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Research Article

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Posted Date: August 5th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10409673/v1>

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Additional Declarations: No competing interests reported.

Perceptions and Determinants of Adaptation to Soil Salinity among Smallholder Farmers in Irrigated Systems of the Abaya–Chamo Lakes Basin, Ethiopia

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Abstract

Soil salinization is a major constraint to agricultural sustainability and food security in arid and semi-arid regions, including the Abaya–Chamo Lakes Basin in southern Ethiopia. This study examined smallholder farmers' perceptions of soil salinity and analyzed the determinants shaping their adaptation strategies in irrigated systems. A mixed-methods approach was used. Data was collected from 380 households selected through multistage stratified random sampling across five purposively selected Kebeles. Household surveys were complemented by key informant interviews, focus group discussions, and field observations. Descriptive statistics were used to summarize socio-demographic, farm-level, and institutional characteristics, while a multinomial logistic regression model identified the factors influencing farmers' adaptation choices. Most farmers perceived soil salinity as severe (85.9%) and chronic (50.5%), although technical awareness of salinity dynamics was only moderate (51.3%). Salinity moderately affected cultivated lands (54.0%), resulting in severe yield losses for major crops, particularly banana (43.2%) and maize (33.9%). Vulnerability was intensified by reliance on on-farm income (47.7%) and low-to-moderate livelihood diversification. Institutional dissatisfaction regarding salinity management support was extensive (71.6%), with a low mean satisfaction score of 1.45 out of 5. Farming experience, landholding size, labor availability, and income diversification significantly influenced adaptation and coping choices. Notably, a capacity–vulnerability paradox emerged, as resource-endowed farmers adopted more advanced measures yet experienced greater absolute income losses. Adaptive capacity alone is not sufficient to offset vulnerability to soil salinity. Strengthening resilience in the basin requires integrated, context-specific interventions that combine technical salinity mitigation, institutional support, and livelihood diversification.

Keywords: Adaptation strategies, determinants, farmers' perceptions, Soil salinity, Smallholder farmers, Abaya–Chamo Lakes Basin, Ethiopia

Abbreviations: FGD-Focus Group Discussions, MNLR- Multinomial Logistic Regression, SI-Supplementary Information, SDS-Simpson Diversification Score

1. Introduction

Soil salinization, the excessive accumulation of soluble salts in the root zone, constitutes one of the most pressing environmental, agricultural, and socio-economic challenges of the twenty-first century [1-4]. Globally, salt-affected soils cover over 1.1 billion hectares, of which 60% are saline, 26% sodic, and 14% saline-sodic [5]. In irrigated systems, it accelerates human-induced land degradation [6], impairs soil health, reduces crop productivity, and endangers food security [7]. These effects are particularly acute in arid and semi-arid regions, where evapotranspiration consistently exceeds precipitation, promoting salt accumulation in the root zone [8]. Salinization arises from both natural (primary) and human-induced (secondary) processes. Primary causes include high evaporation rates, saline groundwater intrusion, coastal influences, and salt-bearing parent materials, while secondary factors encompass poor irrigation practices, inadequate drainage, over-fertilization, groundwater over-extraction, deforestation, and unsustainable land use [9-11]. Climate change further exacerbates the problem through rising temperatures, erratic rainfall patterns, and increased evapotranspiration [12].

The severity of salinization is mediated by biophysical factors such as topography, geology, and soil properties and socio-economic conditions, including crop choice, infrastructure, and farmer management practices [13]. The scale of the threat is staggering. Projections indicate that without intervention, salinization could affect 50% of global arable land by 2050 [14]. Of 310 million hectares under irrigation, 20% are already salt affected, with an annual loss of 1.5 million hectares and yield reductions on an additional 20 to 46 million hectares [8]. Africa remains disproportionately vulnerable, with over 200 million hectares affected, including 19 million in Sub-Saharan Africa [5]. The consequences span agriculture, local economies, society, and ecology collectively fueling food insecurity [1, 3, 10]. Comprehensive income loss estimates remain scarce, underscoring the urgency of systematic assessments to inform mitigation strategies [7]. Ethiopia faces a severe salinization crisis, ranking seventh globally and first in Africa, with approximately 44 million hectares (36% of its land area) at risk and roughly 11 million hectares already affected [13, 15]. Within this context, the Abaya–Chamo Lakes sub-basin is especially susceptible due to its fragile hydrogeology, intensive irrigation practices, and climate-driven groundwater fluctuations [16]. Salinization here is driven by lake water intrusion,

erratic climate, rising water tables, sedimentation, and underlying geological formations, all of which threaten agricultural productivity and ecosystem integrity [17, 18].

Although salinity poses a severe challenge, existing research has primarily focused on biophysical drivers, often neglecting smallholders' perceptions and indigenous adaptive strategies [16,19, 20]. Integrating local knowledge is crucial for developing context-specific and sustainable interventions that complement technical approaches [21, 22, 23]. The disconnect between biophysical knowledge and socioeconomic realities represents a significant knowledge gap, which undermines the effectiveness of salinity management policies and limits smallholder farmers' access to appropriate adaptation strategies. In response, this study examines how socioeconomic heterogeneity influences farmers' perceptions of and responses to salinization. The objectives are to: (i) assess farmers' perceptions regarding the onset, drivers, impacts, extent, and severity of salinity; (ii) evaluate current adaptive strategies and coping mechanisms; and (iii) identify barriers and determinants influencing the adoption of management practices. Synthesizing these aspects, the study aims to inform evidence-based and socially responsive intervention frameworks that enhance resilient salinity management and livelihood security.

2. Methodology

2.1. Study site description

The study was conducted in the Arba Minch Zuria and Mirab Abaya districts of the Gamo Zone, situated within the Abaya–Chamo Lakes sub-basin along the southwestern escarpment of the Ethiopian Rift Valley in the South Ethiopia Region (Figure 1). Geographically, the area extends between 37°15'36"E to 38°42'58"E longitude and 5°25'5"N to 8°7'4"N latitude, with elevations ranging from 972 to 1,404 m a.s.l. [24]. The focal sites are located on the Rift Valley floor at elevations between 1,098 and 1,404 m. a.s.l. [25]. The study area experiences a hot, semi-arid to arid tropical climate, heavily shaped by altitudinal shifts and the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ) [26]. Rainfall follows a bimodal pattern, with the primary *Belg* (March–May) and secondary short rains (September–November), while the Kiremt contributes minimal [24]. Annual precipitation ranges from 500 to 1,240 mm, with mean air temperatures varying between 17 and 39 °C (Figure 2), and soil temperatures from 22 and 35 °C.

High potential evapotranspiration (~2,300 mm/year), peaking in April–May and August–September, intensifies soil moisture deficits and salinization [20]. This climatic variability volatility exacerbates drought, land degradation, and irrigation demands [19]. The region's hydrology is dominated by the Abaya–Chamo lake system, whose perennial and ephemeral tributaries support irrigation, fisheries, transport, and tourism, yet face threats from flooding, siltation, erosion, and settlement expansion [16, 17, 26]. Land use (Figure SI 1) features a mosaic of riparian vegetation, shrublands, grasslands, wetlands, forests, croplands, and growing built-up areas [16, 27]. Agriculture is smallholder-based and rain-fed, producing banana, maize, cotton, and other crops, but poor practices have rendered over 70% of irrigated land saline or sodic [19, 20]. The landscape's diverse soils including Nitisols, Acrisols, Luvisols, Vertisols, and Fluvisols reflect its complex tectonic, volcanic, and lacustrine origins [28] (Figure SI 2).

