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Assessing the Spatial Variability of Soil Acidity in Assosa District, Northwestern Ethiopia

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ABSTRACT

Soil acidity negatively affects agricultural productivity, biodiversity, and food security in the tropical and subtropical regions. It exhibits significant spatial variability arising from natural soil-forming processes and anthropogenic factors. This study aimed to analyze the spatial variability of soil acidity, develop digital maps of acidity levels, and characterize selected soil properties related to acidity in cultivated land. A total of one hundred georeferenced composite surface soil samples were collected using multistage, stratified, and random sampling techniques. Samples were analyzed for pH in both H_2O and KCl solution, soil organic matter (SOM), cation exchange capacity (CEC), exchangeable acidity (EA), exchangeable aluminum (EAl), and soil texture. The results showed that the soil pH in H_2O ranged from 5.06 to 6.60 (mean 5.56), while the pH in KCl ranged from 3.95 to 5.17 (mean 4.43). The consistent acidity across both measurements, with a mean ΔpH of approximately 1.13, indicates that the soils are predominantly acidic, likely due to significant levels of Al^{3+} and H^{+} ions on the exchange sites. Geostatistical analysis identified the Gaussian model as the best fit, with a spatial range of 18.95 km, well above the average sampling distance of 3.2 km. Ordinary kriging showed that soil pH variation was moderately influenced by intrinsic soil properties and external environmental or management factors. The resulting spatial map classified the study area into three soil acidity levels: strongly acidic soils (38.2%, ~49,606 ha), moderately acidic soils (38.4%, ~49,830 ha), and neutral soils (23.4%, ~30,397 ha). The generated soil acidity map provides baseline information and can serve as a valuable tool to develop targeted management strategies for soil acidity. Future studies should focus on periodic assessments of soil acidity and its spatial variability in the study area, along with detailed mineralogical analyses to support precision agriculture and optimize acid soil management.

1 | Introduction

Acidic soils occupy approximately 30%–40% of agricultural land globally and negatively impact agricultural productivity, biodiversity, and food security [1, 2]. Soil acidity adversely affects plant growth and productivity by reducing nutrient availability, altering microbial communities, and increasing the availability of toxic heavy metals, thereby threatening soil health and food security [3–6]. In Ethiopia's agrarian economy, soil acidity is a major constraint: 43% of farmland is acidic, with 28% classified as strongly acidic [7–9]. A site-specific study of soils around Assosa and Wellega further indicates that approximately 67% of the assessed area had a pH < 6 [3].

Acidic soils exhibit significant spatial variability, arising from both natural soil-forming processes and anthropogenic influences such as the agronomic practices [10, 11]. This heterogeneity is evident at multiple scales, with factors like

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geochemical processes and management practices, including irrigation and erosion, causing soil pH to vary markedly across landscapes [12, 13]. In Ethiopian agro-ecosystems, for instance, soil pH values vary significantly (pH 4.1–5.5), necessitating precision agriculture over uniform management to address heterogeneity [3, 7, 14]. Understanding this spatial variation is crucial for tailoring acidic soil management practices, as the severity of acidity and the required interventions vary considerably from field to field. Modern geostatistical tools, such as kriging, utilize spatial autocorrelation to generate detailed soil acidity maps, enabling site-specific recommendations that enhance productivity, profitability, and environmental sustainability [15]. Ultimately, recognizing spatial variability in soil acidity enables precise mapping and site-specific amendments, optimizing resource use [16].

Soil acidification is the process by which the activity of hydrogen ions (H^+) increases in the soil, lowering soil pH and making soils acidic [10]. This process naturally occurs but is also accelerated by agricultural activities such as continuous cropping without adequate fertilization and the use of nitrogenous fertilizers [9, 17]. As soil acidity rises, the concentrations of acidic cations, aluminum (Al^{3+}) and hydrogen (H^+) in the soil increase while base cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+) are leached from the soil [18]. These base cations play a critical buffering role in noncalcareous soils by neutralizing acidity and supporting plant growth. Their depletion is a significant concern because it exacerbates soil acidification and nutrient deficiency, directly affecting crop productivity [17, 19]. With a growing population and increasing food demand in Ethiopia, alleviating soil acidification is crucial.

To counter soil acidification, the application of lime together with other complementary agricultural practices and amendments has been proposed [6, 20–23]. Liming is the most widely used and effective method to neutralize soil acidity, increase the availability of exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}), and reduce phosphorus immobilization, thereby improving soil fertility and crop productivity [18, 24, 25]. Applications of organic amendments such as biochar, compost, manure, and crop residues have been shown to increase soil pH, alleviate aluminum toxicity, improve nutrient availability, and enhance microbial diversity in acidic soils [26–29]. These organic amendments can partially or fully substitute lime. Biochar, in particular, has been shown to increase soil pH, reduce aluminum toxicity, and improve enzymatic activities that support root growth and plant health [30, 31]. Combining inorganic fertilizers with organic amendments and liming further improves soil physical and biological properties, leading to higher crop yields [17, 32]. Additionally, optimizing nitrogen fertilizer type and application rates is critical for mitigating acidification caused by nitrogen transformations, which are a major anthropogenic driver of soil acidification [33, 34].

The efficacy of soil acidity management, however, hinges on inherent physical and chemical soil properties that govern soil responsiveness to amendments. Additionally, soil attributes and nutrient concentrations frequently exhibit spatial variability within agricultural fields, driven by diverse soil-forming processes [31]. Thus, implementing site-specific management approaches, adapted to localized soil characteristics, is critical for sustainable mitigation of soil acidification while enhancing agricultural productivity.

