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Integrating farmer perceptions and scientific assessments of soil acidity in the Upper Blue Nile Basin, Ethiopia

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KEYWORDS

Liming, lupin, soil acidity, sustainability, Upper Blue Nile Basin

HIGHLIGHTS

- Soil acidity constrains agricultural productivity in Ethiopia.
- Farmers identify soil acidity via yield loss and stunted crop growth.
- Perceptions partly differ from scientifically measured soil acidity.
- Local practices-organic inputs, rotation and lupin use- support soil management.
- Integrating knowledge improves soil management and resilience.

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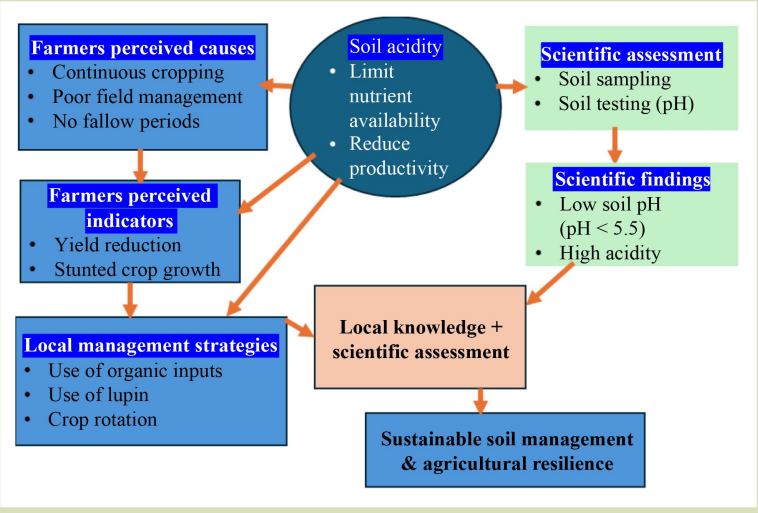
GRAPHICAL ABSTRACT



ABSTRACT

Soil acidity is a major land degradation issue in sub-Saharan Africa, critically affecting agricultural productivity and food security, especially in the Ethiopian highlands. This study examines farmer perceptions, adaptive strategies, and the correspondence between local and scientific assessments of soil acidity in northwestern Ethiopia. Using a cross-sectional survey, data were collected from 292 households across three kebeles in the Amhara region, complemented by field observations and soil sampling. Farmers identified yield reduction and stunted crop growth as primary indicators of soil acidity, attributing the issue largely to continuous cropping, poor field management and limited fallow periods. Laboratory results revealed discrepancies between farmer perceived acidity levels and measured soil pH, with many fields

classified as very strongly to extremely acidic. Farm management strategies, such as organic fertilization, crop rotation, and the use of acid-tolerant crops (bitter white lupin, *Lupinus albus*), align with sustainable practices but are constrained by inconsistent lime application due to its cost and perceived inefficacy. The findings highlight the gap between scientific assessment and local perception, underscoring the need for integrated approaches that combine local knowledge with empirical data to enhance soil management. This study underscores the need to integrate the local knowledge of farmers with scientific assessments to enhance soil acidity management. Expanding early detection tools, strengthening extension services and testing locally adapted liming and soil restoration practices are key to improving soil health and agricultural resilience in acid-prone areas.

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1 Introduction

Land degradation, particularly soil acidity, poses a significant global challenge for sustainable agriculture, impacting food security, soil health, and ecosystem stability. Globally, acidic soils constitute nearly 30% of ice-free land and over half of the potentially arable land, severely limiting agricultural productivity and expansion[1–3]. In sub-Saharan Africa (SSA), the problem is particularly acute, affecting over one-third of arable land and expanding in both scale and severity[4,5]. Acidification is especially pronounced in the humid and subhumid regions of East, Central, West, and Southern Africa, where high rainfall accelerates nutrient leaching[5]. Ethiopian highlands, critical for national agricultural production, are no exception. Alarmingly, close to half of Ethiopia's rainfed agricultural land is acidic, with about 12% classified as strongly to extremely acidic (pH < 5.5)[6], leading to declining crop yields and productivity constraints[7,8]. In the Upper Blue Nile Basin of Ethiopia, the focal region of this study, a substantial proportion of agricultural soils are affected by acidity that significantly impair soil fertility.

From a scientific standpoint, soil acidification in these landscapes results from the interaction of natural and anthropogenic factors. High annual rainfall promotes the leaching of base cations such as Ca^{2+}, Mg^{2+}, and K^{+}, while increasing the accumulation of Al^{3+} and H^{+} ions, leading to progressive declines in soil pH[9]. These inherent processes are exacerbated by continuous cultivation under intensive, cereal dominated cropping systems, where nutrient removal through harvest is seldom balanced by adequate replenishment[5]. In addition, frequent application of ammonium-based fertilizers undergoes nitrification, releasing H^{+} ions into the soil systems[4,10]. On cultivated slopes, soil erosion compounds the problem by mostly removing organic matter-rich topsoil with higher buffering capacity, thereby intensifying soil acidity and structural degradation. Collectively, these processes explain the spatial prevalence and severity of soil acidity in the Upper Blue Nile Basin and underscore the need to examine both biophysical drivers and land management practices when addressing the problem.

Established soil management strategies in SSA follow a top-down approach, prioritizing scientific interventions such as lime application to mitigate soil acidity[9]. While these methods have provided some success, they often fall short due to their limited adaptability to local conditions. This shortcoming has motivated a paradigm shift toward participatory research frameworks that integrate the local knowledge of farmers and experience to develop more contextually appropriate and resilient soil management practices[9]. Farmers in Ethiopia, as for many across SSA, possess generations of accumulated knowledge on soil health, nutrient cycling and degradation processes, including soil acidification. However, this local knowledge remains underutilized in mainstream agricultural policies and research[6].