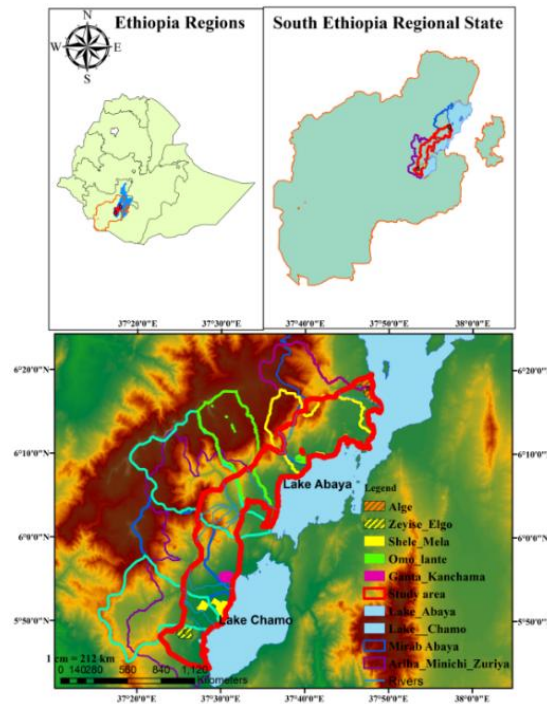


Figure 1: Location Map of the study area

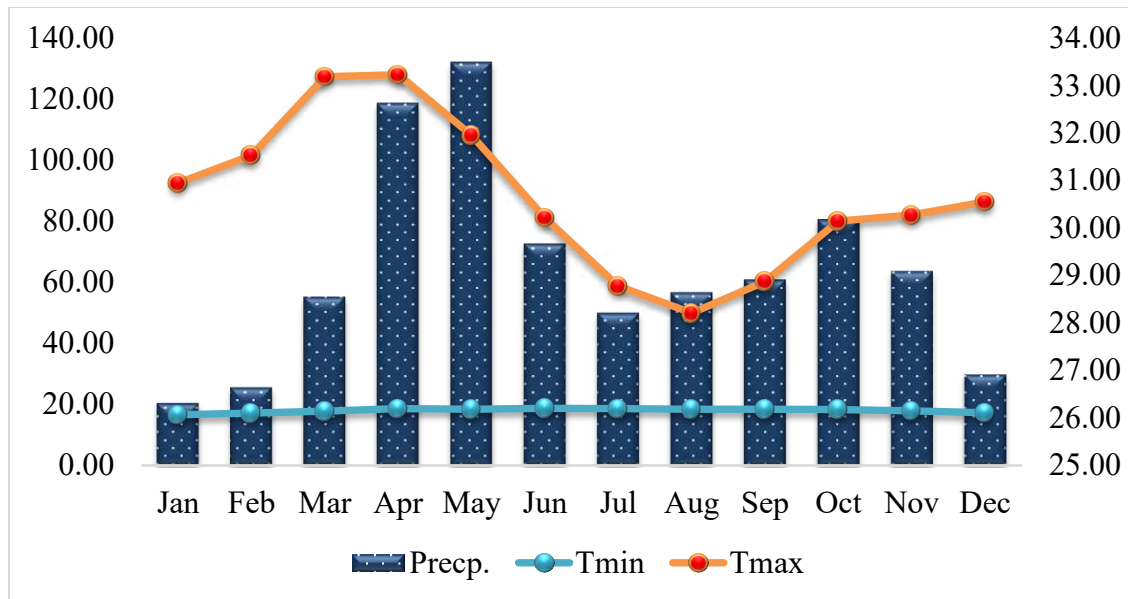


Figure 2: Annual Mean Climate Data of the study area (1987-2025). Source: Ethiopia Meteorological Agency

2.2. Research design and sampling procedures

A semi-structured household survey was designed, pre-tested with 25 households, and digitized in Kobo Toolbox. It covered sociodemographic attributes, farm management practices, livelihood strategies, salinity perceptions, coping mechanisms, adaptation measures, barriers to adoption, governance constraints, and institutional access. A multistage sampling design was then employed: two districts (Mirab Abaya and Arba Minch Zuria) and five *Kebeles*; Ganta Kanchama, Shelle Mella, Zayse Elgo, Umo Lante, and Alge were purposively selected based on salinization prevalence and irrigation reliance. Household lists of farmers with salinized land served as sampling frames, with systematic random sampling applied. Following the formula recommended by [29], we determined the minimum sample size necessary to detect significant differences at a 95% confidence interval (Equation 1). Prior to data collection, formal informed consent was obtained from all participants in strict compliance with ethical research standards (see section 2.4).

$$n = \frac{N}{1 + N(e)^2} = \frac{7885}{1 + 7885(0.05)^2} \approx 380 \dots \dots \dots 1$$

Where n = sample size; N= total households = 7,885 (Ganta Kanchama=2,404, Zayse Elgo = 2,316, Shelle Mella= 1,524, Umo Lante = 910, and Algae = 731), and *e* = precision (sampling

error) level (0.05) at 95% confidence level. Proportional stratified sampling ensured representative allocation across Kebeles (Equation 2):

$$n = \frac{N_h}{N} \cdot n \dots\dots\dots 2$$

Where n = sample size of kth Kebele, N_h = household size of kth Kebele, N = total household (N= 7885), and N = Grand sample size (N=380). A total of 380 households were surveyed, distributed as shown in Table 1.

Table 1. Sample size distribution per research site

S/no.	Selected administrative wards	Total households (N _h)	Sample size (n)
1	Ganta Kanchama	2,404	116
2	Zayse Elgo	2,316	112
3	Shelle Mella	1,524	73
4	Umo Lante	910	44
5	Algae	731	35
Total		7,885 (N _t)	380 (N)

Source: Districts finance and plan offices (2025). Grand sample size, N = 380, n_i = Sample sizes per each Kebele.

Fifteen trained extension workers (three per site) administered the survey face-to-face between March and April 2025. Data was submitted daily, cleaned, and stored in CSV (Comma-Separated Values) format, with Kobo Toolbox enhancing accuracy and enabling realtime validation. At each site, five key informants: a model farmer, an elder, a kebele leader, and two agronomy experts participated in face-to-face interviews averaging one hour. Three case studies per site provided insights from farmers with diverse farm sizes. FGDs, held in kebele offices with 10 participants (adolescents, women's groups, development agents, model farmers, and elders), lasted 90 minutes. Both interviews and FGDs employed close- and open-ended questions. Individual narratives were recorded verbatim, transcribed, and triangulated with quantitative survey data to ensure rigor and consistency [23].

2.3. Hypotheses, variable operationalization, and analytical frameworks

The study hypothesized that: (1) farmers' perceptions of soil salinity are shaped by socio-economic, institutional, and environmental factors, and (2) these same dimensions influence the adoption of salinity mitigation and adaptation strategies in irrigated agriculture. To test these hypotheses, the survey employed a polytomous dependent variable reflecting whether farmers

perceived soil salinity from past and present experience. Predictor variables were selected from theory, prior studies, expert consultation, and local farming practices [31]. According to [23], predictor variables recorded were: (i) demographic (age, gender, marital status, education, family size); (ii) farm-level (farming experience, farm size, cropping system, income source, input availability); and (iii) institutional (extension access, land tenure security, irrigation access, information access, cooperative membership, credit access, and barriers). Outcome variables assessed: (i) adaptation responses (adopted management options, coping strategies); (ii) perceptual measures (perceived severity, extent, awareness); and (iii) performance metrics (drivers, impacts, farm-level indicators, and estimated economic loss). Full variable definitions are presented in Tables SI 1, SI 4, and SI 6 of the supplementary information. Variables were measured using nominal, ordinal, binary (eg., gender, extension access, information access), and index-based scales (eg., livelihood diversification score) [9]. Nominal variables were dummy-coded, while ordinal variables were treated as ranked values or dummy-coded depending on model specification [32]. This structure enabled the model to capture key determinants shaping both salinity perception and adaptive responses. Adoption outcomes were modeled using multinomial logistic regression against a reference group [33, 34]. Multicollinearity was checked via VIF, retaining predictors with $VIF < 2.5$.

2.4. Ethical considerations

The institutional review board of Arba Minch University granted ethical approval for this study. All research activities adhered to the ethical standards set forth in the Declaration of Helsinki (1964 and subsequent revisions). Before commencing data collection, written informed consent was obtained from all participants, who were clearly informed that their participation was voluntary and that they could withdraw at any time without prejudice [82]. Confidentiality was maintained through anonymization and coding of all data, which were stored on password-protected devices. No individually identifiable data is presented in this manuscript.

2.5. Statistical analysis

Data collected using Kobo Collect were exported as CSV files and imported into Microsoft Excel for cleaning, coding, and initial organization. The cleaned data was then analyzed using descriptive and inferential statistics. Results were presented as counts, proportions, standard

deviations, chi-square tests, and p-values, with statistical significance set at $p < 0.05$. All analyses were conducted using Python 3.0.

2.5.1. Multinomial Logistic Regression modelling

To assess determinants of two nominal outcomes: adoption of management options and implementing coping strategies; and income loss intensity, multinomial logistic regression (MNLr) models were fitted in Python. MNLr is proper for dependent variables with more than two unordered categorical outcomes, as it estimates the log-odds of each non-reference category relative to a baseline category while controlling multiple predictors [35]. For a dependent variable Y with J categories (with category 1 as the reference), the general equation is (Equation 3):

$$\log \left(\frac{P(Y = j|X)}{P(Y = 1|X)} \right) = \beta_{0j} + \beta_{1j}X_1 + \beta_{2j}X_2 + \dots + \beta_{kj}X_k \text{ for } j = 2, 3, \dots, J \dots \dots \dots 3$$

where $P(Y = j | X)$ is the probability of outcome j , $X = (X_1, \dots, X_k)$ represents the predictor variables, β_{0j} is the intercept for category j , and β_{ij} are the regression coefficients for predictor i in category j . Models were estimated using maximum likelihood estimation. Prior to model estimation, diagnostic tests were conducted. Independence of observations was verified, multicollinearity was assessed (all VIF < 2.5), and the independence of irrelevant alternatives (IIA) assumption was confirmed using Hausman–McFadden and Small–Hsiao tests. Model adequacy was evaluated using McFadden's pseudo- R^2 and log-likelihood ratio tests, with classification accuracy benchmarked against established thresholds [36]. Exponentiating coefficients yielded odds ratios ($OR = e^{\beta_{ij}}$), interpreted as the change in odds per one-unit increase in predictor X_i , holding others constant. Each OR is reported with 95% confidence intervals and p-values from Wald tests (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). $OR > 1$ indicates higher odds, $OR < 1$ lower odds. $OR > 10$ considered substantially higher, $OR < 0.20$ strongly protective. Categorical predictors were dummy coded using the first level as reference.

