogen (N), 2206 tonnes of phosphorus (P), and 4511 tonnes of potassium (K). These quantities are significant in the context of Ethiopia's reliance on imported synthetic fertilizers, suggesting that treated fecal waste could provide a locally available, circular alternative to improve soil fertility and support smallholder agriculture.

Nitrogen recovery from human fecal resources ranges from ≤7.5 t per year to ≤93.1 t per year across administrative units. The lowest values are prevalent in the southern and southwestern regions, while the highest class is observed in the northeast, forming a contiguous high-value zone. The highest nitrogen recovery (>57 t per year) is localized in unit 4300; see Map A.

Phosphorus recovery ranges from ≤2.3 t per year to ≤27.9 t per year. The lowest class is mainly found in the southern and southwestern units, while the highest class is concentrated in the northeast. Phosphorus mirrors potassium distribution, peaking in central zones but dropping sharply in peripheral districts; see Map A.

Potassium content varies from ≤4.6 t per year to ≤57.5 t per year, following the same general spatial pattern as nitrogen. The lowest values are in the southern and southwestern units, with peak values (>35.2 t per year) in central units (3900–4100); see Map A.

Regional patterns, clustering, and spatial gradients

A spatial gradient refers to a consistent geographic pattern in the distribution of a variable across space—in this case, the gradual increase in fecal waste, biomethane potential, and nutrient recovery from the northern to southern districts of Oromia. This gradient was identified through spatial interpolation and classification mapping in QGIS, based on district-level data derived from rural population density and experimentally validated yield estimates.

A consistent spatial clustering of high values for all variables is observed in the northeastern part of Oromia, corresponding to administrative units with higher population densities. The southwestern and central regions also emerge as high-potential zones, particularly for fecal production and methane generation. The analysis reveals a clear north-to-south escalation across all parameters: fecal production rises from less than 4.8 kt per year in the northern units (3500–3700) to more than 15.4 kt per year in the southern districts (4100–4300). Similarly, bio-CH_4 potential increases from under 1.87 million m^3 per year in the north to over 6.05 million m^3 per year in the southwest. Nutrient recovery (N, P, K) follows the same trend, increasing by factors of 5 to 12 between low-output and high-output zones.

The southwestern and central regions (units 3900–4300) account for over 75% of the highest value thresholds, primarily due to high rural population concentrations. In contrast, the northern and eastern districts (units 3500–3700) consistently fall below key resource thresholds.

Spatial analysis reveals six tiers of resource density per km^2, with highest-yield zones concentrating ≤46 t feces, ≤18 300 m^3 biomethane, and nutrient fluxes up to 0.17 t N, 0.11 t K, and 0.05 t P annually; see Map B.

Discussion

Biomethane potential and energy implication

Our model estimates that rural Oromia generates over 2 million tonnes of human feces annually, potentially yielding approximately 27.89 PJ of methane energy—a substantial yet underutilized opportunity to reduce reliance on traditional biomass fuels, which are a major contributor to indoor air pollution and respiratory diseases in Ethiopia.[12,17,25] This aligns with findings from other regions, where fresh fecal sludge can produce 234–627 mL CH_4/g VS when digested promptly,[96,97] though delayed emptying and weak sanitation services, as observed in Pakistan, reduce energy and nutrient recovery.[98] Despite this potential, only ∼0.3% of Ethiopian households currently use biogas systems, and over 60% of these are non-functional due to technical failures and poor maintenance.[26,39]

Household biogas in Oromia could be financially attractive if implemented properly. Similar studies also show that biogas digesters yield positive returns, especially when nutrient savings from bioslurry are considered.[99,100] Programs such as the Africa Biogas Partnership Program (ABPP) have demonstrated reduced fuel consumption, improved crop yields, and health benefits.[101] Nevertheless, widespread adoption is constrained by high upfront costs, limited credit access, and maintenance challenges.[101,102] Successful deployment requires building technical capacity, education, and local supply chains.[102–104]

Given limitations such as low livestock ownership and land scarcity in parts of Oromia,[25,105] Resource-oriented toilet systems (ROTS) provide a practical alternative for sustainable sanitation and energy production. Human feces have demonstrated significant biogas potential under these systems,[22] reducing firewood and charcoal consumption.[29] Integration of human and livestock waste in mixed farming systems can further enhance methane yields and nutrient recovery, potentially decreasing dependence on mineral fertilizers. Socioeconomic factors influence adoption and management practices, underscoring the need for context-specific implementation strategies.[33]