Despite increasing global recognition of farmer perspectives on soil health, research on their specific perceptions of soil acidity remains limited, particularly across broad acidity categories[4,10,11]. Most studies in Ethiopia have focused on the effectiveness of lime in mitigating soil acidity, often neglecting the traditional adaptive strategies of farmers and how these align or diverge from scientific assessments. This oversight

underscores an important crucial research gap, as understanding local perceptions and responses to soil acidity could significantly enhance the effectiveness and adoption of sustainable management practices. Also, the failure to incorporate farmer insights into soil management solutions can impede technology adoption, as interventions designed without end-user engagement frequently are met with resistance or have limited long-term impact[12].

While Ethiopian farmers are aware of soil acidity and its effects, little research has systematically explored their nuanced understanding of its causes, symptoms and coping mechanisms across varied socioeconomic and biophysical contexts[10,13–15]. Farmers have developed local strategies, including crop rotation, organic fertilization and the cultivation of acid-tolerant species, yet these practices are rarely integrated into broader agricultural policies and extension programs. This study hypothesizes that incorporating farmer perspectives into research frameworks could offer a more comprehensive understanding of acidity management, one that aligns scientific knowledge with local realities and promotes sustainable agricultural practices[14,15].

Recognizing this gap, the current study seeks to examine the intersection of local perceptions and scientific assessments of soil acidity in the Upper Blue Nile Basin, a region marked by intensive agricultural activity and widespread soil acidity. Specifically, the three key objectives of this study are: (1) to evaluate farmer perceptions regarding the causes and widespread effects of soil acidity; (2) to document established coping mechanisms of farmers to mitigate the impacts of soil acidity; and (3) to correlate farmer perceptions with scientifically based evaluations of soil acidity in cultivated lands. By bridging the divide between local knowledge and scientific analysis, this study seeks to inform more inclusive and effective soil management policies. Ultimately, integrating farmer-driven insights with scientific approaches will be instrumental in enhancing soil health, improving agricultural productivity and strengthening the resilience of farming communities in Ethiopia and beyond.

2 Materials and methods

2.1 Description of the study areas

The study was conducted in three kebeles (the smallest administrative unit) in Amhara Region of Ethiopia, encompassing diverse agroecological zones with varying climatic and topographic features. The selected kebeles were Debre Kelemua (10°28′ 18″ N, 37°34′ 34″ E) and Limichim (10°9′ 32″ N, 37°45′ 36″ E) in the Machakel and Baso Liben Districts of the East Gojjam Zone, respectively, and Sankit Lideta (10°56′ 8″ N, 36°52′ 22″ E) in the Banja District of the Awi Zone. These kebeles are part of the northwestern highlands of the Upper Blue Nile Basin, Ethiopia.

According to the established agroecological classification in Ethiopia, which is mainly based on altitude, Sankit Lideta (2520–2712 masl) is in the Dega agroecological zone. Debre Kelemua (2259–2587 masl) the Woyina Dega zone and Limichim (2192–2378 masl) the Dega zone. Climate records from 2012 to 2022 indicate distinct precipitation and temperature patterns across the kebeles. Mean annual rainfall was 1981 mm for Debre Kelemua, 1610 mm for Limichim, and 2419 mm for Sankit Lideta. Rainfall follows a unimodal pattern, starting in May, peaking in July and August, concluding in September, with monthly precipitation often exceeding 150 mm during this period. The mean annual temperatures were 18 °C in Debre Kelemua, 22 °C in Limichim and 18 °C in Sankit Lideta.

The dominant farming system in the study area is a mixed crop-livestock system, with cattle, horses, sheep and donkeys as the main livestock. The dominant soil types across the three kebeles are Luvisols in Sankit Lideta, Luvisols and Nitisols in Debre Kelemua, and Nitisols in Limichim.

2.2 Data, data collection and sampling

The study applied a cross-sectional household survey design to gather data on soil acidity perceptions and their management practices among rural households. Our data collection tools included household face-to-face interviews using structured questionnaires and key informant interviews, as well as field observations and soil sampling. In January 2022, an initial rapid rural appraisal was made with 12 key informant interviews (6 agriculture experts and 6 knowledgeable farmers) and several field observations. These activities provided an understanding of local agricultural practices, the extent and severity of soil acidity issues, and the management practices adopted by farmers and promoted by agricultural offices. Insights from this appraisal informed the development of our research questions and helped in designing a draft survey

instrument that captured key aspects of soil acidity perceptions and mitigation practices. The draft questionnaire was further refined through a review of relevant literature to reduce potential biases and ensure comprehensive coverage of farmer experiences with soil acidity.

The initial draft questionnaire, developed in English, was translated into local language (Amharic) to facilitate clear communication during data collection. Prior to training the data collectors and launching the main survey, a pilot survey was conducted with 50 respondents. These responses were excluded from the final analysis but were instrumental in assessing the clarity, reliability and validity of the questions. The pilot also helped identify any practical issues in survey administration and ensured that respondents could understand and accurately respond to the questions. Following the pilot, minor adjustments were made to the questionnaire to address any identified concerns.

