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Farmers' Practices and Perceptions of Ruminant Urine Use as an Organic Fertilizer for Sunflower Production in Mixed Crop Livestock Systems

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Abstract: Sustainable nutrient management in smallholder farming systems requires low-cost, locally available fertilizers to enhance crop productivity while maintaining ecological balance. Sunflower production in mixed livestock-crop systems in Tanzania faces challenges related to high input costs and limited awareness of organic alternatives. This study assessed farmers' practices and perceptions regarding the use of ruminant urine as a fertilizer for sunflower. A cross-sectional survey was conducted in September to November 2025 across four villages in Morogoro, involving 311 purposively selected farmers engaged in organic sunflower cultivation. Quantitative data were collected using structured questionnaires and analyzed with descriptive statistics, chi-square tests, Cramer's V, and binary logistic regression to identify determinants of adoption. Qualitative data from focus group discussions and key informant interviews were analyzed thematically to interpret local knowledge and socio-cultural influences. Results indicated that adoption of ruminant urine varied widely, with Mikese exhibiting the highest usage (70.8%), moderate uptake in Vianzi (25.0%) and Kimambila (25.8%), and minimal use in Mafuru (1.1%). Regression analysis identified village of residence, awareness of urine as fertilizer, and livestock ownership—particularly goats—as significant predictors of adoption. Farmers applied urine primarily to sunflower and maize, with collection and storage constrained by livestock management and infrastructure. FGDs and KIIs revealed that experiential knowledge, peer exchange, and demonstration plots influenced acceptance, while limited formal training restricted wider adoption. These findings suggest potential for integrating ruminant urine into nutrient management strategies, especially in villages with zero- or semi-zero-grazing systems, and strengthen resilience in mixed crop–livestock systems.

Keywords: Agroecological practices, Climate-resilient farming, Novel fertilizer, Soil health, Sustainable agriculture.

INTRODUCTION

Livestock–crop production systems dominate smallholder agriculture across Africa, Asia, and other climate-vulnerable regions, where households integrate ruminant keeping with annual and oilseed cropping to stabilize food supply and income. Rising demand for animal-source foods has intensified livestock production globally, increasing the volume of manure generated and its interaction with agroecosystems (Chávez-Fuentes et al., 2017; Giamouri et al., 2023). Manure contains carbon, nitrogen, phosphorus, potassium, sulphur, and water, making it both a nutrient resource and a driver of greenhouse gas (GHG) emissions when poorly managed (Irshad et al., 2013; Chadwick et al., 2011). In many smallholder systems, manure management remains informal, spatially concentrated, and weakly regulated, creating conditions for nitrogen losses and atmospheric emissions while crop nutrient demand remains unmet (Symeon et al., 2025; Petersen et al., 2013).

Ruminants hold a central position in these systems because of their capacity to convert fibrous biomass into milk and meat while supplying manure to cropland (Eisler et al., 2014; Pulina et al., 2017). Nitrogen use efficiency in ruminants is low, with 75–90% of ingested nitrogen excreted in urine and faeces (de Klein et al., 2001). Urine typically contains a high proportion of readily hydrolysable nitrogen, often exceeding plant uptake capacity at deposition sites, which promotes nitrate leaching, ammonia volatilization, and nitrous oxide (N_2O) formation (de Klein et al., 2001; Wattiaux et al., 2019). Nitrous oxide has a global warming potential far greater than carbon dioxide and also contributes to stratospheric ozone depletion (Ravishankara et al., 2009; IPCC, 2022). Agriculture accounts for the majority of anthropogenic N_2O emissions, with ruminant excreta representing a substantial share of this total (IPCC, 2022; Smith et al., 2007).

Greenhouse gas formation from livestock manure reflects interacting microbial pathways operating during storage and following land application. Methane production arises mainly from anaerobic decomposition of organic matter and responds strongly to temperature, substrate availability, and management conditions (Sommer et al., 2007; Ni et al., 2008). Nitrous oxide originates from nitrification and denitrification processes driven by ammonia-oxidizing, nitrite-oxidizing, and heterotrophic microbes in soils receiving urine or slurry inputs (Petersen et al., 2013). These processes are especially pronounced in urine patches, where nitrogen loading is localized and soil aeration fluctuates, leading to emission pulses after rainfall or irrigation (de Klein et al., 2014; Lombardi et al., 2021).

At the same time, smallholder farmers face constraints in accessing mineral fertilizers, including high prices, supply instability, and timing mismatches with crop demand. Reliance on synthetic nitrogen fertilizers can also elevate indirect emissions associated with manufacture and transport while contributing to soil degradation when misapplied (Symeon et al., 2025; Yu et al., 2025). Replacing or supplementing mineral fertilizers with farm-derived nutrients has therefore attracted attention as a pathway for climate-smart agriculture that links emission mitigation with soil fertility management (Giamouri et al., 2023; Wattiaux et al., 2019). Within this context, ruminant urine represents a largely underutilized nutrient stream. Compared with solid manure, urine contains nitrogen predominantly in soluble forms that are rapidly plant-available, suggesting potential value as a fertilizer when appropriately managed (Hao et al., 2005).

Research on ruminant nutrition has shown that dietary manipulation can alter nitrogen partitioning and the composition of excreta. Reducing crude protein intake or modifying rumen undegradable protein sources has been explored as a means to influence nitrogen losses, with mixed outcomes for N_2O emissions (Zhou et al., 2019; Coelho et al., 2022). Supplementation with sodium chloride has altered urine volume and nitrogen concentration, affecting subsequent soil emissions (Zhou et al., 2019; Liu & Zhou, 2014). A growing body of work has examined phytobiotic additives, including tannins, saponins, essential oils, and glucosinolate-containing forages, for their capacity to modify ruminal ammonia production and shift nitrogen from urine to faeces (Santoso et al., 2007; Stewart et al., 2019; Wu et al., 2018; Ahmed et al., 2024). Such shifts may reduce the intensity of nitrogen loading in urine patches and alter downstream N_2O formation (Bao et al., 2018; Zhao et al., 2023).

Beyond dietary effects, some plant secondary metabolites excreted in urine or deposited through grazing can influence soil nitrogen transformations directly. Compounds such as aucubin from *Plantago* species and isothiocyanates from *Brassica* forages have shown inhibitory effects on soil nitrogen mineralization and nitrification, leading to lower N_2O emissions following urine deposition (Dietz et al., 2013; Totty et al., 2013; Luo et al., 2015). These findings indicate that urine chemistry, shaped by animal diet, can functionally resemble a fertilizer with embedded biological regulation of nitrogen cycling. Despite these advances, most studies have focused on emission responses within pasture systems, while less attention has been given to the agronomic value of urine as a fertilizer for arable crops under smallholder management.

Oilseed crops such as sunflower are widely grown by smallholders as cash and food crops and exhibit high nitrogen demand during vegetative growth. Previous work has shown that cattle diets incorporating oilseeds can influence manure nutrient characteristics, yet the reciprocal use of ruminant urine to fertilize oilseed crops remains weakly explored (Hao et al., 2005). Evidence linking urine-based fertilization to crop productivity alongside quantified GHG outcomes under field conditions is limited, particularly in diversified systems where livestock are housed, grazed, or tethered across seasons.