2.5.2. Assessment of livelihood diversification

Household income diversification was assessed using an adapted Simpson's Diversity Score (SDS), a widely recognized measure in economics and agricultural studies for capturing

income-source heterogeneity [37-39]. The general SDI model (Equation 4) was employed to compute diversification levels across different income bases.

$$SDS = 1 - \sum_{i=1}^n p_i^2 \dots \dots \dots 4$$

where: n = number of income sources categories (4 in this study), p_i = proportion of total household income derived from the i^{th} income (p_i = Income from source i / Total household income, with $0 \leq p_i \leq 1$ and $\sum p_i = 1$). The index ranges from 0 (no diversification; single source) to 1 (perfect diversification; multiple sources). Diversification levels were classified as: low ($SDS < 0.25$), medium ($0.25 \leq SDS \leq 0.50$), and high ($SDS > 0.50$) [38]. In this study, annual household income (in Ethiopian Birr [ETB], $n = 380$) was estimated from six distinct income source categories, identified through a participatory prioritization process across the five study sites. These sources include Crop Income (CI), Livestock Income (LI), Wage Income (WI), Petty Trading Income (PTI), Aquaculture-Poultry Income (API), and Rent Income (RI). Total Annual Household Income (TAHI) was computed as the sum of all six sources ($TAHI = CI + LI + WI + PTI + APBI + RI$), and the Simpson Diversification Index (SDI) for each household was subsequently calculated using Equation 5.

$$SDI = 1 - \left[\left(\frac{CI}{TAHI} \right)^2 + \left(\frac{LI}{TAHI} \right)^2 + \left(\frac{WI}{TAHI} \right)^2 + \left(\frac{PTI}{TAHI} \right)^2 + \left(\frac{API}{TAHI} \right)^2 + \left(\frac{RI}{TAHI} \right)^2 \right] \dots \dots 5$$

3. Results and Discussion

3.1. Socio-demographic, farm, and institutional support characteristics

Substantial heterogeneity in socio-demographic, farm, and institutional characteristics was observed across the sampled Kebeles (Table 2). Participation rates were highest in Ganta Kanchama (29.5%), Zayse Elgo (30.5%), and Shelle Mella (19.2%), driven by population density and farming intensity. Gender was heavily skewed toward males (97.4%), reflecting traditional rural Ethiopian customs where men lead agrarian decision-making [40]. The age profile centered on 26–45 years (55.5%; mean = 44, range 21–69), representing an active workforce capable of driving technology adoption and providing farm labor [41-43]. Nearly all respondents were (98.4%) married, strengthening household stability. However, formal education remained low: 56.6% completed elementary school, 24.2% had no education, and

19.2% attained higher education, a shortfall that constrains extension engagement and technology acceptance [44]. Farming experience was substantial, with 49.2% exceeding 31 years and 42.6% having 21–30 years, deeply shaping local agronomic knowledge, risk perception, and adaptation strategies. Households averaged 3.3 working members (57.2% aged 15–64, resulting in a high dependency ratio (75%) that strains resources [45] (Table SI 3). Landholdings were characteristically small, with 90.6% owning under 2 ha (mean = 0.9 ha, range: 0.125–8.5 ha), aligning with broader national patterns of Ethiopian smallholder agriculture [46]. To cope with production shortfalls, households diversified their income streams: farming contributed 47.9%, off-farm activities 25.5%, non-farm sources 15.5%, and mixed sources 11.1% [47, 48]. Financially, most households (70.5%) generated between 60,001 and 100,000 ETB annually, while 22.1% earned under 60,000 ETB. Collectively, these socio-demographic and economic conditions govern how smallholders perceive environmental risks and execute salinity-adaptation strategies, reflecting moderate-to-low economic strata typical of smallholder systems. These socio-demographic and farm-level factors do not operate in isolation; rather, they shape how smallholders perceive environmental risks and make adaptive decisions [9, 23, 49, 50]. Institutional support varied significantly across Kebeles (Table SI 6). Agricultural extension access was constrained; only 39.7% reported regular contact, and 23.7% received no visits. Cooperative membership reached 46.1%, but credit accessibility was weak, with 47.6% reporting difficulties and 31.0% lacking access entirely. Despite strong land tenure security (94.7%), peer-to-peer networks remained the primary source of agricultural information (39.5%), while 20.0% lacked reliable sources. These institutional deficits likely hinder salinity risk perception and delay adaptive capacity [41, 42].

Table 2. Socio-demographic, farm and household characteristics of respondents (N = 380)

Variables	Category	Mirab Abaya				Arba Minch Zuria						Total	
		Alge		Umo Lante		Shelle Mella		Ganta Kanchama		Zayse Elgo			
		<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>n</i>	%	<i>N</i>	%
Gender	Female	3	0.8	1	0.3	2	0.6	1	0.3	3	0.8	10	2.6
	Male	32	8.4	43	11.3	71	18.7	111	29.2	113	29.7	370	97.4
Age	<25	0	0.0	0	0.0	2	0.5	6	1.6	3	0.8	11	2.9
	26-45	30	7.9	22	5.8	33	8.7	86	22.6	40	10.5	211	55.5
	46-64	4	1.1	18	4.7	30	7.9	8	2.1	56	14.7	116	30.5
	>64	1	0.3	4	1.1	8	2.1	12	3.2	17	4.5	42	11.1
	Marital status	Married	34	8.9	41	10.8	73	19.2	111	29.2	115	30.3	374
	Separated	1	0.3	-	-	-	-	-	-	-	-	1	0.3
	Single	0	0.0	2	0.5	0	0.0	-	-	-	-	2	0.5
	Widowed	0	0.0	1	0.3	0	0.0	1	0.3	1	0.3	3	0.8
Education level	Non-educated	9	2.4	15	3.9	15	3.9	32	8.4	21	5.5	92	24.2
	Primary	20	5.3	23	6.1	47	12.4	74	19.5	51	13.4	215	56.6
	Secondary	2	0.5	3	0.8	9	2.4	3	0.8	26	6.8	43	11.3
	Higher	4	1.1	3	0.8	2	0.5	3	0.8	18	4.7	30	7.9
Farming experience (year)	<10	0	0.0	0	0.0	2	0.5	6	1.6	3	0.8	11	2.8
	11-20	6	1.6	0	0.0	11	2.8	5	1.3	0	0.0	22	5.4
	21-30	19	5.0	26	6.8	34	8.9	38	10.0	45	11.8	162	42.6
	>31	10	2.6	18	4.7	26	6.8	63	16.6	70	18.4	185	49.2
Farm size (ha)	Marginal (<1)	17	4.5	30	7.9	25	6.6	22	5.8	24	6.3	118	31.1
	Small (1.1- 2)	18	4.7	14	3.7	44	11.6	78	20.5	72	18.9	226	59.5
	Medium (2.1-5)	0	0.0	0	0.0	2	0.5	3	0.8	15	3.9	20	5.3
	Large (5.1-10)	-	-	-	-	2	0.5	9	2.4	5	1.3	16	4.2
Income range (ETB/year)	>40,000	3	0.8	4	1.0	9	2.4	5	1.3	2	0.5	23	6.0
	40,001-60,000	12	3.2	6	1.6	15	3.9	10	2.6	18	4.7	61	16.0
	60,001-80,000	11	2.8	21	5.5	35	9.2	46	12.1	54	14.2	167	43.9
	80,001-100,000	5	1.3	10	2.6	12	3.1	39	10.3	35	9.2	101	26.6
	>100,001	1	1.05	3	0.8	2	0.5	12	3.1	7	1.8	28	7.4

% calculated within Kebeles (lower administrative units in Ethiopia); *n* denotes sample counts. Farm size classes follow Ethiopian thresholds: marginal (<1 ha), small (1.1–2 ha), medium (2.1–5 ha), large (5.1–10 ha). Income is reported in Ethiopia birr. “–” indicates missing data.