A multistage sampling procedure was applied to select the study areas and respondents. In the first stage, three districts: Machakel, Baso Liben and Banja were selected based on their soil acidity profiles, which are representative of the broader regional patterns in northwestern Ethiopia. This selection was made in consultation with agricultural experts from the East Gojjam and Awi Zone agriculture offices. In the second stage, kebeles within each district were categorized by soil acidity severity to ensure representative site selection. Based on this categorization, one kebele was randomly selected from each district: Debre Kelemua in Machakel, Limichim in Baso Liben and Sankit Lideta in Banja. To ensure a representative sample of households, comprehensive household rosters were obtained from the respective local agricultural offices. Using these rosters as sampling frames, we used a simple random sampling technique to select 292 households from the three kebeles: 96 from Debre Kelemua, 96 from Limichim and 100 from Sankit Lideta.

A team of six trained field operatives conducted face-to-face interviews with household representatives. Members of this team attended a one-day training session, which included mock interviews to standardize the survey approach, clarify questionnaire content and minimize biases during data collection. The final questionnaire covered topics such as household socioeconomic profiles, farm characteristics, soil acidity severity and management practices, crop production systems, field history, livestock holdings, grazing land management, tree planting, annual crop types and yields, crop and tree evolution, and soil conservation strategies.

Face-to-face interviews were chosen as the primary data collection method to engage effectively with a largely illiterate population. The survey began with a verbal informed consent process, in which participants were informed that participation was voluntary, that they could withdraw at any time, and that responses would be anonymized and analyzed in aggregate. Each interview lasted about 1 h. Data collection for the final survey took place between February and April, 2022.

2.3 Soil sampling and laboratory analysis

Following the formal survey, a stratified random sampling approach was used to validate farmer perceptions of soil acidity using scientific measurements. Each soil sample was directly paired with the corresponding plot surveyed by the farmer, ensuring that laboratory measurements could be directly compared with the farmer perceptions of soil acidity for the same field. Based on questionnaire responses, farmers were grouped into three perceived acidity categories: high (n = 67), medium (n = 194) and low (n = 31). Within each sampled kebele, systematic sampling was conducted, resulting in the selection of 50 farmers (and corresponding fields) from Sankit Lideta and 48 each from Debre Kelemua and Limichim kebeles. Of these, 34 fields were classified as high, 98 as medium and 14 as low perceived acidity, yielding a total of 146 composite soil samples. This stratified sampling design ensured representative coverage across the farmer-perceived acidity gradient and enabled robust comparisons with laboratory-determined soil pH (H_2O) and Munsell color categorization.

Soil samples were collected from the 0–20 cm depth using a systematic transect walk across each field to ensure representativeness. Farmers who owned the sampled plots were also asked to describe the soil color. In each field, five subsamples were collected following an X-pattern and combined into a 500 g composite sample. Samples were labeled, sealed in plastic bags and transported to the Debre Zeit Agricultural Research Center, Ethiopia, for laboratory analysis. Prior to transportation, the color of each composite sample was determined on a moist basis using the Munsell Soil Color Chart[16]. In the laboratory, soil pH was measured in 1:2.5 soil: water suspension using a pH meter following the procedure described[17].

2.4 Statistical analysis

Survey data were entered into SPSS (version 26.0, IBM, Armonk, NY, USA) for descriptive statistics, data management, basic ANOVA and assumption checking. Normality of continuous variables was assessed using the Shapiro-Wilk test and supported by histogram and stem-and-leaf plots, and homogeneity of variance (homoscedasticity) was examined using Levene's test. Laboratory data and analyses requiring non-parametric methods, including Spearman's rank correlation and chi-square tests, were performed in R (version 4.5.2)[18]. To directly assess the alignment between farmer classifications and laboratory measurements, correspondence matrices were constructed and analyzed, presenting the percentage and count of fields in each farmer category corresponding to each scientific class. Scientific acidity classes were defined following Jones[19] based on pH (H_2O) ranges: extremely acidic (< 4.5), very strongly acidic (4.5–5.0), strongly acidic (5.1–5.5) and moderately acidic (5.6–6.0) and slightly acidic (6.1–6.5). These analyses provided insights into the relationships between farmer perceptions of soil acidity and laboratory-measured soil properties.

3 Results

3.1 Demographic and socioeconomic characteristics of the surveyed respondents

Table 1 presents a summary of the demographic and socioeconomic characteristics of the surveyed respondents. The surveyed respondents had an average age of about 50 years, with over 30 years of farming experience. Most households (96%) were male led, with an average household size of 5.8 persons. On average, respondents had completed slightly more than two years of schooling. The sampled households had an average landholding of 1.47 ha and an annual income of 1945 USD. Almost all respondents were members of agricultural cooperatives, while nearly 40% of households received credit, and 60% participated in off- and non-farm income-generating activities. Also, most farmers (89%) participated in compressive training on soil and water conservation practices.

3.2 Farmer indicators and causes of soil acidity

Farmers predominantly identified yield reduction (> 97%) and stunted crop growth (> 90%) as the most prominent indicators of soil acidity, with these perceptions consistent across different categories of perceived acidity severity (Fig. 1). In contrast, difficulty in plowing was the least recognized indicator across all acidity categories. Notably, Fig. 1 shows that farmers who perceived medium levels of soil acidity severity reported all indicators more frequently than those perceiving low or high severity.

The top three causes of soil acidity identified by farmers were

Table 1 Summary statistics for demographic and socioeconomic characteristics of the surveyed respondents

Variable (unit)	Mean ± SD
Age of the household head (years)	50.0 ± 11.4
Male-headed household (%)	96
Educational levels of household head (years)	2.31 ± 2.89
Household size (no. of members)	5.80 ± 1.81
Farm experience of household head (years)	30.2 ± 11.7
Livestock holding size (TLU)	6.67 ± 3.31
Landholding size (ha)	1.47 ± 0.99
Participation in off- and non-farm income activities (%)	60
Membership in agricultural cooperatives (%)	99
Households received credit (%)	39
Total household income (USD*)	1945 ± 1523
Participation in soil and water management training (%)	89

Note: *During the study period, currency local exchange rate was 1 USD = 52 Birr.