Agricultural value and nutrient recovery

According to our model, the reuse of treated human feces in Oromia could supply approximately 7309 t N, 2206 t P, and 4511 t K annually, equivalent to over 2.6 billion Birr in synthetic fertilizer imports. Globally, studies demonstrate the agronomic benefits of treated fecal sludge and composted human waste, including improved crop yields for leafy vegetables, maize, soybean, and other crops.[106–111] Economic assessments indicate that including nutrient recovery substantially enhances returns, with IRRs exceeding 50% in some contexts.[63,100,112,113]

Safe recovery is essential due to public health risks from pathogens such as *Escherichia coli* and *Ascaris* spp. Effective treatment methods include thermophilic composting, solar drying, urea stabilization, urine diversion, fecal separation, co-digestion with agricultural residues, and extended storage, all of which reduce pathogen loads and preserve nutrient content.[114–122] Context-specific, decentralized solutions are critical where centralized treatment is unavailable.

Psychosocial, socioeconomic and institutional constraints

Despite technological feasibility, the adoption of ecological sanitation and biogas systems in rural Ethiopia faces significant cultural, behavioral, and institutional barriers. Over 70% of households in rural Oromia view human waste reuse as culturally unacceptable.[39] Adoption is shaped by attitudes, subjective norms, perceived behavioral control, and technology compatibility, as explained by the theory of planned behavior[123] and the diffusion of innovation model.[124,125] Other barriers include construction costs, limited awareness, low household income, land scarcity, livestock ownership, and infrastructure constraints.[26,38,39,42,100,124,126–130]

Institutional and technical challenges further limit adoption. Inadequate training, supply chain gaps, and insufficient maintenance services reduce functionality, with programs like Ethiopia's National Biogas Programme achieving only ∼50% of targets.[27,28,131] Addressing these constraints requires integrated, multi-level interventions, including financial incentives, microfinance, hands-on training, culturally tailored education, and private-sector engagement to support safe, efficient, and economically viable resource recovery.[39,42,132–139]

Collectively, these insights highlight the potential of treated human waste to enhance soil fertility, support sustainable agriculture, and provide energy, while emphasizing that socio-cultural and institutional factors must be addressed to realize the full benefits of ecological sanitation in Oromia.

Resource-oriented sanitation technology suitability in Oromia

The spatially integrated overlay in Fig. 5 is based on the wealth index, climate zones, agricultural typologies, and soil nutrient clusters from Fig. 4 across Oromia, and reveals distinct regional entry points for deploying resource-oriented sanitation technologies (ROST) that align with ecological capacity and agricultural demand while remaining socio-economically viable.

This approach quantifies potential biomethane and nutrient recovery while accounting for settlement morphology, population density, and ecological capacity.

High-wealth zones, predominantly in central and western mixed farming highlands, exhibit strong feasibility for household- and community-scale biogas systems. These areas coincide with livestock-dense agricultural typologies, stable climates favorable for anaerobic digestion (tropical monsoon to warm-temperate), and nutrient-rich soil clusters (C1, C11, C16, C20). Resilient soils, including Nitisols and Andisols, can safely receive digestate, enabling integrated waste treatment and enhanced soil fertility.[37,140–142]

Peri-urban and upper-middle wealth belts, intersecting moderate-to-high agricultural opportunity zones with partial aridity and moderately receptive soils (C3, C4, C5, C14, C17, C19), are suited for decentralized urine-diverting dry toilets (UDDTs). These systems produce concentrated nitrogen–