3.3. Livelihood diversification profile

Livelihood diversification for 380 households was quantified using the Simpson Diversification Score (SDS) (Table 2). Households were classified as none (8.1%), low (43.2%), medium (38.4%), or highly (10.3%) diversified. The overall mean SDS was 0.4215 (SD = 0.1613), indicating moderate diversification; highly diversified households had a mean SDS of 0.7584, while non-diversified households scored 0.00. More than half of households (51.3%) exhibit low-to-no diversification, relying on a narrow agricultural income base (crops and livestock) that heightens their exposure and sensitivity to soil salinity [39, 51].

Table 3. Livelihood diversification profile of respondents (N=380)

Diversification rank	SDS Range	Frequency	Proportion (%)	SD	Mean SDS
No-Diversification	0.00-0.25	31	8.1	0.0000	0.0000
Low	0.26 – 0.39	164	43.2	0.0876	0.3421
Medium	0.4 – 0.69	146	38.4	0.0678	0.4903
High	≥ 0.70	39	10.3	0.0542	0.7584
Total	—	380	100.0	0.1613	0.4215

SDS= Simpson Diversification Index; SD = Standard Deviation. Diversification ranks (No Diversified (SDS: 0.00–0.25), Low (SDS: 0.26–0.39), Moderate (SDI: 0.40–0.69), and High (SDS: ≥ 0.70).

Salinity-driven crop failure thus poses direct income shocks, constraining households' capacity to finance adaptation measures such as salt-tolerant varieties, drainage, and soil management [37]. Conversely, medium-to-high diversified households (48.7%) are better able to smooth income losses through nonfarm activities (wage income, petty trade, aquaculture, poultry, beekeeping, and rent) enhancing resilience to shocks [38,52, 53]. However, only 10.3% are highly diversified, showing substantial available potential for diversification as an adaptation pathway.

3.4. Farm management and production characteristics

3.4.1. Irrigation practices

Descriptive analysis shows flood irrigation as the dominant practice across sampled Kebeles (74.7%), followed by furrow (21.3%) and rainfed systems (4.0%). Surface water from rivers and lakes (70.5%) is the primary source, while boreholes (11.8%) and ponds (11.3%) are less

common. Scheduling is largely informal, with most farmers (61.9%) relying on visual judgment. Spatially, irrigation methods are uniform ($\chi^2 = 14.545$, $p = 0.069$), yet water sources ($\chi^2 = 27.671$, $p = 0.006$) and frequencies ($\chi^2 = 38.212$, $p < 0.001$) vary significantly, suggesting shared economic pressures drive low-cost flood irrigation, while local conditions shape water access and timing [54]. However, dependence on unregulated flood irrigation threatens long-term soil health. Despite low cost and simplicity, it promotes excessive water use, high evaporation, and salt build up in semi-arid zones with poor drainage [55, 56]. Subjective scheduling worsens over-irrigation, raising water tables and driving capillary salt rise. Consistent with Ethiopian findings, prolonged flooding and inadequate drainage lead to waterlogging, salinization, and yield decline [57]. Conversely, efficient alternatives like deficit or drip irrigation can reduce salinity and boost water productivity [58].

Table 4. Distribution of irrigation practices by study site (N = 380)

Variable / Category	Alage (n= 35)	Umo Lante (n = 44)	Shelle Mella (n = 73)	Ganta Kanchama (n = 112)	Zayse Elgo (n = 116)	Total (N = 380)	χ^2 test	p-value
Irrigation Method							14.545	0.069
Furrow	8 (22.9)	14 (31.8)	13 (17.8)	24 (21.4)	22 (18.9)	81 (21.3)		
Flood	22 (62.8)	27 (61.4)	58 (79.4)	87 (77.7)	90 (77.6)	284 (74.7)		
Rainfed	5 (14.3)	3 (6.8)	2 (2.8)	1 (0.9)	4 (3.5)	15 (4.0)		
Irrigation Source							27.671	0.006**
Borehole	0 (0.0)	5 (11.4)	2 (2.8)	3 (2.6)	18 (15.5)	45 (11.8)		
River / Lakes	28 (80.0)	32 (72.7)	59 (80.8)	87 (77.7)	79 (68.1)	268 (70.5)		
Pond / Reservoir	4 (11.4)	5 (11.4)	8 (10.9)	14 (12.5)	12 (10.3)	43 (11.3)		
Mixed	3 (8.6)	2 (4.5)	4 (5.5)	8 (7.2)	7 (6.1)	24 (6.3)		
Irrigation Frequency							38.212	<0.001***
Every 2–3 Days	5 (14.3)	2 (4.5)	3 (4.1)	2 (1.8)	5 (4.3)	17 (4.4)		
Once per week	9 (25.7)	4 (9.1)	15 (20.6)	17 (15.2)	8 (6.9)	53 (13.9)		
Once every 7–15 days	11 (31.4)	11 (25.0)	18 (24.6)	14 (12.5)	21 (18.1)	75 (19.7)		
As required	10 (28.6)	27 (61.4)	37 (50.7)	79 (70.5)	82 (70.7)	235 (61.9)		

Frequencies and percentages in parentheses, statistically significant level: ** p < 0.01, *** p < 0.001, n= sample size/each site.

3.4.2. Fertilization, cropping systems, and cropping patterns

Fertilization and cropping practices were widespread and intensive at the aggregate level, yet significant spatial heterogeneity emerged in fertilizer type, cropping patterns, and systems. Fertilizer application was common (86.1%), with farmers primarily using inorganic inputs alone (37.1%) or combined organic-inorganic applications (44.2%), though access was often constrained by market supply and household finances. Cropping systems reflected diversification: most households grew both perennial and annual crops (62.9%), and mixed cropping dominated (65.0%), compared with monocropping (12.6%) and crop rotation (11.6%). While these practices may support short-term yield gains, they risk accelerating land degradation, reducing resource efficiency, and promoting salinization, consistent with earlier findings [57, 59, 60]. Spatial analysis revealed no significant variation in overall fertilizer use across sites ($\chi^2 = 9.054$, $p = 0.060$), indicating broadly uniform adoption [54]. However, fertilizer type ($\chi^2 = 24.113$, $p = 0.002$), cropping pattern ($\chi^2 = 26.072$, $p = 0.001$), and cropping system ($\chi^2 = 26.734$, $p = 0.008$) differed significantly, though effect sizes remained small (Cramér's $V = 0.153$ – 0.185). These differences likely reflect local variations in market access, wealth, extension services, agroecology, and irrigation infrastructure [61–63]. Overall, the results reveal a shared productivity focus, but with locally shaped choices in input use and cropping arrangements, highlighting the need for tailored interventions that balance yield objectives with long-term sustainability [64].

3.5. Farmers' perceptions of salinity

Table 4 illustrates respondents' awareness, perceived spatial extent, and visual diagnostic indicators of soil salinity across the study sites. In this study, farmers' perceptions of soil salinity were significantly shaped by household attributes, socioeconomic profile, farm characteristics, and institutional arrangements. Moderate awareness was most prevalent, accounting for 51.3% of respondents, with the highest proportion of high awareness recorded in Shelle Mella (7.1%) and Ganta Kanchama (5.5%). Conversely, low awareness was concentrated in Zayse Elgo (8.9%) and Ganta Kanchama (7.4%). The temporal dimension of salinity also exhibited significant spatial variation ($\chi^2 = 23.47$, $df = 8$, $p = 0.003$), with chronic salinity being the most frequently reported pattern (50.5%), particularly in Zayse Elgo (18.4%) and Ganta Kanchama (12.4%). In contrast,

field-level indicators showed no significant spatial heterogeneity ($\chi^2 = 0.46$, $df = 16$, $p = 1.000$); visible salt crusts (47.6%) and poor crop emergence (26.6%) emerged as the dominant detection cues across all sites, reflecting reliance on visual symptom-based diagnosis consistent with findings from similar smallholder systems [6, 12, 33].

Figure 3: shows Spatial variation in farmers' perceptions of soil salinity across study sites, based on the CISE coding framework (i.e., C-Cause, I-Impact, S-Severity, and E-Extent). Respondents most often attributed salinization to climate aridity (27.9%) and high evaporation (24.5%), then rising water tables (18.7%), poor irrigation practices (17.1%), and geologic factors (8.2%); only 3.7% linked it to management-related causes (excessive fertilizer use or saline irrigation). These perceptions align with established processes in arid and semi-arid environments, where high evaporative demand and shallow groundwater promote root-zone salt accumulation [48,56,65]. Perceived severity was notably high: 52.4% of households rated it very severe, and 33.5% severe.