Initial discussions during a stakeholder workshop held in November 2023 involving researchers from Sokoine University of Agriculture, staff from Sustainable Agriculture in Tanzania, and organic farmers revealed that several households were already experimenting with ruminant urine as a soil amendment and reported perceived improvements in crop performance. These farmer-led experiences motivated a preliminary field investigation conducted between April and July 2024 in selected sunflower plots. Although the observations were exploratory and not designed for statistical yield evaluation, they highlighted variation in urine handling, application timing, and crop responses across farms. To complement these field observations, soil samples were subsequently collected from participating farms and analysed to characterize baseline fertility conditions. The laboratory results generally indicated clay-dominated soils with low to moderate nitrogen and phosphorus status, very low salinity, and bulk densities within ranges considered suitable for crop production. These findings suggested that nutrient limitations rather than physical soil constraints may influence sunflower productivity in the study areas.

A follow-up stakeholder workshop in November 2024 confirmed continued farmer interest in the practice while also revealing uncertainty regarding its agronomic reliability and environmental consequences. The present study, therefore, does not evaluate yield effects directly; instead, it documents farmer practices and perceptions while situating them within the measured soil fertility context. This approach provides an empirical basis for interpreting farmer experiences without assuming that perceived benefits necessarily reflect measured productivity gains.

This study investigates ruminant urine as a fertilizer for sunflower production through a farmer-based survey conducted within mixed livestock-crop systems. The overall objective is to assess farmers' current practices, perceptions, and constraints related to ruminant urine handling, field application, and its perceived effects on sunflower productivity and greenhouse gas emissions. Specific objectives are to document sources and management of ruminant urine across different livestock rearing settings, to examine how urine is applied to sunflower and other crops relative to inorganic fertilizers, and to evaluate farmers' awareness of emission-related outcomes linked to urine use. The study, therefore, tests whether farmers who intentionally collect and apply ruminant urine report perceived improvements in sunflower performance and reduced reliance on mineral fertilizers, rather than asserting that these outcomes have been experimentally verified.

MATERIALS AND METHODS

Study Area

The study was conducted in Morogoro Region, eastern Tanzania, within Morogoro Rural and Mvomero Districts. Data were collected from four villages: Mikese in Mikese Ward, and Kimambila, Vianzi, and Mafuru in Lubungo Ward. Mikese village is located at approximately 6°44′01″ S and 37°55′14″ E, while Lubungo Ward lies around 6°46′35″ S and 37°31′37″ E. The area experiences a tropical climate with bimodal rainfall. Annual rainfall ranges from 600 to 1,200 mm in Morogoro Rural District and from 800 to 1,200 mm in Mvomero District, with a mean annual temperature of about 24°C. These climatic conditions support both rainfed and irrigated sunflower production and integrated livestock keeping.

Sunflower cultivation in Tanzania is concentrated in semi-arid central regions such as Singida and Dodoma, with additional production zones extending into parts of Morogoro (Shio et al., 2025). The selected study villages, therefore, represent a transitional production environment where sunflower is cultivated alongside mixed crop–livestock activities rather than in the country's main commercial sunflower belt.

Use of ruminant urine as a soil amendment in Tanzania has mainly been reported in Morogoro following farmer sensitization on organic agriculture practices facilitated by Sustainable Agriculture Tanzania (SAT). The study villages were purposely selected because farmers in these communities had prior exposure to organic nutrient management approaches promoted through SAT training programmes. The study population, therefore, represents smallholder farmers engaged in sunflower production who are familiar with ruminant urine use within organic farming contexts, rather than representing Tanzanian smallholders as a whole.

To characterize the agronomic context in which farmer perceptions were formed, soil samples were collected from participating farms and analysed for texture, pH, organic carbon, electrical conductivity, macro- and micronutrients, and bulk density. The analytical results are presented in Supplementary Table S1. Across sites, soils were predominantly clayey with moderately acidic to slightly acidic pH, low available nitrogen and phosphorus, and generally low salinity levels. Bulk density values fell within ranges considered suitable for crop growth. These measurements provide background information on soil fertility conditions but were not used to verify crop yield responses to urine application.

The present study relied on farmer-reported experiences and management practices, and no independent agronomic measurements of sunflower yield or fertilizer response were undertaken. Consequently, the findings describe farmer perceptions and practices within a defined organic-oriented production setting rather than providing experimentally verified agronomic outcomes or nationally representative estimates.

All selected villages participate in organic farming initiatives coordinated by SAT and represent communities where sunflower is cultivated as one of the main crops within mixed livestock–crop systems.

Research Design

A cross-sectional survey design was employed to document farmers' practices and perceptions related to the use of ruminant urine as a fertilizer for sunflower production. The study focused on farmers involved in organic farming for sustainable agriculture under SAT programs. Data collection was carried out during September and October 2025. The design enabled documentation of existing nutrient management practices, sources of farmer knowledge, and perceived agronomic and environmental outcomes associated with urine use under smallholder conditions.

Sampling Strategy and Participant Selection

A total of 311 farmers participated in the survey, representing approximately 30% of the population cultivating sunflower as one of their main crops in each village. Of the total respondents, 130 farmers (52%) were from Mikese village, 90 farmers (24%) from Mafuru, 60 farmers (14%) from Vianzi, and 31 farmers (10%) from Kimambila. Eligibility criteria included active sunflower cultivation, involvement in organic farming practices promoted by SAT, ownership or management of ruminants, and willingness to participate in the study. Within each village, respondents were purposively selected from village farmer lists to ensure representation across gender, age groups, and herd sizes. Table 1 summarizes the total number of sunflower growers per village and the final number of participants included in the study.

Table 1: Distribution of sunflower growers and survey participants by village

Village	Total sunflower growers	Survey participants (n)	Population surveyed
Mikese	310	130	52%
Mafuru	312	90	24%
Vianzi	316	60	14%
Kimambila	300	31	10%
Total	1,238	311	25%

Data Collection Methods

Household Questionnaire

Quantitative data were collected using a structured questionnaire administered to all selected farmers. The questionnaire captured demographic characteristics, livestock ownership, sunflower production practices, and fertilizer use. Additional sections documented farmers' knowledge of ruminant urine as a nutrient source, methods of urine collection and application, perceived effects on sunflower growth, and comparisons with inorganic fertilizers. The questionnaire consisted mainly of closed-ended questions to allow standardized responses and statistical analysis.

Focus Group Discussions

Four focus group discussions were conducted, one in each village. Each discussion included between five and ten participants selected to reflect variation in gender, age, farming experience, and livestock management systems. The discussions explored shared practices related to urine handling, local interpretations of soil fertility management, labour requirements, and perceived environmental effects of urine use in sunflower fields. All discussions were facilitated using a semi-structured guide, recorded with participant consent, and later transcribed for analysis.

Key Informant Interviews

Key informant interviews were conducted with agricultural extension officers, village leaders, and SAT field facilitators operating in the study area. These interviews provided contextual information on local nutrient management norms, organic certification requirements, and institutional perspectives on the use of ruminant urine in crop production.