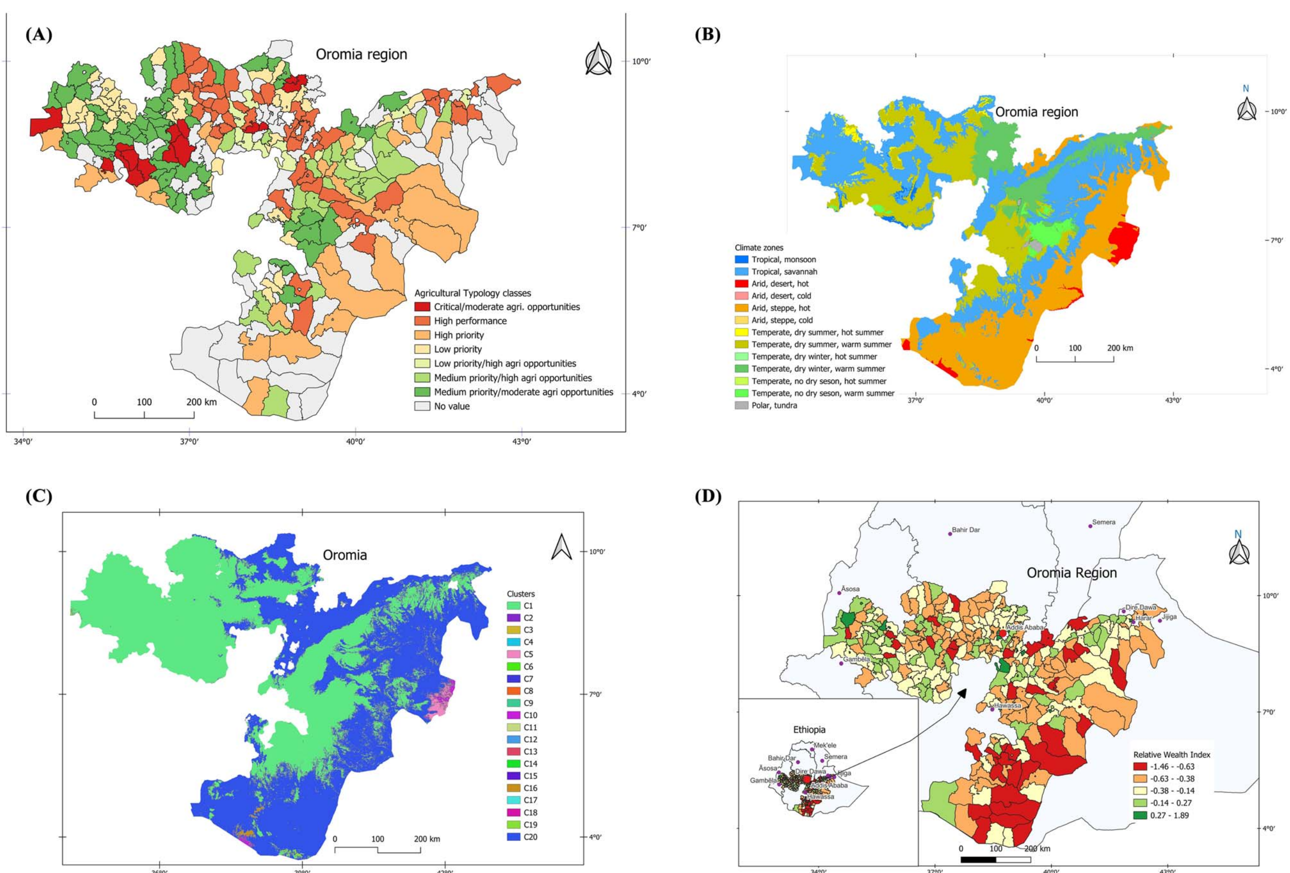

Fig. 4 (A) Agricultural typology map of Oromia (low to high land use), demonstrating spatial variation in crop–livestock intensity and demand for recovered fertilizer inputs based on the FAO Agricultural Typology Dataset.[94]. (B) Climate classification zones of Oromia, representing the biophysical constraints from tropical monsoon to arid steppe belts that inform water-independent *versus* anaerobic digestion suitability, based on the Köppen–Geiger data set.[92]. (C) Soil nutrient-cluster typology of Oromia (band 1, class 1–20), mapping soil organic matter and plant-available NPK receptivity clusters that govern digestate absorption thresholds and urine-fertilizer targeting potential based on the Africa-wide SoilGrids Nutrient Clusters dataset.[95]. (D) Relative Wealth Index spatial distribution across Oromia, showing household investment feasibility gradients derived from the rasterized wealth index surface based on Chi *et al.*'s dataset.[93]