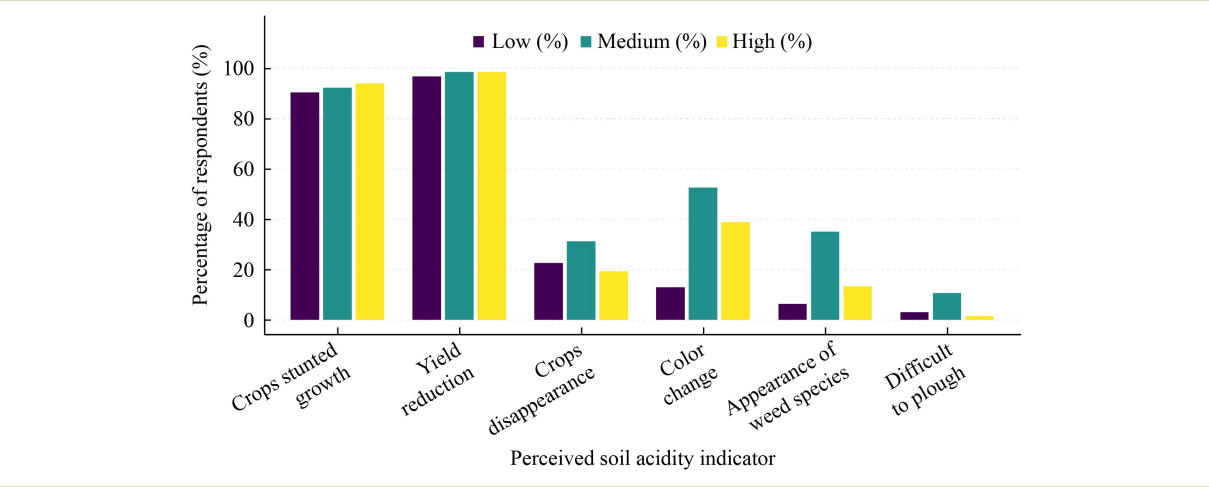

Fig. 1 Farmer perceptions of indicators for soil acidity.

lack of crop rotation, poor field management (continuous cultivation and land compaction), and poor reclamation (inadequate liming, complete removal of crop residues from the farm and poor organic fertilizer management) (Fig. 2). These causes were given by over 70% of respondents who perceived they had low soil acidity severity and by slightly less than two-thirds of those who perceived they had medium severity. In contrast, for farmland perceived to have high soil acidity severity, the predominant causes shifted to lack of crop rotation (79%), absence of fallow periods (57%), and poor field management (52%). Additionally, more than half of the respondents perceiving low and medium soil acidity severity highlighted high rainfall and the continuous use of mineral fertilizers.

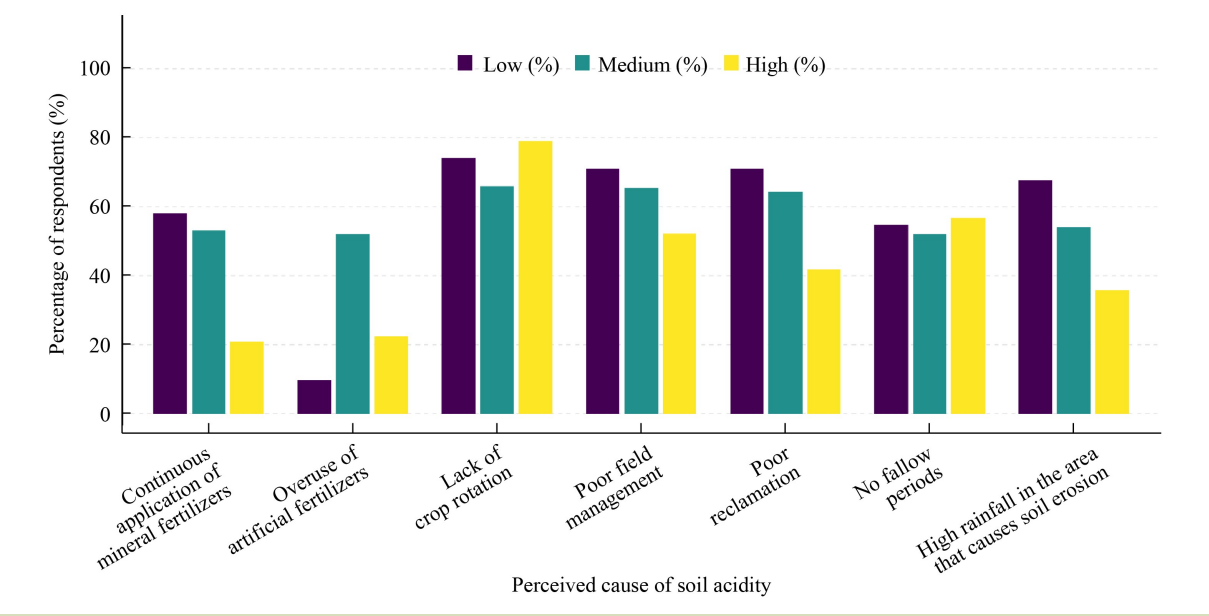

Fig. 2 Main causes of soil acidity as perceived by farmers.