The most important soil physical and chemical properties that affect the effectiveness of soil acidity management are soil reaction (pH), soil organic matter (SOM), exchangeable acidity (EA), exchangeable aluminum (EAl), cation exchange capacity (CEC), and soil texture [24, 35, 36]. Soil pH, which has often been called a measure of soil acidity and alkalinity, greatly affects numerous soil chemical processes, not only affecting nutrient absorption of crops (Huang et al. 2017) but also influencing migration and transformation of metal elements in the soil [37, 38]. The lime requirement of acid soils depends not only on the current soil pH but also significantly on the soil's buffering capacity, which is closely related to its CEC [39]. Soils containing higher levels of clay and organic matter (OM) exhibit a greater CEC, which means they have a larger reserve of acidity that helps buffer against changes in pH [40]. This buffering capacity requires more lime to neutralize both the active acidity (H^+) and the reserve acidity held on exchange sites of clay and OM. Consequently, soils rich in clay and OM demand higher liming to achieve the desired pH increase compared to sandy soils with lower CEC. According to Nelson and Su [41], high CEC and OM improve the soil's buffering capacity, making it more resistant to pH changes and requiring higher lime rates to neutralize acidity. Soil texture, further, modulates this response; clay-rich soils with higher CEC demand more lime than sandy soils, which acidify and respond to amendments more quickly.

Conventional soil pH monitoring is labor-intensive and impractical for large-scale or long-term assessments [7]. In contrast, geostatistical modeling applied widely in modern agriculture helps to quantify spatial variability, addressing challenges in fertilizer and amendment adjustment phases [14, 17, 20, 35, 42, 43]. However, geostatistical information on the status and spatial distribution of soil acidity in the study area is inadequate to plan an appropriate intervention for soil acidity management and the associated problems. Therefore, the objective of this study was to analyze and produce digital maps of the spatial variability of soil acidity levels, providing essential information for targeted and sustainable acid soil management interventions.

2 | Materials and Methods

2.1 | Description of the Study Area

The study was conducted in Northwestern Ethiopia, specifically in the Assosa District of the Benishangul-Gumuz Region. The area lies between 9°40′0″ and 10°20′0″ N latitude and 34°10′0″ and 34°50′0″ E longitude (Figure 1). The total study area covers approximately 196,973 ha, of which 129,834 ha is cultivated land. The region experiences a monomodal rainfall pattern, characterized by a single rainy season from May to October, followed by a dry season from November to April (Figure 2). Analysis of 10 years (2015–2024) of climatic data from the Ethiopian Meteorology Agency, Benishangul-Gumuz Regional Service Center, indicates that mean annual temperatures range between 14.9°C and 27.9°C, with mean annual rainfall of 1182.9 mm. Elevation of the district ranges from 1500 to 2300 m above sea level (m asl).

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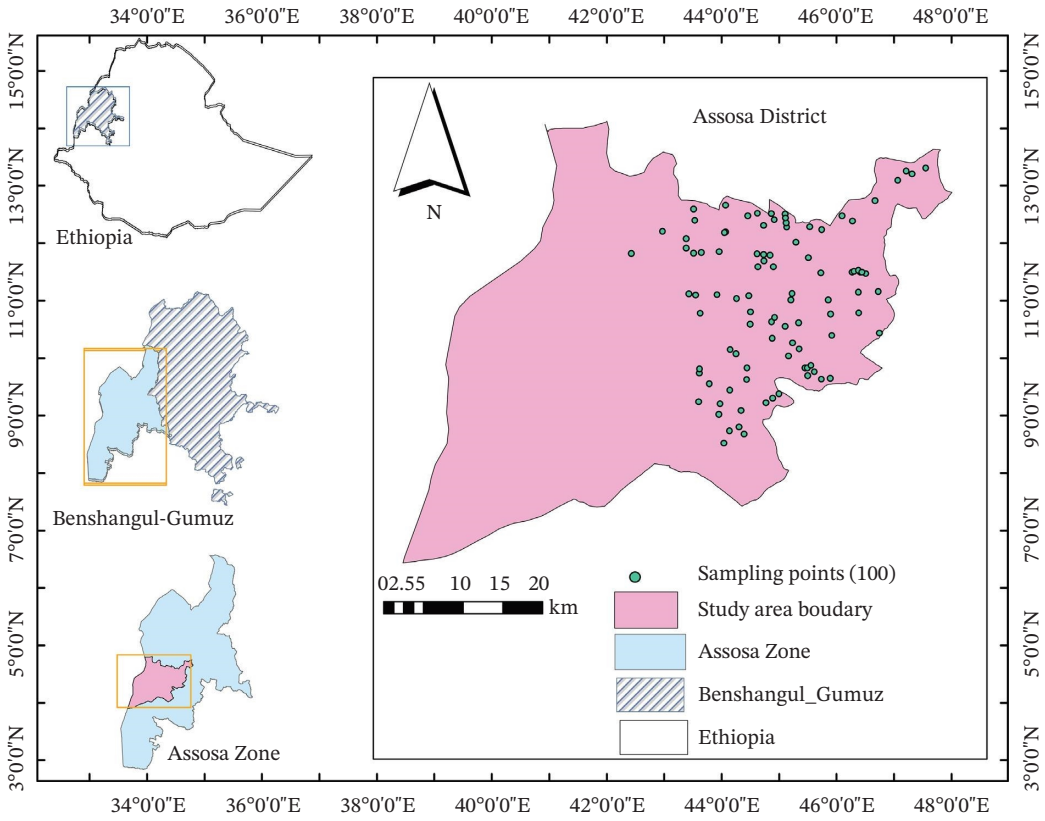


FIGURE 1 | Map of study area for survey, Assosa District.

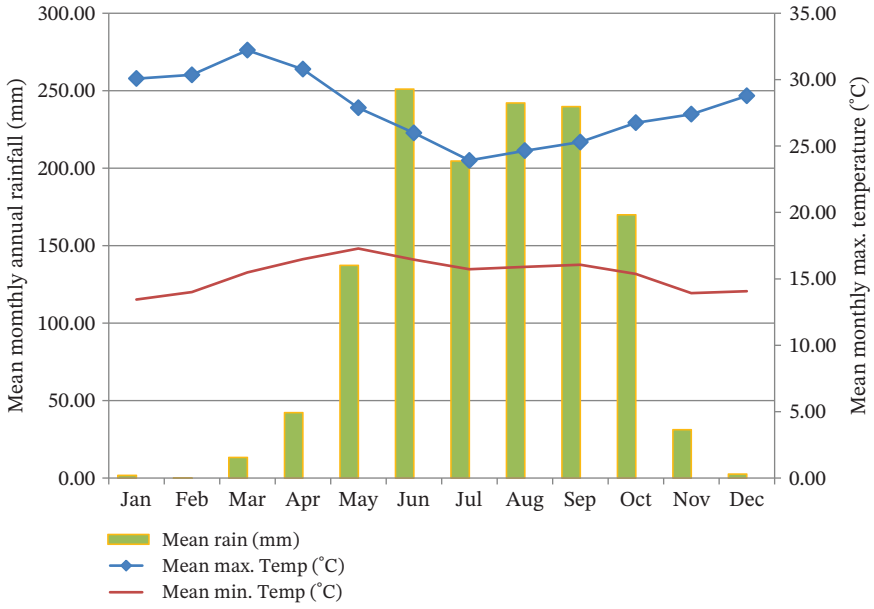


FIGURE 2 | Mean monthly rainfall maximum and minimum temperatures of the Assosa District (2015–2024).