Spatial analysis revealed distinct localized degradation hotspots, with Umo Lante most acutely affected (21.3% very severe), followed by Zayse Elgo (15.4% severe) and Ganta Kanchama (13.9% very severe), while Alge appeared comparatively resilient. Observable symptoms of advanced topsoil salinization included surface salt crusting (47.6%), stunted vegetative growth (26.6%), and marked yield reduction (13.7%). These quantitative thresholds corroborate the broad global trends previously documented by FAO and ITPS, as well as by Qadir et al. [see refs. 62, 63].

Table 5. Farm management and cropping system characteristics of households (N = 380)

Variable	Category	N (%)	Mean (%)	SD ($\pm$)	χ^2 (df)	p-value	Cramér's V	Variance explained (%)
Fertilizer use	Yes	327 (86.1)	86.1	6.7	9.054 (4)	.060 ^{NS}	0.154	2.4
	No	53 (13.9)	13.9	6.7				
Fertilizer type	Inorganic	141 (37.1)	35.3	10.8	24.113 (8)	.002**	0.178	3.2
	Organic	71 (18.7)	21.7	9.2				
	Both	168 (44.2)	44.2	8.9				
Cropping pattern	Perennial	58 (15.3)	14.9	6.4	26.072 (8)	.001**	0.185	3.4
	Annual	83 (21.8)	20.2	7.3				
	Both	239 (62.9)	65.0	11.3				
Cropping system	Mono-cropping	48 (12.6)	12.3	3.2	26.734 (12)	.008**	0.153	2.3
	Mixed	247 (65.0)	63.1	5.8				
	Crop-rotation	44 (11.6)	12.2	6.4				
	Inter-cropping	41 (10.8)	12.4	7.1				

Statistical significance level: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, NS = not significant ($p > 0.05$), N = 380 (overall sample size)

Table 6. Farmers' perceptions of soil salinity awareness, onset, and field indicators across the three study sites (N = 380)

Variables	Category	Algae (n=35)	Ganta Kanchama (n = 112)	Shelle Mella (n = 73)	Umo Lante (n = 44)	Zayse Elgo (n = 116)	Total (N = 380)	χ^2 test	p-value
Awareness	High	9 (2.4)	21 (5.5)	27 (7.1)	8 (2.1)	20 (5.3)	85 (22.4)	24.23	0.019*
	Low	3 (0.8)	28 (7.4)	21 (5.5)	11 (2.9)	34 (8.9)	97 (25.5)		
	Moderate	21 (5.5)	63 (16.6)	25 (6.6)	24 (6.3)	62 (16.3)	195 (51.3)		
	Unaware	2 (0.5)	-	-	1 (0.3)	-	3 (0.8)		
	Total	35 (9.2)	112 (29.5)	73 (19.2)	44 (11.6)	116 (30.5)	380 (100)		
Time of occurrence	Chronic	17 (4.5)	47 (12.4)	39 (10.3)	19 (5.0)	70 (18.4)	192 (50.5)	23.47	0.003**
	Recent/emergency	13 (3.4)	35 (9.2)	26 (6.8)	15 (4.0)	13 (3.4)	102 (26.8)		
	Seasonal	5 (1.5)	30 (7.9)	8 (2.1)	10 (2.6)	33 (8.7)	86 (22.6)		
	Total	35 (9.2)	112 (29.5)	73 (19.2)	44 (11.6)	116 (30.5)	380 (100)		
Field -level indicators	Visible salt crusts	17 (4.4)	53 (14.0)	35 (9.2)	21 (5.5)	55 (14.5)	181 (47.6)	0.46	1.000 NS
	Textural hardness	3 (0.8)	10 (2.6)	6 (1.6)	4 (1.0)	10 (2.6)	33 (8.7)		
	Water ponding	1 (0.3)	4 (1.0)	2 (0.5)	2 (0.5)	4 (1.4)	13 (3.4)		
	Poor emergencies & stunted growth	9 (2.4)	30 (7.9)	19 (5.0)	12 (3.1)	31 (8.1)	101 (26.6)		
	Yield loss	5 (1.3)	15 (4.0)	11 (2.9)	6 (1.6)	15 (3.9)	52 (13.7)		
	Total	35 (9.2)	112 (29.5)	73 (19.2)	44 (11.6)	116 (30.5)	380 (100)		

% and *n* in parentheses, N= total sample size, χ^2 = Pearson Chi-square statistic. * Significant at $p < 0.05$; ** Significant at $p < 0.03$; NS = not significant ($p \geq 0.05$). Missing values (–) show categories not reported.

Although respondents' awareness and perceived timing of salinity onset varied significantly ($\chi^2 = 24.23$, $p < 0.05$; $\chi^2 = 23.47$, $p < 0.01$), 54% of household heads perceived salinity-extent as moderate (54%), with localized and widespread occurrences each at 23.0%. Reported socio-ecological impacts were dominated by yield decline (65.0%), income loss (12.4%), and groundwater salinization (11.6%). Moderate salinity tends to trigger livelihood diversification rather than land abandonment, whereas severe, pervasive salinization limits viable adaptation options, leading to minimal intervention or land idling. Consistent with global evidence, these climate-amplified shocks degrade soil structure and dryland productivity, complicating the design of targeted institutional responses [6, 21, 65].

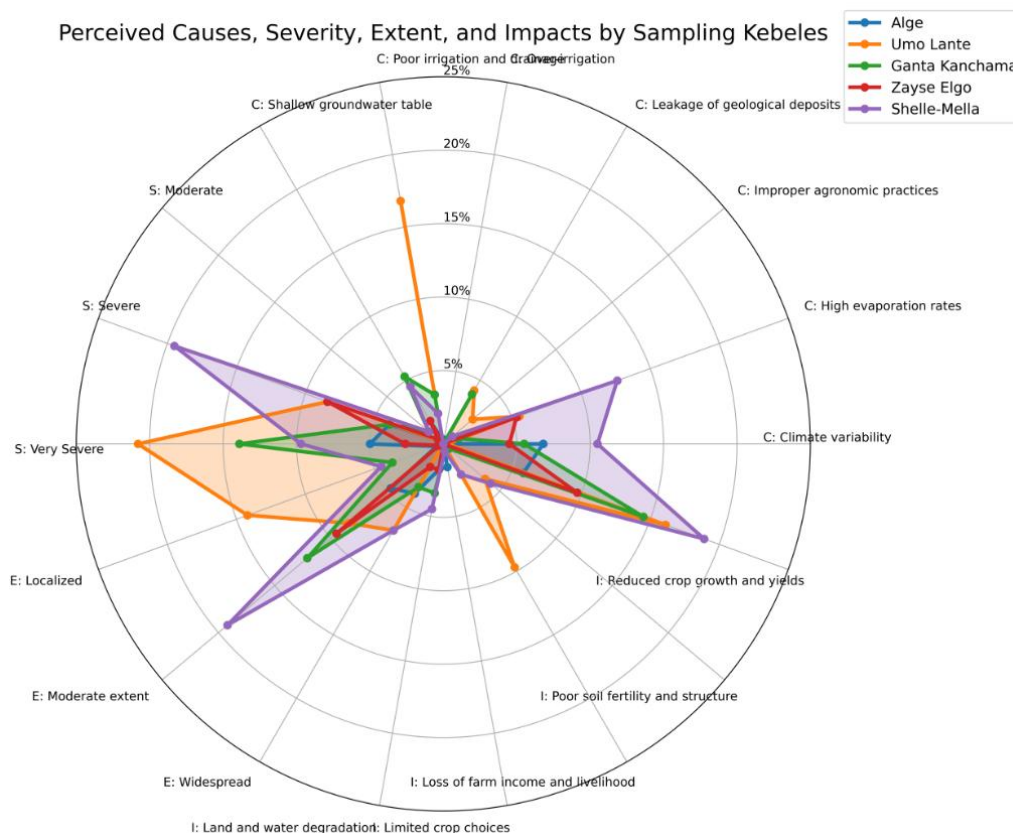


Figure 3. Spatial variability in farmers' perceptions of salinity (N = 380)

From an agricultural and economic perspective, soil salinity imposes severe burdens on farming households through sharp declines in productivity and income. Nearly all respondents reported yield reductions ($n = 365$, 96.1%), with farmers ranking yield decline as the primary impact (65.0%; Figures SI 3, SI 9). Yield reductions were compounded by soil fertility loss (8.4%) and

poor water quality (11.6%), driving income losses reported by 99.7% of respondents. The magnitude of these losses escalates sharply with salinity intensity: nearly half of respondents (47.2%) experienced moderate-income losses (25–50%), while almost one-third (31.0%) suffered high losses exceeding 50% (Table 5). Extreme salinity conditions exacerbated income losses up to 71.6% (Figure SI-4), a trend consistent with prior reports [66]. These findings underscore severe livelihood disruption, as salinity-induced productivity decline directly undermines household food security and adaptive capacity. The results align with broader regional and global evidence of the economic toll of soil degradation on agrarian systems [1, 9, 12, 67, 68].