3.3 Correspondence between farmer perceptions and laboratory measured soil properties

The correspondence between farmer perceptions and laboratory measurements was analyzed for soil acidity and color.

For soil acidity, a significant correlation was found between the categorization (low, medium and high) made by farmers and laboratory-measured soil pH (Spearman's ρ, $P \leqslant 0.001$). The distribution of pH values across farmer categories is given in Fig. S1. The direct alignment between these farmer categories and standard laboratory pH classes is presented in Table 2. This analysis revealed a clear gradient: the proportion of fields classified as extremely acidic (pH < 4.5) increased from 38% in the low category to 51% in medium and 86% in high categories. Conversely, the proportion in the strongly acidic category (pH 5.1–5.5) decreased (31%, 11% and 0%) across the same gradient. A visual representation of this alignment matrix is provided in Fig. S2.

For soil color, visual assessments (brown, red and gray) made by farmers were significantly associated with laboratory-determined Munsell color categories (χ^2 test, $P \leqslant 0.05$). The correspondence matrix (Table 2) shows that the majority of fields described by farmers as brown (71%) or red (81%) were classified within the reddish laboratory hue family (2.5YR, 5YR). Fields identified as gray (n = 2) corresponded to the brown/yellowish red hue family (7.5YR, 10YR). The comparison of farmer and laboratory color categories is visualized in Fig. S3.

3.4 Farmer management strategies for soil acidity

Farmers have adopted several key strategies to manage soil acidity, with the three most common practices being the application of organic fertilizers, planting of bitter white lupin (*Lupinus albus*), and retaining crop residues on the land (Fig. 3). These strategies were consistently ranked highest across different levels of perceived soil acidity.

For farmland with low acidity, most respondents reported using organic fertilizers (97%), planting bitter white lupin (87%), and retaining crop residues (84%). Similarly, on medium-acidity soils, 97% applied organic fertilizers and about 74% practiced both bitter lupin planting and crop residue retention. In highly acidic areas, 91% of respondents used organic fertilizers and planted bitter white lupin and 63% left crop residues on the land.

In addition to these primary techniques, farmers also used crop rotation on over 70% of the farmland perceived as having medium and high levels of acidity. Soil conservation structures were established on about two-thirds of this farmland to help mitigate soil degradation. Additionally, lime was applied to over two-thirds of the farmland with high acidity and about

Table 2 Percentage correspondence between farmer perceptions and laboratory assessments for soil acidity (pH) and color (n = 146 fields)

Farmer	Laboratory		
	Extremely acidic (pH < 4.5)	Very strongly acidic (pH 4.5–5.0)	Strongly acidic (pH 5.1–5.5)
Farmer perception vs laboratory pH-based assessment			
Low (n = 13)	38	31	31
Medium (n = 97)	51	38	11
High (n = 36)	86	14	0
Farmer	**Laboratory**		
	Reddish hues (2.5YR, 5YR)	Brown/YR hues (7.5YR, 10YR)	Grey/neutral hues
Farmer perception vs Munsell color chart categorization			
Brown (n = 51)	71	29	0
Red (n = 93)	81	19	0
Grey (n = 2)	0	100	0

Note: Laboratory pH classes defined following Jones[20].

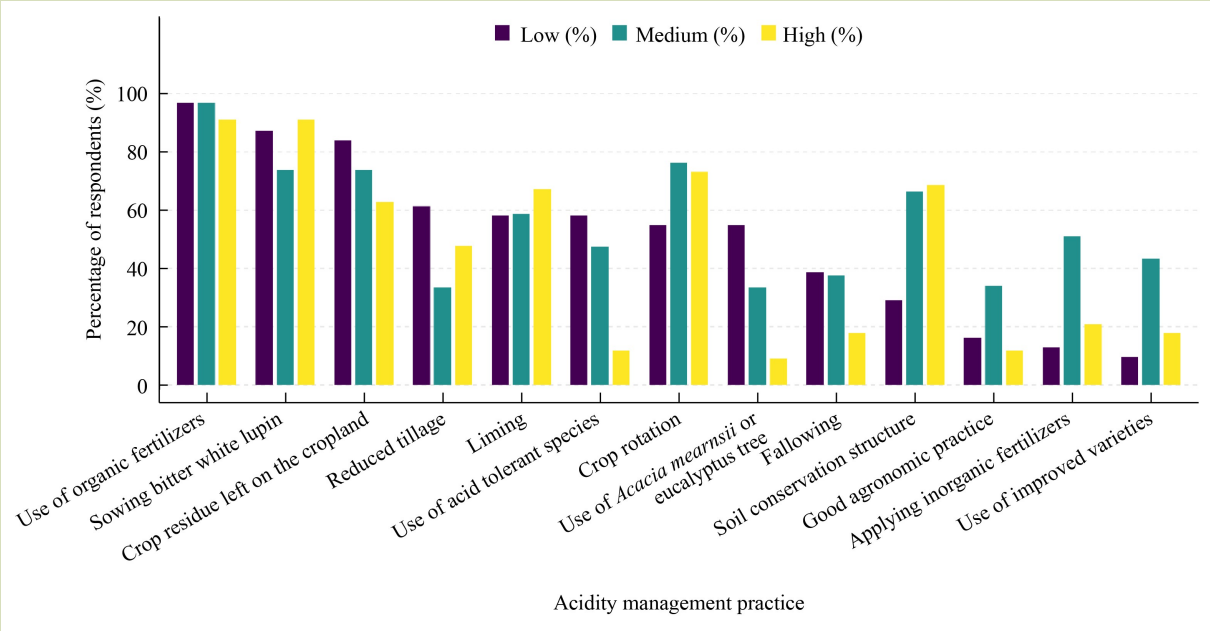

Fig. 3 Farmers practice to manage soil acidity in their farmland.