2.2 | Sampling Design and Site Selection

A multistage, stratified, and random sampling approach was employed to ensure representative coverage of the study area. Initially, a base map was developed by analyzing remote sensing data signatures from Google Earth imagery using ArcGIS Version 10.7.1 software, which facilitated the stratification of the district into cultivated and noncultivated lands. Based on this stratification, predefined sampling points were systematically established across the district using grid sampling techniques, with approximately 95% of points allocated to actively cultivated areas and the remaining 5% to potential agricultural zones, including fallow lands. Within each unit or grid, sampling points were randomly positioned based on observed soil variability and land

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use patterns to enhance representativeness. All sampling points were georeferenced and uploaded to a Garmin eTrex GPS receiver and a tablet-enabled field device to facilitate navigation. Alternative points were also prepared in advance to replace any that proved unsuitable during site inspection. During field verification, any points falling outside agricultural areas were excluded, ensuring that only those within actual or potential agricultural land were surveyed and recorded.

2.3 | Soil Sampling Procedure

During the 2023/2024 main cropping season, a Geographic Information System was employed to randomly select 100 sampling locations from the predefined and verified points across the study area. Field teams navigated to these coordinates using GPS devices. Surface soil samples were collected from a depth of 0–20 cm at each location using a soil auger. Depending on the observed variability and terrain, between 9 and 16 subsamples were taken from each site and thoroughly mixed to form a homogeneous composite sample. Approximately 1 kg of this composite soil was retained for laboratory analysis. All collected samples were stored in clean polyethylene bags, clearly labeled, and transported to the Assosa Agricultural Research Center Soil and Plant Analysis Laboratory for subsequent physicochemical analysis.

2.4 | Sample Preparation and Soil Analysis

Following soil processing, which included drying, grinding, and sieving, the soil physicochemical properties—texture, pH, EA, EAl, OM, and CEC—were analyzed.

Soil texture was analyzed by the hydrometer method following the procedure described by Day [44]. Soil textural class names were determined following the textural triangle of the United States Department of Agriculture [45]. Soil pH was measured using a pH meter with a ratio of 1: 2.5 soil to water [46]. Organic carbon was determined using the wet oxidation method [47], and OM was calculated by multiplying the percent OC by the Sprengel factor of 1.724 [48] for cultivated soils. EA (Al^{3+} and H^{+}) and exchangeable Al were determined by saturating the soil samples with 1 N KCl solution and titrating the filtrate with 0.02 N NaOH and 0.02 N HCl, as described by Rowell [49]. CEC was determined from the ammonium acetate-saturated samples through distillation and measurement of ammonium using the procedure described by Chapman [50].

2.5 | Data Analysis

Statistical and geostatistical analyses were conducted using R statistical software [51] Version 4.4.2 and ArcGIS software Version 10.7.1. Descriptive statistics (mean, SD, median, min, and max) and Pearson's correlation matrix were calculated for soil properties. Spatial variability was assessed via variogram analysis and ordinary kriging to examine spatial relationships.

2.5.1 | Spatial Variability Mapping

Geostatistical analysis was conducted using ArcGIS 10.7.1 for Windows to ascertain the spatial distribution of soil acidity parameters. The spatial autocorrelation of these parameters was quantified through the computation of the semivariogram, employing the formula using equation (1) [52], where n is the number of pairs of sample points separated by distance h and $Z(xi)$ is the value at the ith location ($i = 1, 2, 3, ..., n$).

$$(h) = \frac{1}{N(h)}\sum_{i=1}^{N}[Z(xi) - Z(xi + h)]^2. \quad (1)$$

Ordinary kriging was used for mapping soil acidity parameters, with circular, spherical, exponential, and Gaussian models evaluated. The selection of the best-fit model was determined based on root mean square error (RMSE) as per [53]. Predictions for unsampled locations were generated using this kriging method. Spatial dependence was categorized based on the nugget-to-sill ratio, with classifications of strong (≤ 0.25), moderate (0.25–0.75), and weak (> 0.75) spatial dependence as proposed by Cambardella et al. [54].

3 | Results and Discussion

3.1 | Soil Physical Properties

3.1.1 | Soil Texture

The particle size distribution of soil exhibited spatial heterogeneity across the study area. The clay content ranged from 20% to 90%, sand content from 1% to 53%, and silt content from 4% to 35% (Table 1). On average, the soil was dominated by clay-sized particles (71.8%), with lower proportions of silt (14.38%) and sand (13.82%). Based on the USDA soil texture classification [49], the soils were categorized as clay, clay loam, and sandy clay loam in texture.

The predominance of clay (71.8%) suggests that these soils possess high nutrient and amendment retention capacity. However, the wide range in clay content (20%–90%) indicates substantial textural heterogeneity, which has important implications for site-specific soil management. Similar textural variability has been reported in Ethiopian smallholder farms, where erosion-driven clay redistribution from upper to lower slopes leads to accumulation at foot-slope positions [55, 56].

The high clay content observed in most locations implies that lime and organic amendments will persist longer due to high CEC and buffering capacity, but higher application rates may be required to neutralize acidity compared to coarse-textured soils. This is consistent with findings by Zhang et al. [31], who reported that clay-dominated soils require larger amendment quantities but provide prolonged benefits.

Conversely, areas with sandy textures (up to 53% sand) are more vulnerable to rapid acidification and nutrient leaching. In these locations, split applications of lime combined with OM are recommended to sustain fertility and prevent nutrient loss, as suggested by Mamuye et al. [23] and Geremew et al. [57].