Data Quality and Ethical Considerations

Enumerators received prior training on questionnaire administration and ethical research conduct. Completed questionnaires were reviewed daily to check for completeness and consistency. Participation was voluntary, and informed consent was obtained from all respondents. Personal identifiers were removed during data processing to maintain confidentiality.

Data Processing and Statistical Analysis

Questionnaire data were extracted from Kobo Toolbox, cleaned, and coded using Microsoft Excel before being analyzed in SPSS version 16. Descriptive statistics were generated to summarize respondent characteristics, livestock ownership, and urine management practices. Group comparisons were conducted using t-tests where appropriate.

Adoption of ruminant urine as fertilizer was analyzed using both Chi-square tests (with Cramer's V) to examine associations with categorical variables such as village, livestock ownership, and awareness, and binary logistic regression to identify key predictors of adoption while controlling for potential confounders. Odds ratios (OR) with 95% confidence intervals were used to quantify the strength and direction of associations.

Qualitative data from focus group discussions and key informant interviews were analyzed thematically to identify recurring patterns related to farmer practices, perceptions, and constraints associated with urine use in sunflower production.

Limitations

The cross-sectional design of this study limited interpretation to reported practices and perceptions at a single point in time. Data were based on self-reported information, which may have been influenced by recall bias and social desirability effects. Participants were selected from organic farming initiatives coordinated by SAT, rather than through simple random sampling of the general farming population. This purposive sampling introduces selection bias, as these farmers are already sensitized to organic practices. Consequently, adoption rates reported in this study (e.g., 70% in Mikese) likely overestimate adoption compared with the broader Tanzanian smallholder population. Additionally, the focus on SAT-affiliated farmers constrains extrapolation beyond similar smallholder systems in the Morogoro Region.

Ethical Clearance

Ethical clearance for the study was obtained from the Office of the Deputy Vice Chancellor for Academics, Research, and Consultancy at Sokoine University of Agriculture. Permission to conduct the survey was also granted by district and village authorities in Morogoro Rural and Mvomero Districts. All participants were informed about the purpose of the study before data collection. Participation was voluntary, and verbal informed consent was obtained from each respondent. Confidentiality was maintained by anonymizing all questionnaires, focus group discussion, and interview records, and the collected data were used solely for research purposes.

RESULTS

Socio-demographic and Farming Context of Respondents

The survey showed that the majority of respondents fall within the economically active age range of 31–60 years, indicating that the farming population is predominantly comprised of individuals capable of engaging in labour-intensive agricultural activities. Women constituted a slightly larger proportion of respondents in Mikese, Mafuru, and Kimambila villages, whereas men were more represented in Vianzi village, suggesting a modest gender variation in agricultural engagement across locations. Educational attainment was generally low, with most respondents reporting primary education or no formal education. Secondary and vocational/college education were uncommon across all villages, which may influence the capacity for adopting new agronomic practices, including the use of ruminant urine as fertilizer. Farming experience among respondents was substantial, with more than a third of farmers in each village reporting over ten years of engagement in agricultural activities. This indicates that respondents possess a well-established understanding of local farming systems and crop management practices.

Chi-square analyses indicated that there were no significant ($p > 0.05$) differences between villages in terms of gender, age distribution, education level, or farming experience, suggesting broadly similar socio-demographic profiles across the study area. Nonetheless, the Cramer’s V values indicated moderate to large effect sizes for several variables, which implies that some level of meaningful variation exists in the demographic characteristics of respondents between villages (Table 2). This variation may influence individual or community-level decisions regarding the adoption of novel fertilization strategies such as the use of cattle urine, as differences in gender composition, age structure, or farming experience can shape both labour availability and openness to experimentation.

While Mikese and Vianzi villages have relatively balanced distributions of age and gender, Mafuru and Kimambila villages showed a slightly higher proportion of female farmers and a concentration of respondents in the middle age groups (31–60 years). Farming experience in Mikese and Kimambila villages is characterized by a higher proportion of farmers with over ten years of experience, whereas Mafuru and Vianzi villages have relatively more respondents with shorter farming experience (2–10 years). Educational patterns are relatively consistent across villages, with the majority of farmers having only primary-level education, suggesting limited formal agricultural knowledge and potential reliance on experiential learning and peer-to-peer knowledge transfer.

Table 2: Socio-demographic characteristics of respondents by village and association with village of residence (n = 311). Note: Values are presented as number (percentage).

Variable	Category	Mikese	Vianzi	Mafuru	Kimambila	x^2	df	p-value	Cramer's V
Gender	Male	58 (44.6)	34 (56.7)	33 (36.7)	12 (38.7)	4.55	3	0.208	0.81
	Female	72 (55.4)	26 (43.3)	57 (63.3)	19 (61.3)				
Age group (years)	18–30	15 (11.5)	6 (10.0)	27 (30.0)	3 (9.7)	3.89	9	0.692	0.53
	31–45	44 (33.8)	21 (35.0)	35 (38.9)	16 (51.6)				
	46–60	47 (36.2)	25 (41.7)	20 (22.2)	10 (32.3)				
	Above 60	24 (18.5)	8 (13.3)	8 (8.9)	2 (6.4)				
Education level	No formal education	32 (24.6)	20 (33.3)	30 (33.3)	11 (35.5)	1.56	6	0.67	0.47
	Primary	78 (60.0)	31 (51.7)	48 (53.3)	16 (51.6)				
	Secondary	18 (13.8)	7 (11.7)	12 (13.4)	4 (12.9)				
	Vocational / College	2 (1.6)	2 (3.3)	-	-				
Farming experience (years)	< 2	7 (5.4)	2 (3.3)	12 (13.3)	3 (9.7)	1.56	9	0.67	0.47
	2–5	34 (26.2)	18 (30.0)	29 (32.2)	7 (22.6)				
	6–10	39 (30.0)	14 (23.3)	23 (25.6)	6 (19.4)				
	> 10	50 (38.4)	26 (43.4)	26 (28.9)	15 (48.3)				

Cropping Systems and Importance of Sunflower Production

Across the four study villages, maize emerged as the most widely cultivated crop, with participation rates exceeding 78% in all locations. Sunflower was the second most common crop, with particularly high adoption in Mikese (74.6%) and Vianzi (76.7%) villages, indicating that sunflower occupies an important role in local farming systems. Vegetable cultivation was moderately represented, while rice production exhibited greater variability, being more prominent in Mafuru and Kimambila villages and limited in Vianzi. The extent of crop diversity also varied spatially, with Mikese demonstrating the broadest range of crops and Kimambila the narrowest, reflecting village-specific production priorities and possibly differences in land availability or market orientation (Table 3).

Chi-square indicated significant associations between village of residence and the cultivation of rice ($p = 0.002$) and vegetables ($p = 0.022$), suggesting spatial differentiation in crop choice. In contrast, sunflower and maize cultivation did not differ significantly between villages, implying consistent recognition of their agronomic and economic relevance across the study area. Cramer's V values for rice and vegetables indicate small to moderate effect sizes, reflecting meaningful but not overwhelming spatial variation in crop selection. Sunflower's uniform cultivation across villages highlights its potential as a target crop for nutrient management interventions, including the application of ruminant urine, without being constrained by village-specific cropping patterns.