Table 7. Farmers’ perceptions of salinity-induced income loss (N = 380)

Category	Loss Range	Observations	Proportion
High loss	>50%	118	31.0
Medium loss	25-50%	179	47.2
Low Loss	<25%	54	14.2
No Loss	0	29	7.6

Total sample, N=380, high (>50%), medium (25–50%), low (<25%), none (0%). Observations = Respondent counts

Crop susceptibility varies markedly by species. Banana (43.2%) and maize (33.9%) showed the highest sensitivity, together accounting for over 75% of reported crop failures (Figure SM 5). Their vulnerability is expected given their glycophytic physiology and high-water demands, which reduce tolerance to osmotic and ionic stress [48, 69, 70]. Household vulnerability is compounded by socioeconomic and farm constraints (Table 2): 90.6% of respondents work on less than 2 ha and have low baseline incomes, limiting capacity for adaptive investments [66]. To identify additional drivers of economic loss categories among household heads, multinomial logistic regression was performed, and the resulting empirical outputs were presented in section 3.8 (Table 8 and SI 6–10). Current institutional frameworks appear inadequate, 71.6% of respondents expressed dissatisfaction with ongoing salinity interventions (Figure SI 8), while 99.0% demanded state-led support for soil reclamation, irrigation infrastructure, and salt-tolerant varieties (Figure SI 6). Furthermore, 94.7% preferred that mitigation initiatives be institutionalized under strict government leadership (Figure SI-7). This strong preference reveals

a critical gap in decentralized support systems and underscores the urgent need for well-funded, top-down public policy interventions to remediate salinity and safeguard smallholder livelihoods.

3.6. Barriers to farmers' salinity adaptive responses

Perceived barriers to salinity adaptation differed significantly among sites ($\chi^2 = 38.214$, $p < 0.001$, $V = 0.159$) (Table SI 8). The most prominent constraint was limited technical knowledge (39.5%, $n = 150$), followed by restricted access to extension services (15.3%), financial and input constraints (14.5%), and market uncertainty (13.9%) (Figure 4; Table SI 7). Spatial variation was notable, with Ganta Kanchama showing the highest proportion of technical knowledge gaps (47.3%), Shelle Mella experiencing the most severe financial constraints (30.1%), and Zayse Elgo reporting the greatest market uncertainty (20.7%). These complex challenges are consistent with those identified in other saline-affected systems, where inadequate extension services, limited credit, and weak institutional capacity hinder sustainable land management [23, 48, 71]. These spatial disparities underscore the need for site-specific intervention strategies tailored to local constraints.

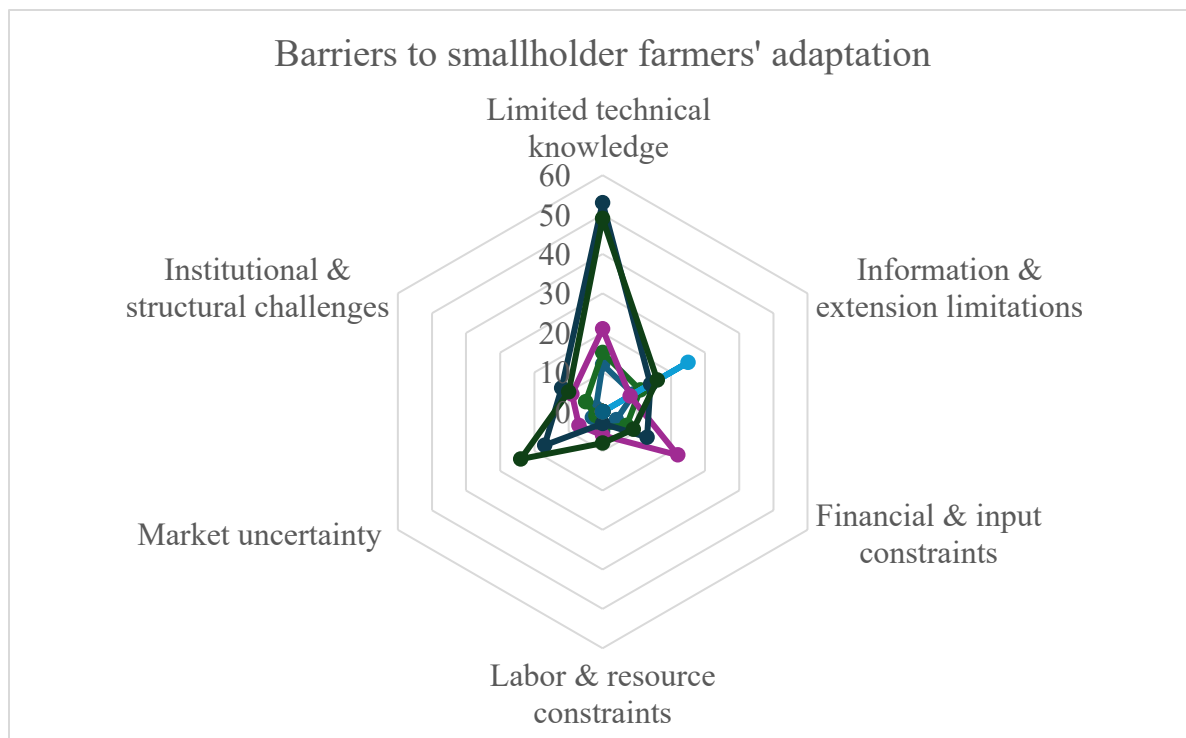


Figure 4. Perceived barriers to salinity adaptation across five study sites (N=380)

3.7. Determinants of farmers' adaptive responses and salinity-induced income losses: Evidence from Multinomial logistic regression

To examine the determinants of farmers' adoption of salinity management practices, coping strategies, and drivers intensifying salinity induced income losses, a Multinomial Logistic Regression (MNL) analysis was performed. The MNL models satisfied all key assumptions: the independence of irrelevant alternatives was confirmed (Hausman–McFadden $\chi^2 = 14.2$, $p = 0.28$; Small–Hsiao tests; $p = 0.31$), no multicollinearity was detected ($VIF < 2.5$), and model fit was robust (McFadden pseudo- $R^2 = 0.412$; log-likelihood = -468.21 ; accuracy = 71.3%).

Determinants of adoption of management practices

Using organic matter addition as the reference category (the most accessible and low-cost practice among smallholders), we estimated odds ratios (OR) and significance levels for five alternative strategies: improved irrigation and drainage, crop and income diversification, improved seeds, conservation tillage, and fallowing. Across all alternatives, adoption patterns consistently aligned with household resource endowments, labor availability, farm size, income diversification, and farming experience, highlighting the role of socio-economic, farm, and institutional factors in shaping farmers' adaptive decisions (Table 8; Table SI 11-14). For irrigation and drainage improvements, adoption likelihood was significantly increased by larger household size (4–7 members; OR = 3.33–5.91, $p = 0.002$ – 0.004), extended farming experience (>30 years; OR = 6.82, $p < 0.001$), larger landholdings (up to 10 ha; OR = 4.68, $p = 0.008$), and diversified income sources (OR = 3.71, $p = 0.012$). Similarly, crop diversification, rotation, and management (Table SI 11) adoption was positively associated with farming experience (OR = 8.14, $p < 0.001$), mixed income (OR = 5.33, $p = 0.003$), and medium to large family size (OR = 3.92, $p = 0.009$).

Table 8. MNLR results for the determinants of adoption of management practices (N = 380)

Predictors	Category (Reference)	Coef. (β)	Std. error	Z	P> z	OR	95% CI [Lower, Upper]
Gender	Male (ref = Female)	0.892	0.409	2.181	0.029 *	2.44	[1.094, 5.443]
	46–64 yrs (ref = <46 yrs)	0.314	0.387	0.811	0.417	1.369	[0.641, 2.924]
Age	>64 yrs (ref = <46 yrs)	0.487	0.521	0.935	0.35	1.628	[0.586, 4.522]
	2–3 (ref = 1)	0.611	0.456	1.34	0.18	1.842	[0.754, 4.501]
Family size	4–6 (ref = 1)	1.201	0.412	2.915	0.004 **	3.326	[1.483, 7.462]
	>7 (ref = 1)	1.777	0.577	3.08	0.002 **	5.91	[1.905, 18.337]
Farming	10–20yrs (ref = <20)	0.693	0.448	1.547	0.122	2	[0.832, 4.808]
	20–30 yrs (ref = <20)	1.108	0.456	2.43	0.015 *	3.029	[1.24, 7.399]
	>30yrs ref = (<20)	1.92	0.492	3.902	<0.001 ***	6.816	[2.599, 17.876]
	1–2 ha (ref = <1ha)	0.877	0.433	2.026	0.043 *	2.404	[1.029, 5.619]
Farm size	2–10 (ref = <1ha)	1.543	0.583	2.647	0.008 **	4.68	[1.492, 14.679]
	non-farm (ref = On farm)	0.112	0.612	0.183	0.855	1.119	[0.337, 3.713]
Income source	Off farm (ref = On farm)	0.498	0.521	0.956	0.339	1.645	[0.592, 4.571]
	Mixed (ref = On farm)	1.311	0.523	2.507	0.012 *	3.709	[1.329, 10.35]
Education	Educated (ref = Non educated)	0.387	0.398	0.972	0.331	1.472	[0.675, 3.212]
Land tenure	Owner (ref = Rented/leased)	0.601	0.441	1.363	0.173	1.825	[0.769, 4.332]
Perceived severity	Very severe (ref = Not severe)	0.698	0.412	1.694	0.09	2.01	[0.898, 4.499]
Awareness level	High (ref = unaware)	0.512	0.398	1.286	0.198	1.669	[0.766, 3.637]
Constant		-3.887	0.712	-5.459	<0.001 ***	0.021	[0.006, 0.073]