The statistical distribution of texture classes (Table 1, Figure 3) confirms pronounced textural heterogeneity, with clay showing a left-skewed distribution (−1.66) and sand exhibiting a right-skewed distribution (1.35). This variability reinforces the need for site-specific amendments: targeted liming in clay-dominated zones and OM incorporation in sandy pockets [58].

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TABLE 1 | Descriptive statistics of selected soil properties in Assosa District (sample size = 100).

Soil properties	Min.	1st Qu	Median	Mean	3rd Qu.	Max	Rang	SD
Chemical properties								
pH-H_2O point observation	5.06	5.38	5.48	5.56	5.75	6.6	1.54	0.28
pH-KCl point observation	3.95	4.26	4.39	4.43	4.53	5.17	1.22	0.22
ΔpH	1.1	1.12	1.09	1.13	1.22	1.43	0.32	0.06
Exchangeable aluminum	0	0	0.16	0.19	0.24	0.96	0.96	0.22
Exchangeable acidity cmol (+)/kg	0.09	0.4	0.58	0.62	0.8	1.52	1.43	0.31
CEC cmol (+)/kg	8	21	26	26.63	30	56	48	8.1
OM (%)	2.56	4.08	4.6	4.71	4.45	6.86	4.3	0.96
Physical properties (texture)								
Sand (%)	1	6	12	13.82	18	53	52	10.83
Silt (%)	4	10	14	14.38	18	35	31	5.42
Clay (%)	20	67.75	74.5	71.8	80.25	90	70	12.06
Textural class: clay, clay loam, and sandy clay loam								

Note: Min: minimum, Max: maximum, 1st Qu: first quartile, 3rd Qu: third quartile.
Abbreviation: SD, standard deviation.

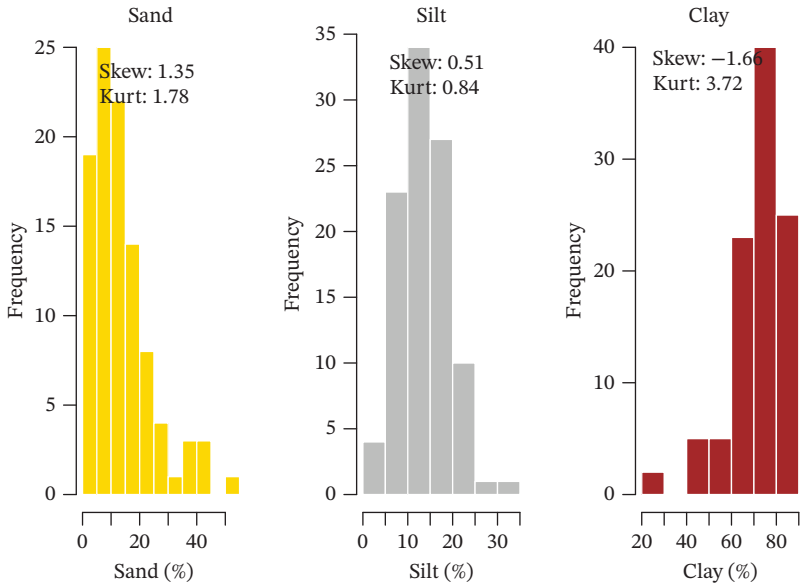


FIGURE 3 | Soil particle size distribution in the study area.

3.2 | Chemical Properties

3.2.1 | Soil pH

Soil pH, measured in water pH-H_2O and potassium chloride pH-KCl solution, exhibited a range from 5.06 to 6.60 and 3.95 to 5.17, with mean values of 5.56 and 4.43, respectively (Table 1). The mean pH-H_2O (5.56) falls below the optimal ranges (5.5–6.8) for many crops [59]. The study area is characterized by acidic soil reaction, as defined by the FAO and ITPS (2015) where soils with a pH-H_2O below 6.5 are classified as acidic.

The difference between pH-H_2O and pH-KCl, ΔpH (pH-H_2O–pH-KCl) ranged from 0.32 to 1.43, with a mean value of 1.13. This suggests high EA and low buffering capacity, meaning pH shifts could occur rapidly if amendments are misapplied. For minor pH adjustments, OM (compost, biochar, etc.) can provide gradual, stable changes, but aggressive acidifiers should be avoided [11].

The predominance of acidic reactions is likely attributable to intensive cultivation, continuous use of acid-forming fertilizers, and high rainfall leading to leaching of basic cations, which are major factors commonly reported in Ethiopian highlands [60, 61, 14, 20, 62, 63]. Similar findings were also reported by Lotse Tedontsah et al. [36] for intensively cultivated soils under cereal systems.

With a standard deviation of 0.28, soil pH exhibited low spatial variability (Table 1), indicating that pH is relatively stable across

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the study area, a characteristic also noted by Bouma and Pinke [62]. The positive skewness of soil pH value (Figure 4) indicates that while most samples cluster around the mean, a few locations have higher pH values. Liming is recommended to raise pH to levels that minimize Al^{3+} toxicity and improve nutrient availability. Acidifying amendments (e.g., sulfur) should be avoided, as they would exacerbate existing acidity.

3.2.2 | EA

EA ranged from 0.09 to 1.52, with a mean value of 0.62 cmol (+)/kg (Table 1). The mean of EA is above the critical level (0.5–1.0 cmol (+)/kg), indicating strongly acidic soil reactions that adversely affect crop production due to aluminum toxicity and nutrient deficiencies.

The moderate spatial variability (SD = 0.31; range = 1.43) suggests that uniform amendment applications would be ineffective, and site-specific management is required to optimize amendment efficiency and remediation precision. This aligns with the observation by Laekemariam and Kibret [43] that EA varies significantly across Ethiopian landscapes due to differences in land use and management history.

The near-symmetrical distribution (skewness = 0.84; kurtosis = 0.84) (Figure 4) indicates relatively stable acidity patterns, which may allow for less frequent resampling [64]. Nevertheless, the mean value above critical thresholds underscores the need for immediate liming interventions.