58% of those with low and medium acidity. Reduced tillage (61.3%) and the planting of acid-tolerant species (58%) were also widely used, especially when soil acidity was perceived as low.

3.5 Lime and organic fertilizer application practices

The findings on the patterns of lime and organic fertilizer application in relation to the severity of soil acidity among farmer fields are presented in Table 3. In total, nearly half of

Table 3 Applications of lime and organic fertilizers across acidity categories

Input	Acidity severity (%)			Total (%) (n = 292)
	Low (n = 31)	Medium (n = 194)	High (n = 67)	
Lime				
No lime application	87.1	49.5	28.4	48.6
Full recommended rates every year	0.0	6.2	6.0	5.5
Full recommended rates once every 3 years	3.2	25.8	44.8	27.7
Full recommended rates once per 5 years	6.5	14.4	13.4	13.4
Full recommended rate divided and applied over 3 or 4 years	3.2	4.1	7.5	4.8
Organic fertilizer				
Compost	96.8	97.9	95.5	95.9
Vermicompost	3.2	11.6	10.4	10.3
Animal manure	71.0	80.0	61.2	73.6
Green manure (mainly bitter lupin)	22.6	52.1	37.3	44.9

Note: Recommended lime rate in the area was 2 t·ha^{-1}.

the farmers (49%) did not apply lime, particularly evident in the low acidity group, where a substantial majority (87%) of participants opted not to use lime. In the medium and high perceived acidity groups, the percentages of non-application were lower, at 50% and 28%, respectively. Among those applying lime, only 13% of the total farmers applied full recommended lime rates once every 5 years. A more frequent approach of applying the full recommended rates once every 3 years was more widely adopted (28% of the samples). This practice was especially prevalent in the high-acidity group, where about 45% of farmers adhered to the three-year cycle, compared to about 26% in the medium-acidity group.

Regarding the use of organic fertilizers, nearly all farmers reported applying some form of organic fertilizer, regardless of perceived acidity levels (Table 3). Compost was the most commonly used, with over 95% of farmers across all categories incorporating it into their fields. Animal manure was also widely applied, particularly in medium-acidity areas (80%), while green manure (mainly bitter white lupin) was used more frequently in medium- and high-acidity fields, at 52% and 37%, respectively.

3.6 Fertilizer applications and wheat yield across acidity severity categories

During the 2021/22 survey year, application of inorganic fertilizers by farmers, specifically urea and NPSB, varied across the perceived soil acidity categories (Table 4). On average, the urea application rate across all categories was 171 kg·ha^{-1}. Farmers in medium-acidity areas used the highest rates, averaging 176 kg·ha^{-1}, followed closely by high-acidity areas at 174 kg·ha^{-1}. Similarly, the overall average NPSB fertilizer application rate was 258 kg·ha^{-1}, with medium-acidity fields receiving 254 kg·ha^{-1}. Notably, farmers in high-acidity areas applied even more NPSB, averaging 304 kg·ha^{-1}.

The analysis of wheat yields over time, based on farmer perceptions of soil acidity, shows notable trends (Table 4). A decade ago, yields were higher across all levels of perceived acidity, with high-acidity fields recording the highest average yield of 3.17 t·ha^{-1}, followed by medium- and low-acidity fields. Five years ago, yields declined slightly but followed a similar pattern, with high-acidity fields again producing the highest yields at 3.02 t·ha^{-1}. In the most recent growing season (2021/22), yields dropped further, with high-acidity fields still leading at 2.77 t·ha^{-1}, followed by medium- and low-acidity fields.

3.7 Crop disappearance, new introductions and farmer choices for adapting to soil acidity

Over the last decade, 94.2% of respondents reported the disappearance of certain crops from their areas, with the highest losses occurring in high-acidity areas (97%) (Table 5). The most affected crops were faba bean (86% loss) and field peas (78% loss), but bread wheat also markedly declined in high-acidity areas (55%). Soil acidity was identified as the primary cause by 69.2% of farmers, with nearly 70% of those in low- to medium-acidity areas and 66% in high-acidity areas attributing crop losses to this issue.

To combat the effects of soil acidity, farmers have introduced

Table 4 Mean inorganic fertilizer application and wheat yield by perceived acidity severity categories

Input use vs yield	Perceived soil acidity			Total (n = 292)
	Low (n = 31)	Medium (n = 194)	High (n = 67)	
Inorganic fertilizer application (kg·ha^{-1})				
Urea	136 (58)	176 (186)	174 (67)	171 (157)
NPSB compound fertilizer	178 (114)	254 (179)	304 (139)	258 (168)
Wheat yield (t·ha^{-1})				
10 years ago	2.42 (1.13)	2.63 (1.17)	3.17 (1.32)	2.55 (1.17)
5 years ago	1.94 (1.12)	2.49 (1.18)	3.02 (1.01)	2.73 (0.13)
Survey year (2021/2022)	2.12 (0.87)	2.48 (1.07)	2.77 (0.96)	2.51 (1.04)

Note: Urea comprises 46% N; NPSB compound fertilizer comprises 19% N, 17% P, 7% S and 0.1% B; standard deviations are in the bracket.