OR = Odds Ratio, CI = Confidence Interval. Statistical significance: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. Reference categories for all categorical variables are shown in parentheses, column 2. The dependent variable is 'adoption of management practices', a binary (1 = adopted one and more coping strategy (s), 0 = non-adopter). The dependent variable reference category is Organic matter addition, against which all alternative management practices (improved irrigation/drainage, crop and income diversification, improved seeds, conservation tillage, and fallowing) are compared. Model diagnostics: Independence of Irrelevant Alternatives (IIA) assumption verified (Hausman–McFadden $\chi^2 = 14.2$, $p = 0.28$; Small–Hsiao $p = 0.31$); variance inflation factors (VIF < 2.5) confirm no multicollinearity; McFadden pseudo- $R^2 = 0.412$; log-likelihood = -468.21; overall prediction accuracy = 71.3%.

Improved seed adoption (Table SI 12), conservation tillage (Table SI 13), and fallowing (Table SI 14) were all consistently linked to greater farming experience, land ownership, off-farm income, and financial barriers. Across all practices, farmers with greater farming experience, larger landholdings, and diversified income sources were 6 to 11 times more likely to adopt advanced salinity management strategies, revealing a distinct capacity gradient. Resource-poor households tended to adopt simpler, less demanding practices, while better-endowed farmers pursued more complex and resource-intensive options. This pattern underscores the role of socio-economic differentiation in shaping adaptive responses, a finding consistently documented across regional and global contexts [21, 22, 50, 66, 72].

Determinants of implementing coping strategies

In the coping strategies model (under similar model assumptions), irrigation and drainage management served as the reference category, with farming experience emerging as the primary driver of adoption across all alternative strategies. Alternative coping strategies including soil amendment, livelihood diversification, crop rotation, and financial/social support were evaluated relative to the baseline (Table 9; Tables SI 15-18). Adoption patterns followed a consistent resource-gradient trajectory, confirming that adaptive capacity fundamentally shapes household responses to salinity stress. Soil amendment adoption (Table 9) was significantly associated with extended farming experience (>30 years; OR = 8.23, $p < 0.001$), large farm size (OR = 6.53, $p < 0.001$), market and institutional barriers (OR = 3.67, $p < 0.003$), and high awareness (OR = 3.04, $p = 0.003$), reflecting the technical knowledge and scale requirements of such interventions. Livelihood diversification (Table SI 16) was primarily driven by long-term farming experience (>30 years; OR ≈ 8.13 , $p = 0.001$) and financial necessity (OR ≈ 5.33 , $p = 0.003$). Similarly, adoption of improved seeds and input management (Table SI 15), along with crop diversification and rotation (Table SI 17), was strongly linked to longer experience (OR = 6.53, $p = 0.001$; and OR = 5.58, $p = 0.001$, respectively) and heightened awareness (OR = 3.33 and 3.65), underscoring the critical role of human capital in facilitating input-intensive coping strategies, a trend consistently mirrored in other global studies [22,74]. Financial and social support mechanisms (Table SM 18) were predominantly sought by highly experienced farmers (OR = 11.25, $p < 0.001$) and large landholders (OR = 5.71, $p = 0.013$), showing how resource-endowed households strategically mobilize social networks during severe salinity shocks [75]. Overall,

veteran farmers (>30 years) demonstrated the strongest shift toward sophisticated coping strategies, with odds ratios ranging from 5.6 to 11.3 for improved seeds, diversification, and support networks relative to the baseline. Larger family size, land ownership, and awareness further facilitated adoption of diversification and conservation tillage, suggesting that scale, tenure security, and knowledge collectively enable more robust coping responses.

Determinants of Salinity-Induced Income Losses

The multinomial logistic regression (reference: 0% loss) revealed a pronounced vulnerability–capacity paradox: resource-rich, highly experienced farmers faced disproportionately greater salinity-induced losses, resounding regional findings [66, 76]. For medium (25–50%) and high (>50%) losses, key predictors significantly expanded risk exposure: extended farming experience increased loss odds by 11.25 and 5.58 times ($p = 0.001$), driven by historical expansion into salinity-sensitive cash crops [77, 78]. Larger landholdings elevated loss odds by 8.13 and 6.53 times ($p = 0.001$), scaling absolute exposure despite enabling adaptive investments [79]. Diversified income sources raised loss odds by 8.23 ($p = 0.001$) and 5.11 times ($p = 0.003$), as diversification can lock households into vulnerable production systems during shifting environmental conditions [80]. Irrigation access reduced loss odds by 70–80% (OR $\approx$ 0.20--0.30) when water quality was adequate, but exacerbated salinization when poor-quality water was used [77] (Table 10; Table SI 9). Irrigated systems in arid zones are highly susceptible to salt build-up, leaving intensive farms vulnerable to severe losses when water quality deteriorates [81].

Table 9. MNLR for the determinants of implementing soil amendments as coping strategy (N=380)

Predictors	Category (Reference)	Coef. (β)	Std. error	z	P> z	OR	95% CI [Lower, Upper]
Gender	Male (ref = Female)	0.912	0.312	2.923	0.003 **	2.49	[1.354, 4.579]
Age	46–64 years (ref = <46)	0.421	0.298	1.413	0.158	1.524	[0.85, 2.733]
	>64 years (ref = <46)	0.698	0.421	1.658	0.097	2.01	[0.881, 4.585]
	10–20 years (ref = <10)	0.876	0.388	2.258	0.024 *	2.401	[1.123, 5.135]
	20–30 years (ref = <10)	1.412	0.401	3.521	<0.001 ***	4.105	[1.881, 8.958]
Farming experience	>30 years (ref = <10)	2.108	0.456	4.623	<0.001 ***	8.232	[3.493, 19.401]
	1–2 ha (ref = <1)	1.101	0.367	3	0.003 **	3.008	[1.465, 6.177]
Farm size	2–10 ha (ref = <1)	1.876	0.498	3.768	<0.001 ***	6.528	[2.355, 18.092]
Land tenure	Owner (ref = Rented/Other)	0.987	0.398	2.479	0.013 *	2.683	[1.231, 5.847]
	Flood (ref = Furrow)	-0.112	0.401	-0.279	0.78	0.894	[0.407, 1.965]
Irrigation method	Rainfed (ref = Furrow)	-0.589	0.445	-1.323	0.186	0.555	[0.232, 1.329]
Perceived severity	Very severe (ref = Not severe)	0.723	0.334	2.164	0.030 *	2.06	[1.07, 3.967]
	Localized (ref = Limited)	0.312	0.298	1.047	0.295	1.366	[0.762, 2.45]
Perceived extent	Widespread (ref = Limited)	0.698	0.356	1.961	0.050 *	2.01	[1, 4.04, 4.04]
Awareness level	High (ref = Unaware))	1.112	0.378	2.941	0.003 **	3.041	[1.45, 6.376]
	Knowledge (ref = None)	-0.112	0.412	-0.272	0.786	0.894	[0.399, 2.005]
	Information (ref = None)	-0.298	0.456	-0.654	0.513	0.742	[0.304, 1.813]
Barriers	Financial (ref = None)	0.876	0.389	2.252	0.024 *	2.401	[1.121, 5.145]
	Market (ref = None)	1.301	0.445	2.924	0.003 **	3.674	[1.538, 8.774]
Constant		-4.112	0.712	-5.775	<0.001 ***	0.016	[0.005, 0.056]

OR = Odds Ratio, CI = Confidence Interval. Statistical significance: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. Reference categories for all categorical variables are shown in parentheses, column 2. The dependent variable is ‘coping strategy adoption’, a binary (1 = adopted one and more coping strategy (s), 0 = non-adopter). The dependent variable reference category is Irrigation and Drainage Management, against which all alternative coping strategies (Soil amendments, Livelihood diversification, Crop rotation, and Financial and social support) are compared. Model diagnostics: Independence of Irrelevant Alternatives (IIA) assumption verified (Hausman–McFadden $\chi^2 = 14.2$, $p = 0.28$; Small–Hsiao $p = 0.31$); variance inflation factors ($VIF < 2.5$) confirm no multicollinearity; McFadden pseudo- $R^2 = 0.412$; log-likelihood = -468.21; overall prediction accuracy = 71.3%.