As illustrated in Figure 4, the skewness and kurtosis values were 0.84 and 0.84, 1.61 and 2.26, 0.66, and −0.05 for soil pH, EA, and EAl, respectively.

3.2.3 | EAl

EAl levels in soils of the study area ranged from 0 to 0.96 cmol (+)/kg, with a mean concentration of 0.19 cmol (+)/kg (Table 1). While the average EAl falls below the general toxicity threshold of 0.2–0.5 cmol (+)/kg [65], the upper range (0.96 cmol (+)/kg) exceeds critical levels, indicating localized Al toxicity hotspots.

The strong right-skewness (1.61) and leptokurtic distribution (kurtosis = 2.26) confirm that high EAl values are clustered in specific locations rather than uniformly distributed (Figure 4). These hotspots are likely associated with areas of severe base cation depletion and low OM, as commonly observed in Ethiopian highland soils [17, 62, 66].

Given that pH values below 5.5 were observed in some areas, the threshold at which Al^{3+} becomes soluble and toxic [6, 8, 18, 67], targeted lime applications combined with organic amendments are recommended for hotspots exceeding 0.5 cmol (+)/kg. For the remaining areas (EAl < 0.2 cmol (+)/kg), preventive measures such as maintaining OM may suffice. This highlights the importance of precision over uniform applications, as noted by Agegnehu et al. [17] and Belay et al. [68].

3.2.4 | SOM

SOM content in the soil samples varied from 2.56% to 6.86% with a mean of 4.71% (Table 1). According to the classification by ATA [7], the district exhibited low to moderate SOM levels. This was possibly because of soil erosion, intensive cultivation, complete crop residue removal, and a high rate of OM decomposition due to high rainfall and temperature.

The near-symmetrical distribution (skewness = −0.05; kurtosis = 2.65) and moderate variability (SD = 0.96) suggest consistent but suboptimal OM depletion across the study area, rather than localized degradation (Figure 5). This pattern reflects widespread practices of residue burning, overgrazing, and continuous tillage, as reported in Ethiopian farming systems [69, 70].

The interaction between low OM and soil acidity is critical in acidic soils, where Al^{3+} dominance can further reduce OM stability [28, 71–73]. Therefore, integrated management combining organic amendments (compost, biochar, etc.) with targeted liming is recommended to address both OM depletion and Al toxicity simultaneously.

3.2.5 | CEC

CEC of the soil varied from 8 to 56 cmol (+)/kg, with a mean value of 26.63 cmol (+)/kg (Table 1). According to soil CEC classification by ATA [7], the study area exhibited low to very high CEC. This variation in soils' CEC could be due to variations

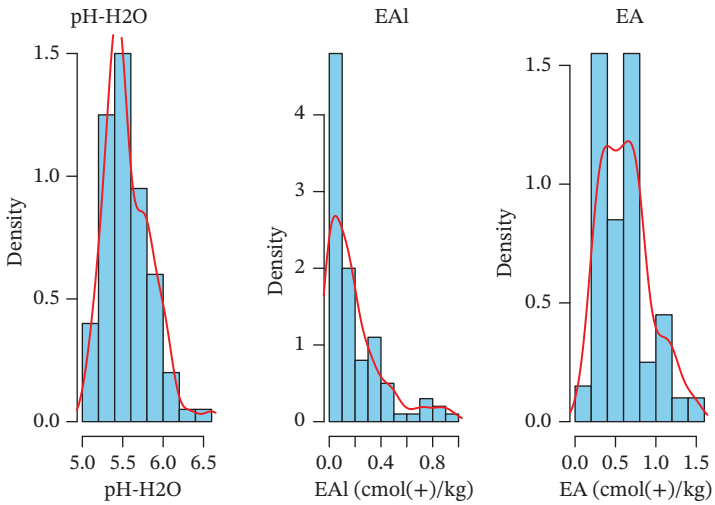


FIGURE 4 | Frequency and distribution of pH (pH-H_2O), exchangeable aluminum (EAl), and exchangeable acidity (EA).

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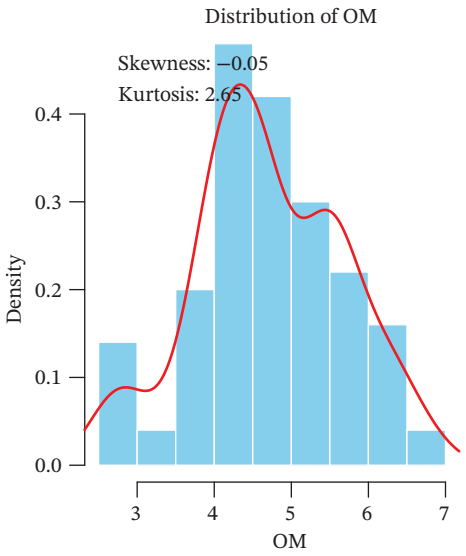


FIGURE 5 | Frequency and distribution of soil organic matter in the study area.

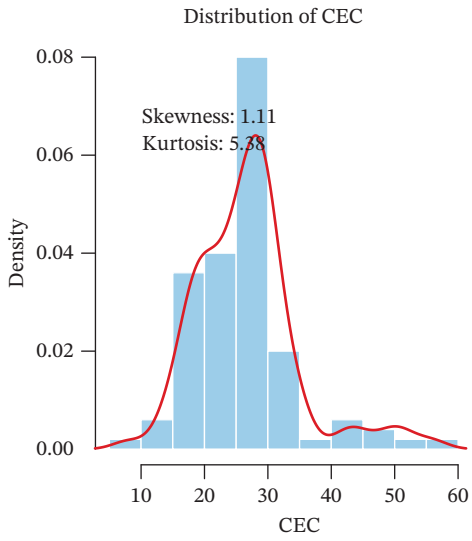


FIGURE 6 | Frequency and distribution of soil CEC values in the study area.

in textural class, mineralogy, pH, and OM across sampling locations.

The positive skewness (1.11) and leptokurtic distribution (kurtosis = 5.38) indicate that while most soils have moderate CEC, a subset of locations exhibit exceptionally high CEC (Figure 6), likely due to localized differences in clay content or OM accumulation [36].