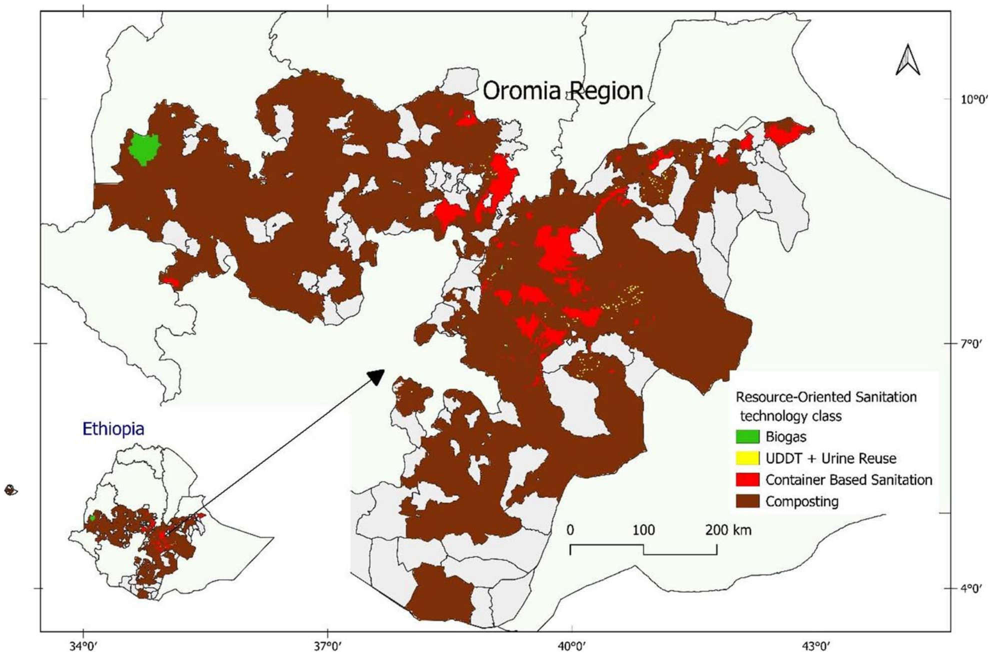

Fig. 5 Final resource-oriented sanitation technology (ROST) targeting map resulting from the 4-layer GIS overlay (wealth + agriculture + climate + soil nutrient clusters), classifying Oromia into discrete reuse-aligned infrastructure zones: Biogas-enabled digesters (green gradient), nitrogen-deficit UDDT urine routes (yellow gradient), road-aligned container-based sanitation corridors (red gradient), and biomass-supported composting belts (brown gradient), 2025.

phosphorus streams that can be applied to cropland in controlled doses without overloading water-limited soils.[143–145]

The poorest, remote, and nutrient-depleted zones (C8, C12, C13) with steep slopes and low agricultural priority are suitable only for light-infrastructure sanitation, such as simplified UDDTs or subsidized CBS networks, with nutrient reuse limited to household gardens, tree pits, or micro-plots. Across all zones, ROST deployment must align sanitation technology with household affordability and ecological nutrient thresholds to maximize recovery while ensuring environmental safety.[1]

Spatial targeting and policy recommendations

Recent GIS-based analyses underscore the resource recovery potential of human waste for biomethane production and nutrient recycling. Globally, human excreta could supply up to 22% of phosphorus demand,[146] while experimental studies in Ethiopia report biomethane yields of 0.393 m^3 kg^{-1} and substantial nitrogen, phosphorus, and potassium content in feces,[22] highlighting its dual role as bioenergy feedstock and organic fertilizer. Complementary global studies demonstrate hotspots of nutrient depletion and accumulation[147] and identify spatial constraints on biomethane and heat production from biomass, emphasizing the feasibility of localized energy recovery near population centers.[148]

Applying these insights to Oromia, high-potential districts emerge where population density, fecal biomass availability, and nutrient output converge, offering strategic targets for pilot circular sanitation projects. Faecal sludge reuse in agriculture presents opportunities for waste management and soil fertility enhancement but requires addressing financial viability, health risks, and cultural perceptions.[149–152]