The observed pattern shows that while staple cereal production dominates, sunflower has achieved substantial adoption in multiple villages, providing a basis for assessing alternative fertilization strategies. Village-level differences in vegetable and rice production may influence localized approaches to nutrient management and the potential for integrating organic inputs such as cattle urine into diversified cropping systems. The data suggest that targeting sunflower for nutrient interventions can leverage its widespread cultivation, while additional considerations may be required for crops with more spatially heterogeneous adoption.

Table 3: Crops commonly grown by respondents by village and association with village of residence (multiple responses). Note: Values are presented as number (percentage). Multiple responses were allowed.

Crop type	Mikese	Vianzi	Mafuru	Kimambila	x^2	df	p-value	Cramer's V
Sunflower	97 (74.6)	46 (76.7)	45 (50.0)	19 (61.3)	3.12	3	0.374	0.1
Maize	102 (78.5)	52 (86.7)	86 (95.6)	28 (90.3)	2.48	3	0.479	0.09
Vegetables	58 (44.6)	29 (48.3)	38 (42.2)	9 (29.0)	9.67	3	0.022	0.18
Rice	26 (20.0)	3 (5.0)	24 (26.7)	11 (35.5)	14.83	3	0.002	0.22
Other crops	62 (47.7)	24 (40.0)	51 (56.7)	14 (45.2)	6.21	3	0.102	0.14

Land Access, Farm Size, and Information Sources

Most respondents owned farmland, indicating relatively stable land tenure across the four study villages. Ownership was particularly high in Mafuru (90.0%) and Kimambila (71.0%) villages, while Mikese and Vianzi reported moderate levels of ownership (60.0% and 51.7%, respectively). Renting or combining ownership with renting was less common, suggesting that smallholder farmers primarily relied on land they controlled for cultivation (Table 4).

Farm sizes were predominantly smallholder in scale, with the majority of respondents cultivating between 1–3 acres. Larger farms (>6 acres) were more prevalent in Mikese (16.9%) and Vianzi (26.7%) compared to Mafuru (5.6%) and Kimambila (9.7%), reflecting spatial variation in land availability. Smaller plots (<1 acre) were notably more frequent in Mafuru (23.3%), highlighting village-level differences in farm size distribution. The chi-square analysis indicated a significant association between village of residence and farm size ($p = 0.049$), with a Cramer's V of 0.22, reflecting moderate variation in land allocation patterns across villages.

Extension officers were the most commonly cited source of agricultural information, with particularly high utilization in Mikese (77.7%) and Kimambila (83.9%) villages. Fellow farmers also served as important sources, especially in Mafuru (73.3%) and Vianzi (68.3%). Radio and television were moderately accessed, while print media and social media had minimal use. The association between village and access to extension services was significant ($p = 0.001$, Cramer's V = 0.24), indicating that information dissemination pathways differed across villages, with some communities more reliant on formal advisory services and others on peer-to-peer learning.

Table 4: Farm characteristics and sources of agricultural information by village, and association with village of residence. Notes: **Values are presented as number (percentage); Multiple responses were allowed for sources of agricultural information.**

Variable	Category	Mikese	Vianzi	Mafuru	Kimambila	x^2	df	p-value	Cramer's V
Land ownership	Own	78 (60.0)	31 (51.7)	81 (90.0)	22 (71.0)	6.84	6	0.336	0.15
	Rent	22 (16.9)	14 (23.3)	6 (6.7)	6 (19.4)				
	Both	30 (23.1)	15 (25.0)	3 (3.3)	3 (9.6)				
Farm size	<1 acre	9 (6.9)	4 (6.7)	21 (23.3)	5 (16.1)	14.92	9	0.049	0.22
	1-3 acres	61 (46.9)	19 (31.6)	49 (54.4)	15 (48.4)				
	4-6 acres	38 (29.2)	21 (35.0)	15 (16.7)	8 (25.8)				
	>6 acres	22 (16.9)	16 (26.7)	5 (5.6)	3 (9.7)				
Source of agricultural information	Extension officer	101 (77.7)	32 (53.3)	58 (64.4)	26 (83.9)	18.37	3	0.001	0.24
	Fellow farmers	79 (60.8)	41 (68.3)	66 (73.3)	21 (67.7)				
	Radio/TV	52 (40.0)	9 (15.0)	36 (40.0)	18 (58.1)				
	Newspaper/magazines/journals	4 (3.1)	7 (11.7)	3 (3.3)	3 (9.7)				
	Social media	0 (0.0)	3 (5.0)	0 (0.0)	0 (0.0)				

Ruminant Livestock Ownership and Awareness of Urine Fertilizer

Ruminant livestock ownership exhibited substantial variation across the study villages. Mikese recorded the highest proportion of respondents engaged in livestock rearing (63.8%), followed by Vianzi (40.0%), Mafuru (37.8%), and Kimambila (25.8%) (Table 5). Households in Mikese and Vianzi more frequently maintained mixed livestock systems, while Mafuru and Kimambila showed lower prevalence of multi-species rearing. Goats were the dominant livestock type across all villages, present in 61.8–83.1% of livestock-owning households, with cattle and sheep rearing reported less frequently but consistently across villages. Chi-square analysis indicated a significant association between village and ruminant rearing ($x^2 = 18.64$, $p = 0.001$, Cramer's V = 0.25) as well as livestock type ($x^2 = 70.71$, $p < 0.001$, Cramer's V = 0.38), reflecting meaningful spatial differentiation in livestock composition.

Table 5: Ruminant livestock rearing, types of livestock, awareness, and sources of ruminant urine fertilizer by village. Multiple responses were allowed.

Variable	Category	Mikese	Vianzi	Mafuru	Kimambila	x^2	df	p-value	Cramer's V
Ruminant rearing	Yes	83 (63.8)	24 (40.0)	34 (37.8)	8 (25.8)	18.64	3	0.001	0.25
	No	47 (36.2)	36 (60.0)	56 (62.2)	23 (74.2)				
Types of ruminant livestock reared	Cattle	46 (55.4)	14 (58.3)	18 (52.9)	5 (62.5)	70.71	6	<0.001	0.38
	Goats	69 (83.1)	17 (70.8)	21 (61.8)	6 (75.0)				
	Sheep	31 (37.3)	9 (37.5)	12 (35.3)	3 (37.5)				
Awareness of ruminant urine as fertilizer	Yes	96 (73.8)	27 (45.0)	29 (32.2)	19 (61.3)	14.27	3	0.003	0.21
	No	34 (26.2)	33 (55.0)	61 (67.8)	12 (38.7)				
Sources of information on ruminant urine fertilizer	Fellow farmers	52 (54.2)	14 (51.9)	12 (41.4)	9 (47.4)	22.91	9	0.006	0.19
	Training/workshops	38 (39.6)	9 (33.3)	11 (37.9)	6 (31.6)				
	Agricultural extension officer	44 (45.8)	11 (40.7)	10 (34.5)	13 (68.4)				
	Radio/TV	21 (21.9)	6 (22.2)	5 (17.2)	4 (21.1)				

Awareness of ruminant urine as a fertilizer was relatively high but unevenly distributed. Mikese recorded the highest awareness (73.8%), followed by Kimambila (61.3%), Vianzi (45.0%), and Mafuru (32.2%). Awareness extended beyond households actively rearing livestock, suggesting that information dissemination occurred through social networks and extension services. Fellow farmers were cited as the primary information source in all villages, complemented by training/workshops and extension officers, with radio and television reported less frequently. Significant associations were observed between village and awareness (x^2 = 14.27, p = 0.003, Cramer's V = 0.21) as well as between village and sources of information (x^2 = 22.91, p = 0.006, Cramer's V = 0.19), indicating that both knowledge levels and information channels differed meaningfully among villages.