For areas with low CEC (e.g., sandy soils), organic amendments are needed to enhance nutrient retention and prevent rapid leaching of applied lime and fertilizers. In contrast, high-CEC areas may require higher lime rates but will benefit from prolonged amendment persistence [74, 75]. This variability reinforces the need for tailored fertility management strategies.

3.3 | Extent and Spatial Variability of Soil Acidity

The spatial analysis of the results of soil pH revealed three groups of soils according to their acidity levels. Strongly acidic soil (pH < 5.5) occupied across 38.2% of the study area, encompassing approximately 49,606.4 ha. Moderately acidic soils (5.5 ≤ pH < 6.5), which covered 38.4% of the study area, spanning 49,830.2 ha (Figure 7). Only 23.4% (30,396.98 ha) of the study area's soils have a neutral reaction (pH-H_2O, 6.6–7.3), which is suitable for crop production and efficient nutrient uptake by plants. However, it requires soil testing and monitoring for changes in the soil reaction. The widespread acidity levels (76%) of the soils (~99,436.6 ha out of ~129,833.6 ha surveyed) have potentially limited crop productivity and require intervention. Figure 7 shows maps of the extent of strongly acidic (pH < 5.5), moderately acidic (pH 5.5–6.5), and neutral (pH 6.6–7.3) soils. Map projection: [WGS_1984_UTM_Zone_37N].

Geostatistical analysis indicated that the Gaussian model best described the spatial structure of both pH-H_2O and pH-KCl, with moderate spatial dependence (nugget/sill ratio = 0.55 and 0.65, respectively) (Table 2). This moderate dependence suggests that both intrinsic factors (such as parent material and topography) and extrinsic factors (including fertilization and cultivation practices) contribute to the observed variability in soil pH. The range value of 18.95 km, which exceeds the actual sampling interval of 3.2 km, confirms that the sampling strategy was adequate to capture the full spatial variability of soil pH. This spatial pattern is further elucidated by the soil pH semivariogram presented in Figure 8 of the Supporting Information.

The selection of the Gaussian model was based on its lowest residual sum of squares compared to other models (e.g., spherical and exponential) during the fitting process. This model is particularly appropriate for soil pH in this landscape, as it assumes high spatial continuity at short distances, reflecting the gradual influence of intrinsic factors like parent material and topography. This interpretation is further supported by the moderate spatial dependence values, indicating that while extrinsic factors (e.g., fertilization) play a role, the underlying soil-forming factors still exert substantial control on pH distribution.

To validate the kriging interpolation and model performance, a cross-validation analysis was conducted. The scatter plot of measured versus predicted pH values (Figure 9) demonstrates the reliability of the interpolation, with points clustering closely around the 1:1 line, indicating minimal bias. The mean error near zero (−0.005) confirms this lack of bias. The RMSE of 0.25 suggests that the model predicts pH values within approximately ±0.25 units on average, which is acceptable for regional-scale soil fertility assessment. Furthermore, the root mean square standardized (RMSS) value of 1.087 is very close to the ideal value of 1, confirming that the model accurately estimates prediction uncertainty (i.e., the prediction standard errors are neither over- nor under-estimated). Similar spatial dependence for soil pH was reported by Laekemariam et al. [76] from the southern region, Ethiopia, and by Bhunia et al. [77] from India, suggesting that such patterns are common in landscapes influenced by both pedogenic and anthropogenic processes.

The widespread distribution of soil acidity observed in this study can be attributed to a combination of natural and human-induced factors. Agegnehu et al. [17], Tadesse [9], and Regasa et al. [78] reported that many soils in Ethiopia are

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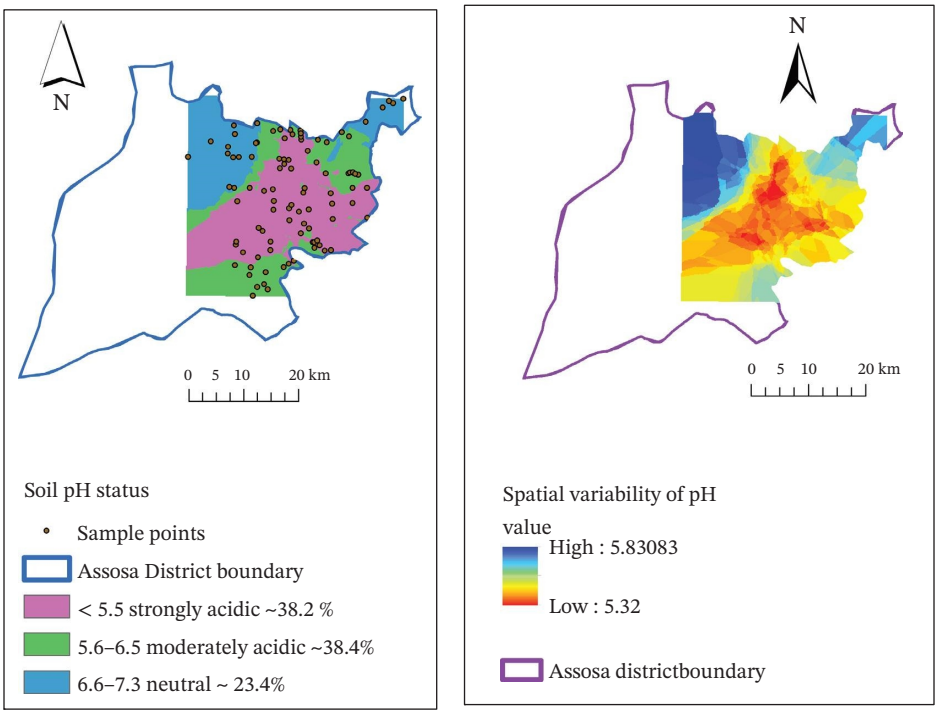


FIGURE 7 | Proportional coverage of soil pH status classes across the study area (a) and spatial distribution of soil pH (b).

TABLE 2 | Model performance and semivariogram characteristics for soil properties.