Table 5 Crop disappearance, new introductions and farmer choices (% of respondents) for adapting to soil acidity

Response	Low (n = 31)	Medium (n = 194)	High (n = 67)	Total (n = 292)
Were there any crop types disappeared in the area in the last ten years?				
Yes	87	94	97	94
No	13	6	3	6
Disappeared crops /tree types				
Food barley	10	18	17	17
Bread wheat	43	19	55	30
Maize	7	1	6	3
Teff	27	12	8	12
Faba bean	77	86	91	86
Field pea	63	81	74	78
Others (niger, linseed and garlic)	10	26	18	23
Reason for the disappearance of earlier adapted crops				
Acidity problem	71	70	66	69
Climate variability	9	22	28	23
Outdated varieties	7	4	3	4
Diseases	3	4	3	4
Newly introduced crops/trees				
Bitter white lupin	31	59	71	59
Oat	15	29	59	34
Triticale	69	51	35	49
Acacia mearnsii	42	52	28	46
E. globulus	8	10	5	9
No new crops introduced	4	4	14	6
Farmers preferred crops/trees				
Bitter white lupin	48	60	89	64
Oat	21	40	60	42
Triticale	55	40	25	38
Potato	55	59	60	58
Acacia mearnsii	21	30	6	23
Eucalyptus trees	3	6	0	4
Fruit trees	0	2	2	1

more resilient crops and trees to sustain agricultural productivity. Bitter white lupin has become the most widely adopted crop, grown by 59% of respondents, particularly in medium (59%) and high-acidity areas (71%). Triticale was also widely adopted (49.2% overall), with higher prevalence in low- and medium-acidity areas. Oats were less common but had notable adoption in high-acidity areas (59%).

In addition to crops, farmers integrated trees to improve soil conditions and counteract the effects of acidity. *Acacia mearnsii* (black wattle) was the preferred species, introduced by 52% of respondents in medium-acidity and 28% in high-acidity areas. Bitter white lupin remained the most preferred option for crop diversification, preferred by 90% of respondents in medium-acidity areas and 60% in high-acidity areas. Oats

followed, mentioned by 60% in high-acidity and 40% in medium-acidity zones. Triticale was also a notable choice, particularly in medium-acidity areas, where 40% of respondents adopted it.

4 Discussion

The findings of this study underscore the essential role of the local knowledge of farmers and adaptive strategies in managing soil acidity, particularly in regions where acidity-induced soil degradation threatens agricultural productivity. Farmers appeared to have a high level of awareness regarding soil acidity, primarily identifying yield reduction and stunted crop growth as key indicators. These perceptions align with previous studies in African highlands, which emphasize vegetation health and crop performance as reliable indicators of soil health[21]. However, the reliance on crop performance as diagnostic tool has its limitations, as symptoms often manifest late in the growth cycle, reducing the opportunity for timely intervention[22,23]. This pattern suggest that farmers tend to recognize soil acidity primarily through its most visible and severe manifestations, whereas early-stage or less perceptible drivers remain underappreciated. This gradient in recognition influences both the timing and intensity of management responses and highlights the value of integrating early detection tools, such as soil testing and field-level monitoring, into farmer decision-making processes to enable more proactive and preventive soil fertility management.

Farmers attributed soil acidification to continuous cropping, poor field management, inadequate reclamation and the absence of fallow periods, which accelerate the depletion of essential base cations, such as Ca and Mg, critical for buffering soil pH[5,24]. Despite these challenges, farmer perceptions of soil acidity and color corresponded with laboratory measurements, demonstrating the reliability of local knowledge in assessing soil conditions. Rather than functioning as direct proxies for specific pH thresholds, the high, medium and low categories used by the participating farmers represent a qualitative ranking of acidity severity. This gradient-based classification indicates that farmers are able to consistently differentiate levels of soil constraint relevant to management and crop performance, even without reference to quantitative soil chemistry. By integrating long-term observations of crop performance, soil color and texture, farmers provide a practical framework for site-specific soil management where formal soil testing is limited or costly[16,22,24,25]. This gradient-based cognition explains why fields perceived as only moderately acidic were often classified as very strongly acidic in the laboratory; farmers are effectively ranking fields by relative problem severity within a uniformly acidic context. Nonetheless, some soils perceived as moderately acidic or of low acidity were classified in the laboratory as very strongly to extremely acidic, reflecting the limitations of visual indicators, field-level variability, seasonal moisture fluctuations and subtle differences in mineral composition[17,20]. Concurrently, the frequency and intensity of management interventions mirrored this recognition gradient, with farmers prioritizing corrective measures such as lime application, organic amendments and acid-tolerant crops in fields where acidity was clearly visibly manifested, while less apparent acidity drivers received comparatively limited attention.

Laboratory analyses confirmed persistently low soil pH, promoting phosphorus fixation by aluminum and iron and reducing its availability for plant uptake, thereby constraining crop productivity[20,24,25]. Acidification also decreases cation exchange capacity through protonation of colloids and organic matter, while leading to increased organic carbon accumulation due to suppressed microbial activity and stabilization of organ mineral complexes[19,26,27]. These findings highlight the importance of integrating the local knowledge of farmers with scientific soil assessments to guide targeted interventions, including lime application, crop selection and nutrient management, ultimately enhancing soil fertility and crop productivity.

In response to soil acidity, farmers have widely adopted organic amendments, such as compost and manure, alongside rotational cropping with acid-tolerant species such as bitter white lupin and triticale. These strategies not only mitigate acidity but also enhance soil organic matter content, improve microbial activity, and sustain crop productivity[28,29]. However, despite its effectiveness, lime application, a direct measure for acidity amelioration, was inconsistently practiced due to cost constraints and skepticism regarding its long-term benefits. Those farmers who applied lime typically followed a 3-year cycle at the recommended rate (2 $t \cdot ha^{-1}$), though application rates varied, reflecting a partial adoption trend observed in other acidic regions[30]. This variability further illustrates how farmer recognition of acidity severity shapes both the choice and intensity of management practices. Strengthening extension services and providing technical

guidance on optimized lime use could significantly enhance its effectiveness and encourage broader adoption.