Adoption of Ruminant Urine Fertilizer and Crop Application Patterns

Use of ruminant urine as fertilizer varied considerably among villages. Mikese recorded the highest adoption rate, with 70.8% of respondents reporting prior use, while Vianzi and Kimambila showed moderate adoption levels (25.0% and 25.8%, respectively), and Mafuru reported minimal uptake (1.1%) (Table 6).

Table 6: Use of ruminant urine as fertilizer, types of crops treated, and associations with village, livestock ownership, and awareness among respondents across study villages. Multiple responses were allowed.

Village	Use of ruminant urine as fertilizer (n, %)	Crops applied with urine fertilizer (n, %)	x^2	df	p-value	Cramer's V
Mikese (n=130)	Yes: 92 (70.8)	Sunflower: 61 (66.3)	64.5	3	<0.001	0.55
	No: 38 (29.2)	Maize: 42 (45.7)				
		Vegetables: 29 (31.5)				
		Rice: 2 (2.2)				
		Other: 11 (12.0)				
Vianzi (n=60)	Yes: 15 (25.0)	Sunflower: 8 (53.3)				
	No: 45 (75.0)	Maize: 7 (46.7)				
		Vegetables: 4 (26.7)				
		Rice: 0 (0.0)				
		Other: 5 (33.3)				
Mafuru (n=90)	Yes: 1 (1.1)	Sunflower: 0 (0.0)				
	No: 89 (98.9)	Maize: 1 (100.0)				
		Vegetables: 0 (0.0)				
		Rice: 0 (0.0)				
		Other: 0 (0.0)				
Kimambila (n=31)	Yes: 8 (25.8)	Sunflower: 3 (37.5)				
	No: 23 (74.2)	Maize: 5 (62.5)				
		Vegetables: 0 (0.0)				
		Rice: 0 (0.0)				
		Other: 2 (25.0)				
Awareness	Yes:		30.2	1	<0.001	0.38
Livestock reared (any)	Yes:		22.7	1	<0.001	0.31
Cattle reared	Yes:		10.5	1	0.001	0.21
Goats reared	Yes:		18.8	1	<0.001	0.27
Sheep reared	Yes:		12.4	1	0.0004	0.23

Non-use was correspondingly higher in Mafuru (98.9%) and Vianzi (75.0%), indicating limited practical implementation despite some awareness in these areas. Application of ruminant urine was concentrated on sunflower and maize, particularly in villages with higher adoption rates. Vegetables were also commonly treated in Mikese and Vianzi, whereas rice was rarely fertilized with urine, reflecting selective crop targeting based on perceived response or practicality. Other crops received moderate application in Mikese and Vianzi, with very limited treatment in Mafuru and Kimambila.

Analyses using Chi-square tests showed a strong and significant association between village of residence and use of ruminant urine (x^2 = 64.5, $p < 0.001$, Cramer's V = 0.55), indicating that geographic location strongly influenced adoption. Awareness of urine fertilizer was significantly associated with use (x^2 = 30.2, $p < 0.001$, Cramer's V = 0.38), suggesting that knowledge alone was an important determinant.

Livestock ownership also influenced utilization, with any livestock rearing (x^2 = 22.7, $p < 0.001$, Cramer's V = 0.31) and specifically goat ownership (x^2 = 18.8, $p < 0.001$, Cramer's V = 0.27) showing moderate associations with adoption. Cattle and sheep ownership were also associated with urine use, though with weaker effect sizes (Cramer's V = 0.21 and 0.23, respectively).

To further explore determinants of adoption, a binary logistic regression model was fitted, with use of ruminant urine as the dependent variable (Yes = 1, No = 0) and village, awareness, and livestock ownership as independent predictors. Table 7 summarizes the regression results.

Table 7: Binary logistic regression of factors influencing adoption of ruminant urine fertilizer.

Predictor	B (log-odds)	SE	Wald x^2	df	p-value	OR (95% CI)
Village (ref = Mikese)						
Vianzi	-2.15	0.48	19.9	1	<0.001	0.12 (0.05–0.28)
Mafuru	-5.12	1.1	21.6	1	<0.001	0.006 (0.001–0.04)
Kimambila	-1.91	0.62	9.5	1	0.002	0.15 (0.05–0.45)
Awareness (Yes vs No)	1.82	0.44	16.9	1	<0.001	6.17 (2.6–14.6)
Livestock ownership (any)	1.01	0.38	7.1	1	0.008	2.75 (1.3–5.7)
Goats reared (Yes vs No)	0.82	0.37	4.9	1	0.027	2.27 (1.1–4.8)

The logistic regression confirmed that village of residence was the strongest determinant of urine fertilizer adoption. Compared with Mikese, farmers in Mafuru were far less likely to use urine (OR = 0.006), reflecting very low uptake. Awareness of ruminant urine as fertilizer significantly increased the likelihood of use (OR = 6.2), indicating that knowledge remains a key driver. Livestock ownership, particularly of goats, was also positively associated with adoption, highlighting the role of resource availability in practical implementation.

Livestock Management Systems and Implications for Urine Availability

Livestock management systems varied notably among the study villages, influencing potential urine availability. Free-range grazing was the most prevalent system overall, with the highest proportions observed in Kimambila (80.0%) and Mafuru (51.7%) villages. Zero-grazing was common in Mikese (41.9%) and Vianzi (33.3%), while semi-zero grazing was less widespread, occurring mainly in Mikese (19.4%) and Mafuru (13.8%). Communal grazing was reported exclusively in Mafuru (20.7%), reflecting village-specific collective management practices (Table 8). The association between village of residence and grazing system choice was significant (x^2 = 24.87, p = 0.003) with a moderate effect size (Cramer's V = 0.23), indicating that spatial factors strongly shaped grazing practices. The distribution of grazing systems suggests that Mikese and Vianzi villages may have higher potential for capturing urine due to greater adoption of zero-grazing and semi-zero grazing, whereas in villages dominated by free-range or communal grazing, urine is likely less accessible for collection and subsequent fertilizer use. Table 7 summarizes the patterns of grazing systems across villages and their statistical association with location.

Table 8: Grazing systems practiced by respondents and association with village of residence across study villages. Multiple responses were allowed.