Semivariogram characteristics	Soil property	
	pH-H_2O	pH-KCl
Model	Gaussian	Gaussian
Nugget (C_0) (m)	0.05	0.03
Partial sill (C1)	0.04	0.02
Sill (C0 + C_1)	0.09	0.05
Range (km)	18.95	23.6
SPD(C0/C0 + C1)	0.55	0.65
SPD level	Moderate	Moderate
Mean	0	0
RMSE	0.25	0.2
Mean standard	−0.018	0
RMSS	1.087	1.06
Av. SE	0.24	0.19

Note: SPD: spatial dependence, RMSE: mean square error, RMSS: root mean square sum errors.

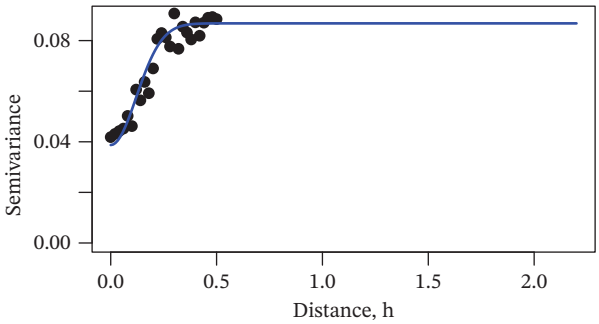


FIGURE 8 | Semivariogram of PH.

naturally derived from acidic parent materials, while others become acidic over time due to human activities like land use change, OM oxidation from repeated tillage, topsoil erosion, and the use of acidifying fertilizers. In the Ethiopian highlands, parent material plays a foundational role; for instance, soils derived from acidic rocks such as Nitisols are naturally prone to acidification [62, 79]. Topography also exerts a strong influence; studies in northwestern Ethiopia demonstrate that lower slope positions accumulate base leached from upper slopes, resulting in higher pH values and nutrient content compared to degraded upper slopes [56]. Similarly, a study on Mount Guna confirmed that elevation and climate significantly affect soil formation and properties, with pH decreasing as elevation increases [80].

Human activity remains a key extrinsic factor driving acidification. Gerbi et al. [81] reported that conversion of natural systems to cultivated land consistently degrades soil properties, leading to lower pH and organic carbon compared to forest or agroforestry lands. Furthermore, the long-term application of acid-forming inorganic fertilizers is a major accelerant of acidification, often intensifying the problem beyond natural causes [33, 34, 79, 82].

The widespread suboptimal acidity (affecting 76.6% of the area) necessitates immediate, site-specific mitigation strategies to prevent further degradation and progression of acidity into subsoil layers. The spatial variability identified in this study

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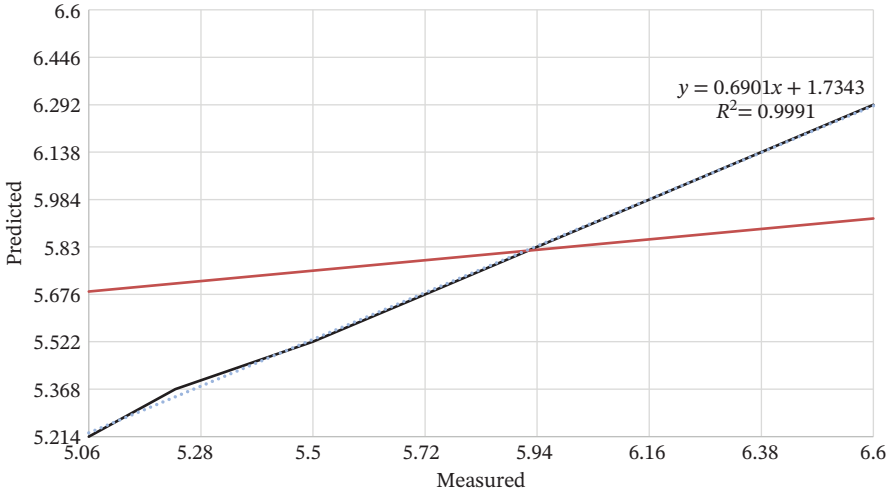


FIGURE 9 | Scatter plot of measured versus predicted soil pH-H_2O from cross-validation analysis.

TABLE 3 | Pearson's correlation matrix between selected soil parameters.

	pH-H_2O	EA	EAl	SOM	CEC	Clay
pH-H_2O	1					
EA	−0.25*	1				
EAl	−0.24*	0.20*	1			
SOM	0.34**	−0.21*	−0.21*	1		
CEC	0.32**	0.01	−0.18	0.31**	1	
Clay	−0.21*	0.02	0.1	0.13	−0.03	1

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

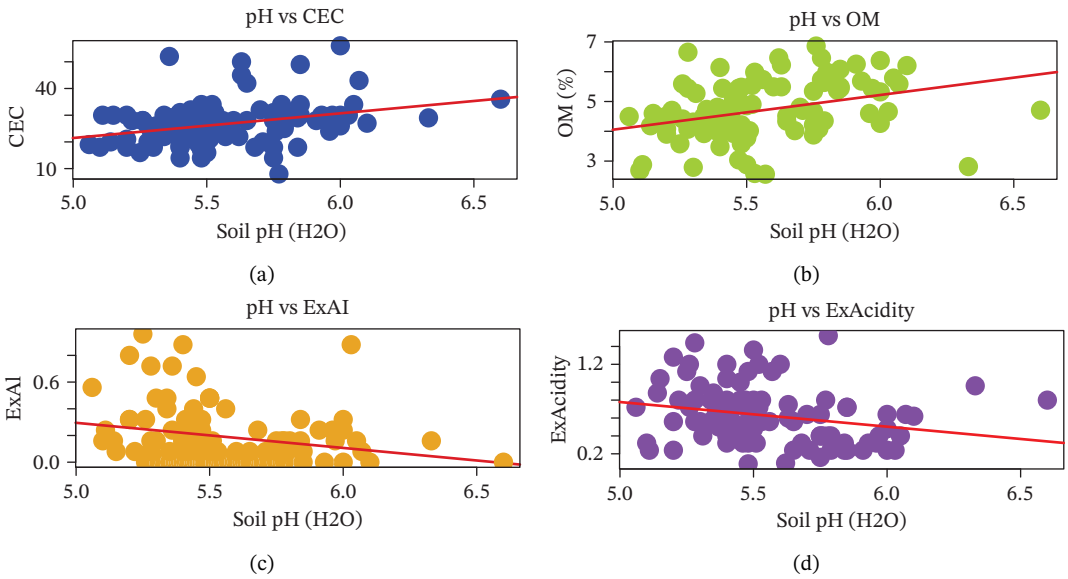


FIGURE 10 | Regression line.