Wheat yield trends reported by farmers reveal a progressive decline over time, largely due to monocropping and insufficient soil conservation measures that accelerate nutrient depletion and soil acidification. Notably, farmers who perceived high levels of acidity reported relatively higher wheat yields, potentially due to improved management practices, including increased lime and inorganic fertilizer applications, as well as the adoption of acid-tolerant crop rotations with bitter white lupin. This underscores the necessity of sustainable nutrient management strategies, as soil degradation directly impacts long-term crop productivity and resilience[5]. Also, the significant decline of legumes, such as faba bean and field pea, due to soil acidity highlights the urgency of introducing alternative legume-based rotation systems that are crucial for maintaining soil fertility and improving farm-level nitrogen availability.

The shift in the crop and tree selections made by farmers further reflects ongoing adaptation to acid-prone environments. The widespread adoption of acid-tolerant crops such as bitter white lupin, triticale and oats demonstrates the proactive efforts of farmers to sustain productivity under acidic conditions. This strategic selection is informed by the same gradient of perceived severity revealed in the correspondence analysis. These species not only tolerate low pH soils but also contribute to soil fertility through biological nitrogen fixation and phosphorus mobilization[29,31,32]. Similarly, the preference for nitrogen-fixing tree species, such as *Acacia mearnsii*, in low- and medium-acidity areas suggests recognition of their role in improving soil structure and nutrient cycling[33,34]. Collectively, these adoption patterns confirm that farmer knowledge of major acidity drivers and their degree of recognition directly inform crop and tree selection as integral components of soil management. These findings reinforce the importance of integrating locally adapted, acid-tolerant species with sustainable soil management practices to enhance resilience against soil acidification and sustain long-term agricultural productivity.

5 Limitations of the study

This study has some limitations that should be considered when interpreting the findings. First, the cross-sectional survey design limits the ability to assess temporal changes in soil acidity and management practices over time. Second, the study was conducted in only three kebeles of the Upper Blue Nile Basin, which may limit the generalizability of the results to other regions. Finally, the number of formal soil tests was relatively small compared to the total number of surveyed fields, which may have constrained the precision of laboratory-based validation.

6 Conclusions

This study highlights the strength of farmer awareness of soil acidity and its detrimental effects on crop productivity, with yield reductions and stunted growth identified as primary indicators. However, relying solely on late-stage symptoms limits proactive management, underscoring the need for rapid soil testing tools, such as affordable pH meters, to facilitate timely interventions. Farmers primarily attribute soil acidification to continuous cropping, inadequate fallow periods and poor field management, practices that accelerate nutrient depletion and soil degradation. These insights align closely with scientific findings, suggesting that sustainable practices such as crop rotation with acid-tolerant species and organic fertilizers could mitigate acidity effectively. Strengthening extension services to promote these practices would enhance soil restoration efforts and mitigate acidification.

A key finding is the nature of the correspondence between farmer perception and scientific measurement. Farmer categories represent a gradient of relative severity within a predominantly acidic environment, rather than a precise mapping to pH classes. This explains why laboratory measurements often indicated more severe acidity than perceived for fields in the “Low” category. Bridging this gap through integrated approaches that combine empirical soil testing with local knowledge of farmers could improve the precision of soil management decisions. Expanding access to soil testing services and fostering stronger linkages between scientific assessments and local observations would facilitate targeted and sustainable interventions for soil acidity mitigation. While farmers widely adopt organic fertilizers, crop rotation, and acid-tolerant species such as bitter white lupin and triticale, lime application remains inconsistent due to skepticism and cost constraints. Further research on lime effectiveness and the integration of locally adapted soil improvement techniques could enhance its adoption, particularly in high-acidity areas.

The continued decline in wheat yields and legume diversity underscores the need for sustainable nutrient management strategies. Acid-tolerant crops such as bitter white lupin, triticale and oats not only demonstrate resilience in acidic soils but also contribute to soil fertility restoration through nitrogen fixation and improved organic matter dynamics. Promoting these crops could boost resilience and food security, particularly in high-acidity areas. Finally, fostering participatory research that integrates farmer insights with scientific methods will be critical in developing effective, context-specific soil health strategies that ensure long-term productivity and sustainability.

7 Recommendations

Based on the findings of this study, we recommend the following actions.

(1) Promote the use of affordable soil testing tools to enable early detection of soil acidity.

(2) Encourage crop rotation with acid-tolerant species such as bitter white lupin, triticale, and oats.

(3) Expand the adoption of organic amendments (compost and manure) to improve soil fertility and mitigate acidity.

(4) Optimize lime application through extension guidance, including recommended rates and timing.

(5) Integrate farmer perception with scientific soil assessments to guide site-specific management practices.

(6) Introduce alternative legume-based rotation systems to sustain nitrogen availability and soil fertility.

(7) Promote the planting of nitrogen-fixing trees, such as *Acacia mearnsii*, to enhance soil structure and nutrient cycling.

(8) Foster participatory research approaches that integrate farmer insights with scientific methods for sustainable soil management.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-26690 contains supplementary materials (Figs. S1–S3).

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Compliance with ethics guidelines

Belstie Lulie, Enyew Adgo, and Zerihun Nigussie declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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