Grazing system	Mikese	Vianzi	Mafuru	Kimambila	x^2	df	p-value	Cramer's V
Free-range	36 (38.7)	18 (50.0)	30 (51.7)	4 (80.0)	24.87	9	0.003	0.23
Zero-grazing	39 (41.9)	12 (33.3)	8 (13.8)	1 (20.0)				
Semi-zero grazing	18 (19.4)	6 (16.7)	8 (13.8)	0 (0.0)				
Communal	0 (0.0)	0 (0.0)	12 (20.7)	0 (0.0)				

Urine Collection and Storage Practices

Ruminant urine collection and storage practices exhibited clear spatial variation across the study villages. In most villages, the majority of respondents did not collect urine at all, with the highest proportions observed in Vianzi (81.7%) and Mafuru (75.6%). When collection was reported, urine traps were the most commonly employed method, particularly in Mikese (30.9%) and Kimambila (17.1%), while direct collection from animal housing floors occurred mainly in Mikese (20.0%). Collection from bedding materials was notable in Mafuru (31.1%), reflecting adaptations in areas with less formal livestock housing infrastructure. Collection directly from concrete floors with slope channels and from urine diverted from dung pits was rare across all villages (see Supplementary Table S2).

Storage practices were generally limited. Immediate use without storage was the dominant approach, with almost all respondents in Mafuru (96.7%) and the majority in Vianzi (86.7%) reporting this practice. Storage in closed drums or barrels was reported primarily in Mikese (21.8%) and Kimambila (17.1%), while plastic buckets were used mainly in Mikese (23.6%). Open containers and underground pits were only occasionally employed in Mikese, and no respondents reported use of tanks with tap outlets. Temporary storage followed by immediate application occurred in small numbers across Mikese, Vianzi, and Kimambila. Results further showed significant associations between village of residence and both urine collection (x^2 = 32.48, p = 0.006, Cramer's V = 0.21) and storage methods (x^2 = 36.91, p = 0.004, Cramer's V = 0.23), indicating that local infrastructure and management practices strongly influenced how urine was collected and handled. These patterns suggest that villages with more developed livestock housing, such as Mikese and Kimambila, had higher potential for systematic urine capture and storage, whereas villages relying on extensive or communal grazing had limited opportunities for collection and retained a reliance on immediate application.

Perceived Information Gaps, Willingness to Adopt, and Extension Preferences

Respondents across all villages generally reported limited access to information and training on the use of ruminant urine as fertilizer, with the proportion perceiving insufficient information ranging from 74.3% in Mafuru to 88.6% in Kimambila. Only a small fraction of respondents indicated that information and training were adequate. Factors that respondents identified as likely to increase their willingness to use ruminant urine included demonstration plots, training, and technical support. Training was consistently emphasized across villages, ranging from 68.6% in Mikese to 77.1% in Kimambila. Demonstration plots were cited by 65.5–94.3% of respondents, with the highest proportion in Kimambila. Technical support was reported less frequently than training or demonstration plots but showed considerable variation, ranging from 30.0% in Mikese to 74.3% in Kimambila (see Supplementary Table S3).

Respondents in all villages indicated that they would attend demonstration plots if invited, with percentages exceeding 98%, reflecting strong readiness to engage in practical learning activities. Results also revealed that perceptions of limited information and willingness to attend demonstration plots did not differ significantly by village. In contrast, preferences for technical support ($x^2 = 19$, $p < 0.001$, Cramer's V = 0.29) and demonstration plots ($x^2 = 9.47$, $p = 0.024$, Cramer's V = 0.18) exhibited significant associations with village of residence, indicating that spatial factors influenced farmers' support needs and preferred extension modalities. These results highlight that while information gaps were broadly perceived, the type of assistance considered most helpful varied by village, with technical support showing the greatest inter-village variation.

Perceptions and Contextual Insights from FGDs and KIIs

Farmers emphasized that learning from fellow farmers and attending local workshops were the most common avenues for acquiring knowledge on ruminant urine use (see Supplementary Table S4). In villages with higher livestock density and structured grazing systems, such as Mikese and Vianzi, participants reported more practical engagement with urine collection and fertilization. In contrast, free-range and communal grazing systems in Mafuru and Kimambila limited hands-on experience, reducing familiarity and adoption rates.

Participants noted that the perceived benefits of urine application—such as improved sunflower vigour and soil fertility—encouraged use, though hesitation persisted where livestock resources were scarce or handling methods were unclear. Farmers highlighted that demonstration plots and direct technical support would increase confidence and encourage consistent application.

Key informants reinforced the importance of extension support, indicating that practical, participatory training approaches were more effective than theoretical sessions. Adoption barriers were not solely knowledge-related; resource availability and village-specific livestock management practices strongly influenced whether farmers could implement urine fertilization effectively. These insights align with the quantitative findings, showing that adoption is a product of both awareness and enabling conditions.

DISCUSSION

The survey results situate ruminant urine within broader debates on nutrient recycling and emission management in mixed livestock–crop systems, particularly under smallholder conditions where livestock keeping remains integral to livelihoods. High volumes of manure and urine generated by ruminants reflect global trends of expanding livestock populations and intensification, which are closely linked to agricultural greenhouse gas emissions (Chávez-Fuentes et al., 2017; Giamouri et al., 2023). Farmers' recognition of urine as a locally available nutrient source aligns with scientific evidence that livestock excreta contain plant-available nitrogen and other nutrients capable of substituting part of mineral fertilizer demand (Irshad et al., 2013; Wattiaux et al., 2019). Within the present study, this alignment should be interpreted as reflecting farmers' awareness of nutrient value rather than confirmation of measured agronomic or environmental effects, although it remains consistent with literature framing livestock-derived nutrients within climate-smart agriculture approaches that integrate production and emission considerations (Symeon et al., 2025).

Farmers' reported interest in using urine for sunflower production reflects agronomic realities in smallholder systems where oilseed crops are cultivated under limited access to external inputs. Previous studies have shown that nutrients derived from ruminant diets influence the chemical composition of manure and urine, with implications for soil fertility when recycled to cropland (Hao et al., 2005). The present study did not verify crop yields or soil responses; therefore, farmers' statements regarding improved crop performance represent experiential observations rather than experimentally confirmed outcomes. Nevertheless, such perceptions correspond with experimental findings showing that urine-based nutrient inputs can support crop growth and nitrogen uptake when applied at appropriate rates (de Klein et al., 2014). In smallholder contexts where formal monitoring of yields and soils is uncommon, these experiential assessments often guide management decisions and shape adoption pathways.

Variation in adoption across communities highlights that access to information, livestock management practices, and local learning environments shape how urine fertilization is implemented. Households managing smaller ruminants or practicing zero-grazing systems reported greater use of urine, reflecting the relative ease of collection and handling in these systems. This pattern resonates with literature emphasizing that livestock integration and manure management infrastructure condition nutrient cycling efficiency and emission outcomes (Petersen et al., 2013; Eisler et al., 2014). Farmers' emphasis on demonstration plots and peer learning mirrors findings from other regions where experiential learning has facilitated uptake of alternative nutrient management practices more effectively than written recommendations alone (Luo et al., 2015; Luo et al., 2018; Mukasa et al., 2025). These observations suggest that social learning processes and practical feasibility, including labour availability and handling requirements, play a central role in shaping adoption of urine-based fertilization.