Effective deployment of circular sanitation and resource-recovery systems in Ethiopia requires coordinated, sector-wide action anchored in clear institutional mandates, strong regulatory frameworks, and integrated planning across ministries. The Ministry of Health should enforce multi-barrier treatment standards for all fecal waste while leading national behavior change campaigns through the Health Extension Program to address cultural resistance to reuse. The Ministry of Water and Energy must integrate waste-to-energy solutions into the national energy strategy, issue technical guidelines for digesters, and expand rural renewable energy programs to include biogas for household and productive uses. The Ministry of Agriculture should formally recognize treated human waste as an approved organic fertilizer, develop nutrient-application guidelines tailored to soil clusters and crop systems, and build the capacity of development agents to promote safe reuse within climate-smart agriculture programs. The Ethiopian Environmental Protection Authority must establish and enforce environmental and public-health regulations governing treatment plants, effluent quality, and nutrient runoff while linking methane-emission reductions to Ethiopia's climate commitments. The Ministry of Urban and Infrastructure needs to strategically plan and allocate land for treatment facilities, integrate container-based sanitation into dense settlements, and standardize designs for decentralized systems in small towns. The Ministry of Finance should create financing mechanisms—including subsidies, tax incentives, and microfinance instruments—to support households, cooperatives, and private actors investing in biogas and resource-recovery technologies. The Ministry of Education and the TVET system must incorporate ecological sanitation, composting, and biogas technical training into curricula to build a skilled workforce, while universities expand research on pathogen removal, digester performance, and nutrient recovery. The Ministry of Industry and SME development agencies should strengthen domestic manufacturing of biogas components, UDDT parts, and CBS equipment and establish quality standards to ensure durable products. Climate and disaster management institutions must prioritize waterless sanitation and biogas systems in drought-prone regions to strengthen resilience and reduce dependence on firewood and imported fertilizers. Regional governments, woredas, and kebeles should use GIS-based targeting to identify suitable zones for specific technologies, mobilize communities, enforce construction standards, and ensure the safe transport and end-use of treated products. Private-sector operators and PPP models are essential for scaling fecal sludge collection, transport, treatment, and nutrient recovery businesses, while civil society organizations play a critical role in community engagement, training, and inclusion of marginalized groups. Collectively, these coordinated actions—supported by cross-sectoral collaboration, regulatory alignment, financing mechanisms, and strong supply chains—are essential for transforming human waste from an environmental liability into a driver of energy security, soil fertility, and sustainable rural development in Ethiopia. These measures can simultaneously improve rural sanitation, energy security, soil fertility, and climate resilience. By adapting best practices to local conditions, Oromia can transform human waste into a vital resource for sustainable development.

Limitations

Reported biomethane and nutrient recovery values are model-derived estimates based on spatially explicit population data and laboratory yields, not direct field measurements. They should be interpreted as indicative potential for planning and prioritization rather than actual recovered resources. A formal sensitivity analysis was not conducted, although laboratory measurements provide a reliable baseline.

Conclusion

Human waste in rural Oromia represents a significant underutilized resource for sustainable energy and agriculture. Our model estimates that over 2 million tonnes of feces could yield ~27.9 PJ of biomethane and supply substantial nitrogen, phosphorus, and potassium—equivalent to over 2.6 billion Birr in synthetic fertilizer. Spatial analysis identifies region-specific opportunities: biogas digesters in livestock-rich highlands, UDDTs in peri-urban zones, and simplified composting or container-based sanitation in low-income, nutrient-depleted areas.

Realizing this potential requires addressing cultural, financial, and institutional barriers through capacity building, tailored education, financial incentives, and cross-sectoral coordination. Safe, context-specific deployment of resource-oriented sanitation technologies can enhance rural energy security, soil fertility, and environmental sustainability, transforming human waste into a vital component of circular sanitation and sustainable development.

Estimates are model-based and intended for planning and prioritization rather than direct field measurement.

Author contributions

T. A. A., S. S., and G. T. T. contributed equally to the conception, the detailed spatial analysis output, and replication of the study's conclusions, which depends on access to the final aggregated woreda-level output table (containing population, feces, methane, and N, P, K totals). All authors read, reviewed, and approved the final version.

Conflicts of interest

The authors declare that they have no competing interests.

Data availability

The dataset supporting the findings of this study is publicly available in Zenodo at https://doi.org/10.5281/zenodo.17292356.

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