Table 10. MNLR results for the determinants of salinity-induced income losses (25-50%) (N = 380)

Predictor	Category (Reference)	Coef. (β)	Std. error	z	P> z	OR	95% CI [Lower, Upper]
Gender	Male (ref = Female)	-0.876	0.398	-2.202	0.028 *	0.416	[0.191, 0.908]
	46-64 yrs (ref = <46 yrs)	0.512	0.356	1.438	0.15	1.669	[0.832, 3.348]
Age	>64 (ref = <46 yrs)	-1.201	0.612	-1.963	0.050 *	0.301	[0.091, 0.997]
	10–20 yrs (ref = <10 yrs)	1.112	0.467	2.381	0.017 *	3.041	[1.217, 7.599]
Farming Experience	20–30 yrs (ref = <10 yrs)	1.876	0.521	3.601	<0.001 ***	6.528	[2.348, 18.147]
	> 30 yrs (ref = < 10 yrs)	2.421	0.556	4.354	<0.001 ***	11.255	[3.781, 33.509]
	1-2 ha (ref = <1ha)	1.321	0.445	2.968	0.003 **	3.743	[1.564, 8.961]
Landholding	>2ha (ref = <1ha)	2.096	0.612	3.425	0.001 **	8.134	[2.499, 26.468]
	Non-farm (ref = On farm)	0.987	0.512	1.928	0.054	2.683	[0.984, 7.315]
	Off farm (ref = On farm)	1.543	0.556	2.775	0.006 **	4.68	[1.574, 13.914]
Income source	Mixed (ref = On farm)	2.108	0.521	4.045	<0.001 ***	8.232	[2.964, 22.872]
Access to irrigation	Yes (ref = No)	-1.632	0.498	-3.278	0.001 **	0.195	[0.074, 0.518]
Constant		-5.889	0.912	-6.458	<0.001 ***	0.003	[0.001, 0.015]

At the minimal loss tier (<25%), predictor magnitudes moderated: moderate experience (> 30 years; OR = 2.99, $p = 0.016$) and smaller landholdings (OR = 2.68, $p = 0.020$) increased loss likelihood, while managed irrigation remained protective (OR = 0.42, $p = 0.033$) (Table SI 10). Overall, high-capacity, irrigated farmers exhibited 5 to 11 times higher odds of medium-to-high losses, suffering the greatest absolute damage [75]. This calls for targeted support for resource-rich smallholders alongside baseline measures for marginal farmers [72], proving that adaptive capacity and environmental vulnerability coexist.

3.8. Study limitations

Several methodological and structural limitations constrain the interpretation and generalizability of this study. First, the cross-sectional design (March–April 2025) provides only a single temporal snapshot, which limits causal inference and restricts understanding of seasonal salinity dynamics. Second, reliance on self-reported household survey data may result in recall and social desirability biases in yield and income estimates. Third, the lack of plot-level biophysical measurements, such as Electrical Conductivity (ECe), pH, Sodium Adsorption Ratio (SAR), and Exchangeable Sodium Percentage (ESP), prevents objective validation of perceived salinity severity. Finally, purposive hotspot sampling further limits statistical generalizability to the broader region, and the predominantly male sample omits important gendered and youth-specific adaptation perspectives.

3.9. Conclusion and Policy Implications

This study demonstrates that soil salinity poses a severe, chronic threat to smallholder livelihoods in the Abaya–Chamo Lakes Basin, Ethiopia, significantly impacting agricultural productivity, income security, and rural resilience. A central insight is the vulnerability–capacity paradox: well-resourced, commercially oriented farmers face the highest absolute income losses due to intensive exposure within irrigated systems, while resource-constrained households remain trapped in low-productivity cycles. Driven by faulty irrigation management and climatic aridity, the impacts of salinization are systematically shaped by household endowments and institutional weaknesses, including technical knowledge gaps and limited access to extension services. Ultimately, building long-term resilience requires moving beyond uniform technical fixes toward integrated, context-specific solutions. The empirical insights from this research

necessitate a strategic shift from top-down, uniform agricultural interventions toward precision-targeted, capacity-sensitive frameworks. First, policymakers must implement a dual-track approach that simultaneously protects high-capacity irrigated systems through public drainage infrastructure, specialized crop insurance, and salt-tolerant crop varieties, while deliberately lifting marginal smallholders out of low-output traps through subsidized inputs, tailored extension services, and livelihood diversification. Second, structural and institutional constraints must be resolved by strengthening land-use planning, securing tenure arrangements, and offering targeted credit programs to overcome severe land fragmentation and restricted investment capacities. Third, addressing the risks of male-dominated decision-making requires gender-responsive policies that actively promote women's participation in agricultural training, resource access, and local planning forums to secure diverse adaptation pathways. Finally, rigid administrative structures must be replaced with participatory, farmer-centric governance models. By strengthening extension-farmer linkages, establishing farmer field schools, and creating platforms for collective action, regional planning can integrate local priorities. Ultimately, aligning these multi-level policy frameworks with the heterogeneous, localized realities of farming households will allow stakeholders to foster sustainable, resilient agricultural systems capable of safeguarding smallholder livelihoods against escalating environmental pressures.

3.10. Future research tips

To address study limitations, future research should prioritize four areas. Methodologically, longitudinal panel data integrate household surveys with time-series soil and water testing are essential to capture dynamic salinity fluctuations, alongside gender and youth responsive frameworks for equity analysis. Economically, rigorous cost-benefit analyses of specific adaptation options must be conducted to guide resource allocation. Structurally, advanced multi-level or structural equation modeling should be developed to clarify how socio-economic heterogeneity, institutional performance, and market access influence long-term adoption persistence. Finally, comparative studies across diverse agroecological zones will enhance external validity and support scalable, context-sensitive policy frameworks.

3.11. Recommendations

Based on empirical findings, five strategic interventions are proposed to address soil salinity. First, agricultural extension services should be tailored to household capacities, supplying advanced technologies to high-capacity farmers while offering accessible, low-cost organic solutions to resource-limited households. Second, investments must prioritize breeding and distributing salt-tolerant maize and banana varieties, supported by field demonstration plots to encourage adoption. Third, upgrading irrigation infrastructure and drainage systems is critical to control secondary salinization. Fourth, promoting livelihood diversification through microfinance, vocational training, and market linkages will reduce vulnerable households' over-reliance on farming. Finally, implementing participatory governance models will ensure farmers actively co-design sustainable salinity-management programs.

Declaration Statements

Funding: This research was supported by Arba Minch University under the SP4 project of the Institutional University Cooperation (AMU-IUC) program. The AMU-IUC program was financed by VLIR-UOS, which funded the project “Reducing land degradation through and for sustainable rural land use research” (ET2022IUC035A101); VLIR-UOS funding covered data-collection costs only. Additional support was provided by the Ethiopian Ministry of Education and the Arba Minch University Research Directorate through PhD subsidiary funds.

Acknowledgements: The authors gratefully acknowledge the support of the participating institutions and the farmers who took part in the study.

Declaration of competing interests: The authors declare no competing interests.

Ethical approval: The study received approval from the Arba Minch University Ethical Clearance Committee. All procedures complied with international and institutional ethical guidelines (details provides in methods sections 2.2 and 2.4).

Consent to Participate: Informed consent was obtained from all individual participants/farmers included in the study prior to questionnaire administration and interviews.

Consent to publish: Not applicable. This manuscript does not contain any individual person's

data in any form (including individual details, images, or videos).

Author contributions: Yohannes Goldia Apira — conceptualization, methodology, software, data curation, analysis, interpretation, and manuscript drafting. Dereje Tsegaye Salfeko — manuscript review and editing, supervision, validation, and project administration, resources. Tizita Endale Elcho — manuscript review and editing, supervision, fund acquisition, resources. Azemera Walche Mengesha — manuscript review and editing, supervision, validation, project administration. All authors have accepted responsibility for the entire content of this manuscript and consented to its submission, reviewed all results, and approved the final version.

Data availability statement: The data generated and analyzed in this study are confidential but available from the corresponding author upon reasonable request.

Supplementary information: The supplementary materials for this article including additional tables, figures, and supporting data will be made available online alongside the published manuscript.

Declaration of generative AI use: Microsoft Copilot was used for grammatical refinement. The authors retain full responsibility for the accuracy of the content and the conclusions drawn.

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