From a management perspective, farmers' awareness of environmental effects associated with urine handling intersects with established knowledge on greenhouse gas formation from livestock excreta. Nitrous oxide emissions from urine patches arise from concentrated nitrogen inputs that stimulate nitrification and denitrification processes in soil (de Klein et al., 2001; Lombardi et al., 2021). However, the survey design did not measure emissions or storage conditions quantitatively, and therefore cannot confirm environmental outcomes associated with the reported practices. Storage and application practices reported in this study, particularly the use of open containers and immediate field application, were primarily explained by farmers in terms of labour demands, container availability, and ease of transport rather than emission considerations. Research indicates that storage and timing of application can influence nitrogen losses and associated emissions (Chadwick et al., 2011; Sommer et al., 2007), yet the present findings should be interpreted as documenting management constraints and decision contexts rather than validating specific emission pathways.

Dietary strategies discussed in the literature provide additional context for farmers' perceptions of urine quality and effectiveness. Studies on tannins, saponins, essential oils, and protein composition demonstrate that urine nitrogen concentration and composition can vary with feed management, with downstream implications for soil processes (Zhou et al., 2019; Coelho et al., 2022; Santoso et al., 2007; Stewart et al., 2019). Research on phytochemical-rich forages further indicates that compounds excreted in urine may influence nitrification and nitrous oxide fluxes (Dietz et al., 2013; Luo et al., 2015). These mechanisms were not examined in this survey, and therefore references to dietary effects serve only as contextual background rather than evidence of on-farm biochemical responses. Farmers' perceptions of reduced environmental risk when using urine therefore reflect experiential reasoning linked to nutrient recycling practices rather than measured mitigation outcomes, even though such reasoning is compatible with trends reported in experimental literature (Zhao et al., 2023).

Economic considerations emerged implicitly through farmers' comparison of urine with inorganic fertilizers. High costs, inconsistent availability, and dependence on external markets continue to constrain fertilizer use among smallholders, reinforcing interest in farm-derived alternatives. Replacing part of mineral fertilizers with urine-derived nutrients can lower input expenditure and reduce indirect emissions associated with fertilizer manufacture and transport, which contribute to agricultural greenhouse gas budgets at global scale (IPCC, 2022; Smith et al., 2007). Similar dynamics have been observed in other livestock systems, including poultry, where nutrient recycling and dietary modulation have been framed as mitigation pathways with co-benefits for farm resilience (Yu et al., 2025). Within the present study, these economic considerations emerged as primary drivers of interest in urine use, indicating that affordability and input access rather than environmental outcomes were the dominant motivations shaping farmer practices.

CONCLUSION AND RECOMMENDATIONS

The study demonstrated that smallholder farmers possess moderate to high awareness of cattle urine as a potential fertilizer, yet actual adoption is constrained by multiple socio-economic, infrastructural, and knowledge-related factors. Adoption patterns varied significantly across villages, reflecting differences in livestock ownership, particularly goats, and livestock management systems that influence urine availability. Sunflower and maize emerged as the primary crops targeted for urine application, indicating both the relevance of these crops in local farming systems and the potential for targeted nutrient interventions. Farmers' preference for hands-on learning, including training and demonstration plots, highlighted the need for practical extension approaches to facilitate proper application and storage practices. Collection and storage of urine remain largely informal, with immediate application being the predominant practice, suggesting that nutrient losses through volatilization and suboptimal timing may limit agronomic effectiveness and environmental benefits. The findings also indicated that village-specific social networks and extension accessibility significantly shape knowledge diffusion and adoption behaviours, emphasizing the importance of localized strategies for integrating cattle urine into climate-smart nutrient management.

Recommendations derived from the study emphasize actionable steps for multiple stakeholders. Farmers should be encouraged to adopt structured urine collection and storage methods, such as closed drums or covered containers, to enhance nutrient retention and allow for stage-specific crop application. Integration of urine fertilization into crop rotation and intercropping systems, particularly for sunflower and maize, can optimize nitrogen utilization while reducing reliance on synthetic fertilizers, thereby lowering associated greenhouse gas emissions. Training programs and demonstration plots should be expanded and tailored to village-specific contexts, leveraging peer learning and extension networks to disseminate the best practices for collection, storage, and application. These interventions should include guidance on appropriate dilution rates, timing aligned with crop growth stages, and integration with other organic or inorganic nutrient sources to maximize yield outcomes and environmental benefits.

For extension services and agricultural development organizations, the study suggests prioritizing technical support in villages with lower adoption and limited infrastructure. Capacity-building initiatives should focus not only on awareness creation but also on practical skills for urine management, including handling, storage, and nutrient application strategies that minimize nitrogen losses. Collaborating with local farmer groups and livestock cooperatives can facilitate collective approaches to urine collection, pooling resources to overcome individual limitations in storage infrastructure and livestock access. Extension interventions should also consider the socio-economic context of farmers, ensuring that recommended practices are cost-effective and feasible within smallholder systems.

Policymakers should recognize cattle urine as a legitimate, climate-smart nutrient input and incorporate its use into national and regional nutrient management guidelines. Incentive schemes, such as support for low-cost storage infrastructure, subsidized training programs, and integration into climate-smart agriculture initiatives, can enhance adoption. Policies that facilitate knowledge exchange among farmers and between research institutions and local communities will strengthen technology transfer and encourage environmentally responsible fertilizer use. Monitoring and evaluation frameworks could track adoption rates, nutrient efficiency, and greenhouse gas mitigation outcomes to inform evidence-based policy adjustments.

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Credit Authorship Contribution Statement

Mustapha Daniel Yohana: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Visualization, Writing – original draft, Writing – review and editing. Eliakira Kisetu Nassary: Supervision, Validation, Visualization, Writing – review and editing. Mawazo Jamson Shitindi: Supervision, Validation, Visualization, Writing – review and editing. Nuru Nassoro Kipato: Supervision, Validation, Visualization, Writing – review and editing.

DECLARATIONS

Clinical Trial Number

Not applicable.

Ethics Statement

This study involved human research participants and was conducted in accordance with the ethical guidelines and regulations of the Research Ethics Committee of Sokoine University of Agriculture (SUA-REC). The research protocol was reviewed and approved by the Research Ethics Committee of Sokoine University of Agriculture in accordance with the Code of Conduct for Research Ethics of Sokoine University of Agriculture (Revised version of 2012), under reference number SUA/ADM/R.1/8/1450.

Consent to Participate

All participants involved in this study were adults and voluntarily agreed to participate after being informed about the purpose of the study, the nature of their participation, confidentiality of their responses, and their right to withdraw at any time without any consequences. Freely given informed consent was obtained from all participants before data collection. No participants under the age of 16 were involved in this study.

Consent for Publication

Not applicable.

Declaration of Competing Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Table S1: Physicochemical properties [(a), (b)] and fertility indicators of soils sampled from participating farms in Morogoro Region, Tanzania, used to describe the production environment in which farmer perceptions of ruminant urine fertilization were formed. Values are based on laboratory analyses of surface soils collected from both conventional and organic farms; ratings indicate interpretive classes used to contextualize nutrient status rather than to infer crop response.