requires tailored management approaches. For strongly acidic soils (38.2%), an aggressive liming program is required to neutralize acidity and reduce aluminum toxicity, which can dramatically improve phosphorus and nitrogen use efficiencies [10, 83, 84]. For moderately acidic soils (38.4%), the focus should be on maintenance, that is, liming combined with integrated soil fertility management to prevent further acidification [29, 71, 73, 85–87]. For neutral reaction soils (23.4%), vigilant monitoring is essential to preserve their optimal productivity, as they remain susceptible to acidification pressures from ongoing

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management practices. Several studies conducted in the Ethiopian highlands have consistently demonstrated that liming is a prerequisite for improving crop yields and nutrient use efficiency in acidic soils [6, 22, 83, 88, 89].

3.4 | Pearson's Correlation Matrix Between Selected Soil Parameters

The correlation matrix reveals key relationships among soil parameters that are directly or indirectly relevant to acid soil management. The correlation coefficient values of soil parameters versus soil texture, soil pH, EA, EAl, CEC, and SOM were determined for the surface soils and are presented in Table 3, and the regressions between soil pH and CEC (a), pH and OM (b), pH and EAl (c), and pH and EA (d) shown in Figure 10 are further elaborated in Supporting Information.

Soil pH showed a significantly ($p \leq 0.05$) negative correlation with EA ($r = -0.25^{*}$) and exchangeable Al ($r = -0.24^{*}$) (Table 3). The results reveal that soils with higher pH levels tend to have lower levels of EA and EAl, and vice versa, which implies that increases in pH reduce the availability and mobility of aluminum ions in the soil. Laekemariam and Kibret [43] also reported a significantly negative correlation of soil pH with EA and EAl.

The positive correlation between pH and SOM ($r = 0.34^{**}$) suggests that organic amendments can enhance pH, likely through proton buffering and Al^{3+} complexation [90]. Conversely, the negative correlation between clay content and pH ($r = -0.21^{*}$) implies that clay-rich soils retain more acidic cations (H^{+} and Al^{3+}), possibly due to their high CEC [72]. Notably, SOM is negatively correlated with EA and EAl ($r = -0.21^{*}$ and -0.21^{*}, respectively), reinforcing the role of OM in mitigating acidity by binding Al^{3+} and reducing exchangeable forms [91]). CEC shows no significant relationship with EA or EAl; however, its positive link with SOM ($r = 0.31^{**}$) highlights how organic amendments can improve nutrient retention without necessarily exacerbating acidity.

These correlations support an integrated approach to acid soil management, combining pH adjustment (liming) with OM additions to simultaneously address Al toxicity, nutrient availability, and soil fertility [22, 24, 28, 29, 73, 92].

4 | Conclusions

The spatial analysis of soil pH and related acidity parameters confirms that soil acidity is a widespread constraint in the Assosa District. The predominance of clayey soils with high CEC offers a favorable nutrient retention capacity; these soils remain inherently acidic, and effective neutralization will likely require higher initial lime rates than typically recommended.

Correlation analyses provided key insights into the mechanisms governing acidity dynamics. The strong negative relationships between pH and both EA and aluminum align with the well-established principle that increasing pH mitigates aluminum toxicity. Notably, SOM exhibited strong positive correlations with pH and negative correlations with EA and aluminum, suggesting that organic amendments can play a complementary role by buffering protons and complexing phytotoxic aluminum. In contrast, clay content was negatively associated with pH, pointing to inherent acidity in finer-textured soils. The lack of a significant relationship between CEC and acidity indicates that improving nutrient retention via OM addition is possible without worsening acidity levels.

Geostatistical modeling demonstrated that the Gaussian model best captured the spatial structure of both pH-H_2O and pH-KCl, providing the most accurate semivariogram fits. The moderate spatial dependence observed for pH-H_2O confirms that the sampling strategy adequately captured variability across the landscape. Ordinary kriging delineated the study area into three distinct acidity classes, with strongly acidic soils covering 38.2% (~49,606 ha) and moderately acidic soils covering 38.4% (~49,830 ha). Collectively, these results reveal that over 76% of Assosa's cultivated soils are constrained by suboptimal pH and elevated aluminum toxicity risk, posing a serious limitation to crop productivity.

Results of this study underscore the necessity of site-specific, integrated soil management strategies for sustainable soil health and crop productivity. Combining lime application with OM incorporation offers a synergistic approach to sustainably ameliorate acidity, reduce aluminum toxicity, and enhance soil fertility. In strongly acidic zones, precision liming guided by comprehensive soil testing, including assessments of buffering capacity and mineralogy, should be prioritized. Future research should focus on integrating spatial acidity maps with nutrient availability patterns to support precision agriculture and optimize input use efficiency across the district.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

The following Supporting files provide additional details supporting the manuscript on assessing the spatial variability of soil acidity in cultivated tropical lands. **Supporting Information 1.** Research_Highlight.docx. This document summarizes the key findings, implications, and novelty of the study, highlighting: Significant spatial variability of soil acidity in cultivated tropical lands. Digital mapping showing 38.2% strongly acidic and 38.4% moderately acidic soils. Soil pH range of 5.06–6.60, indicating widespread acidity. Moderate spatial dependence of soil pH revealed by geostatistical analysis. Acidity maps enabling targeted management for improved agricultural productivity. **Supporting Information 2.** Row_Data.xlsx. This Excel file contains the complete raw dataset, including GPS coordinates of soil sampling points, laboratory analyses of soil physicochemical properties, and inputs for statistical analyses used to generate the manuscript results. **Supporting Information 3.** Supportive Results. This file presents additional results, including: The experimental semivariogram of soil pH measured in water (pH-H2O), illustrating spatial variability and correlation distance of soil pH values (Figure 9). Regression analysis between soil pH and CEC (a), pH and OM (b), pH and EAl (c), and pH and EA (d) shown in Figure 10 is further elaborated in Supporting Information (Figure 10).

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