Physical Properties

Farm type	Sand (%)	Silt (%)	Clay (%)	Texture	Bulk density	Dry soil	Wet soil
Conventional farm	9.2	26	64.8	Clay	1.16	7.5YR Reddish Yellow 6/8	7.5YR Reddish Yellow 8/6
Ratings					Ideal		
Organic farm	10.2	20	69.8	Clay	1.09	10YR Brownish Yellow 6/8	Dark Yellowish Brown 4/6
Ratings					Ideal		
Conventional farm	8.2	25	66.8	Clay	1.2	Olive Yellow 6/6	Olive Brown 4/4
Ratings					Ideal		
Conventional farm	5.2	27	67.8	Clay	1.2	Yellow 8/6	Yellow 7/6
Ratings					Ideal		
Organic farm	7.2	29	63.8	Clay	1.12	Brownish Yellow 6/8	Dark Brown 4/4
Ratings					Ideal		
Conventional farm	8.2	26	65.8	Clay	1.02	Olive Yellow 6/6	Olive Brown 4/4
Ratings					Ideal		

Chemical properties

Farm type	pH (H2O)	OC (%)	EC	N (%)	P	S	Na	K	Ca	Mg	CEC	Mn	Zn	Fe	B
Conventional farm	5.6	1.2	0.16	0.14	6.2	1.1	0.13	0.37	0.67	0.1	20.9	43.9	0.78	103.7	0.02
Ratings	Moderately acid	Moderate	Very low	Low	Low	Very low	Low	Low	Low	Very low	High	Adequate	Marginal	Very high	Deficient
Organic farm	5.5	1.3	0.15	0.17	6.2	1.2	0.17	0.44	0.22	0.53	18.5	33.12	0.4	112.1	0.01
Ratings	Strongly acid	Moderate	Very low	Low	Low	Very low	Low	Low	Very low	Low	Moderate	Adequate	Deficient	Very high	Deficient
Conventional farm	5.9	1.5	0.13	0.16	7.1	1	0.25	0.51	0.55	0.1	22.1	54.35	0.85	96.8	0.01
Ratings	Moderately acid	Moderate	Very low	Low	Low	Very low	Low	Low	Low	Very low	High	High	Marginal	High	Deficient
Conventional farm	5.7	1.7	0.23	0.18	6.5	1.1	0.31	0.44	0.19	1.35	23.2	46.93	0.72	83.4	0.02
Ratings	Moderately acid	Moderate	Slightly saline	Low	Low	Very low	Moderate	Low	Very low	High	High	Adequate	Marginal	High	Deficient
Organic farm	6.1	1.6	0.19	0.16	8.2	1.4	0.29	0.47	0.6	1.72	25.1	22.19	0.31	74.7	0.01
Ratings	Slightly acid	Moderate	Very low	Low	Low	Very low	Low	Low	Low	High	High	Adequate	Deficient	High	Deficient
Conventional farm	6.3	1.6	0.21	0.15	9.4	1.3	0.43	0.32	0.7	1.13	26.3	36.38	0.63	80.4	0.01
Ratings	Slightly acid	Moderate	Slightly saline	Low	Low	Very low	Moderate	Low	Low	High	High	Adequate	Marginal	High	Deficient

Table S2: Methods and storage of ruminant urine by respondents and association with village of residence across study villages. Multiple responses were allowed.

Category / Method	Mikese	Vianzi	Mafuru	Kimambila	x^2	df	p-value	Cramer's V
Urine collection methods:					32.48	15	0.006	0.21
Directly from animal housing floor	22 (20.0)	3 (5.0)	1 (1.1)	0 (0.0)				
Through urine traps	34 (30.9)	4 (6.7)	1 (1.1)	6 (17.1)				
From concrete floors with slope channels	10 (9.1)	1 (1.7)	0 (0.0)	0 (0.0)				
From bedding materials	18 (16.4)	2 (3.3)	28 (31.1)	1 (2.9)				
Urine diverted from dung pits	0 (0.0)	1 (1.7)	0 (0.0)	0 (0.0)				
Not collected at all	61 (55.5)	49 (81.7)	68 (75.6)	21 (60.0)				
Urine storage methods:					36.91	18	0.004	0.23
In plastic buckets	26 (23.6)	2 (3.3)	0 (0.0)	1 (2.9)				
In closed drums/barrels	24 (21.8)	0 (0.0)	1 (1.1)	6 (17.1)				
In open containers	31 (28.2)	0 (0.0)	0 (0.0)	0 (0.0)				
In underground storage pits	3 (2.7)	0 (0.0)	0 (0.0)	0 (0.0)				
In tanks with tap outlets	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)				
Stored temporarily, then used immediately	5 (4.5)	4 (6.7)	0 (0.0)	1 (2.9)				
Not stored at all (used immediately)	68 (61.8)	52 (86.7)	87 (96.7)	23 (65.7)				

Table S3: Perceived information gaps, willingness-enhancing factors, participation in demonstration plots, and association with village of residence across study villages. Multiple responses were allowed for the factors increasing willingness to use ruminant urine.

Variable / Factor	Mikese	Vianzi	Mafuru	Kimambila	x^2	df	p-value	Cramer's V
Perceived limited information/training:					6.84	3	0.077	0.15
Yes	108 (77.1)	41 (74.5)	52 (74.3)	31 (88.6)				
No	32 (22.9)	14 (25.5)	18 (25.7)	4 (11.4)				
Factors increasing willingness to use ruminant urine:								
Training	96 (68.6)	39 (70.9)	49 (70.0)	27 (77.1)	2.31	3	0.51	0.09
Technical support	42 (30.0)	31 (56.4)	28 (40.0)	26 (74.3)	19	3	<0.001	0.29
Demonstration plots	121 (86.4)	36 (65.5)	58 (82.9)	33 (94.3)	9.47	3	0.024	0.18
Willing to attend demonstration plots:					3.12	3	0.374	0.1
Yes	138 (98.6)	54 (98.2)	70 (100.0)	35 (100.0)				
No	2 (1.4)	1 (1.8)	0 (0.0)	0 (0.0)				

Table S4: Thematic findings from focus group discussions and key informant interviews across study villages (Mikese, Vianzi, Mafuru, Kimambila).

Theme	Observed pattern	Implications
Knowledge acquisition and information networks	Farmers relied heavily on peer-to-peer learning and local workshops; formal training on urine fertilizer was limited.	Informal social networks play a key role in spreading awareness; targeted extension services could improve adoption rates.
Livestock management and resource availability	Villages with zero- or semi-zero grazing (Mikese, Vianzi) had higher urine collection potential; free-range and communal grazing (Mafuru, Kimambila) limited access.	Adoption of urine fertilizer is constrained by livestock management systems; infrastructural improvements may increase availability.
Perceived benefits and cultural acceptance	Farmers reported improved crop vigour and soil fertility with urine application; some hesitation in villages with low livestock ownership or unfamiliarity with handling practices.	Positive outcomes encourage uptake, but practical barriers and cultural factors may slow adoption; demonstration plots can reinforce confidence.
Extension support and technical guidance	KIIs indicated that demonstration plots, hands-on training, and advisory visits were considered most effective for adoption.	Practical and participatory approaches are more likely to convert awareness into consistent usage across villages.
Adoption drivers and barriers	Awareness alone was insufficient; adoption depended on access to livestock, collection/storage infrastructure, and guidance.	Integrating social learning with formal extension can enhance sustainable use of ruminant urine.