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Community-based strategies for salinity mitigation in sundarban deltaic soils

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Abstract
Soil salinity poses a critical threat to agricultural sustainability and livelihood security in the Sundarban deltaic region, affecting approximately 4.2 million hectares of coastal land in India and Bangladesh. This study evaluated the effectiveness of community-based salinity mitigation strategies implemented across 45 villages in the Indian Sundarban region over a 24-month period. A mixed-methods approach combining soil analysis, socio-economic surveys, and participatory action research was employed to assess six primary interventions: rainwater harvesting, organic amendment application, salt-tolerant crop cultivation, freshwater pond construction, community-led drainage management, and bio-drainage through salt-accumulator vegetation. Soil electrical conductivity (EC) measurements were conducted at three-month intervals across 180 sampling sites, while household surveys (n=675) documented adoption rates and perceived efficacy. Results demonstrated significant EC reduction from baseline mean 8.7±2.3 dS/m to 4.2±1.8 dS/m in intervention zones, compared to minimal change in control areas (8.9±2.4 to 8.5±2.2 dS/m; $p<0.001$). Organic matter content increased from 0.8±0.3% to 2.1±0.6% following farmyard manure and green manure incorporation. Community-managed freshwater ponds reduced dry-season soil salinity by 35-48% within 500-meter radius zones. Adoption of salt-tolerant rice varieties alongside bio-drainage systems yielded crop productivity improvements of 1.8 to 2.4 tonnes/hectare. Socio-economic analysis revealed 73% household participation in collective mitigation efforts, with women's self-help groups demonstrating highest engagement levels. Cost-benefit analysis indicated positive returns within 18-36 months for most interventions. This research demonstrates that integrated, community-driven approaches provide viable, sustainable solutions for salinity management in vulnerable deltaic ecosystems, offering replicable models for similar coastal regions globally facing climate-induced salinization challenges.

Keywords: Soil salinity, sundarban delta, community-based natural resource management, coastal agriculture, salinity mitigation, participatory action research, bio-drainage, climate adaptation

Introduction

The Sundarban deltaic region, spanning the confluence of the Ganges, Brahmaputra, and Meghna rivers across India and Bangladesh, represents one of the world's most ecologically significant yet environmentally vulnerable coastal zones. Encompassing approximately 10,000 square kilometers of mangrove forests, tidal waterways, and agricultural lands, this UNESCO World Heritage Site supports over 4.5 million inhabitants whose livelihoods depend primarily on agriculture, fisheries, and forest resources [1]. However, soil salinity has emerged as one of the most pressing environmental challenges threatening the sustainability of agricultural systems and food security in this region [2, 3].

Soil salinization in the Sundarban occurs through multiple mechanisms including tidal inundation, seawater intrusion into freshwater aquifers, storm surge events, and inadequate drainage infrastructure [4]. Climate change has exacerbated these processes through sea-level rise, increased cyclone frequency and intensity, and altered precipitation patterns, leading to progressive expansion of salt-affected areas [5, 6]. Current estimates suggest that 60-70% of agricultural land in the Indian Sundarban experiences varying degrees of salinity stress, with electrical conductivity levels frequently exceeding 4 dS/m during the dry season [7]. This salinization not only reduces crop yields and agricultural diversity but also triggers soil structural degradation, nutrient imbalances, and loss of beneficial soil microbiota [8].

Previous research on salinity management in deltaic environments has predominantly focused on engineering solutions such as embankment construction, polderization, and large-scale irrigation schemes [9, 10]. While these interventions have achieved localized success, they often prove economically prohibitive for resource-poor farming communities and may create unintended ecological consequences including waterlogging, altered hydrological regimes, and disruption of traditional livelihoods [11]. Furthermore, top-down implementation approaches have frequently failed to account for local knowledge systems, socio-cultural contexts, and the adaptive capacities of indigenous communities [12].

Emerging evidence suggests that community-based natural resource management approaches offer promising alternatives for addressing complex environmental challenges in vulnerable ecosystems [13, 14]. These participatory strategies leverage local knowledge, promote collective action, ensure equitable benefit distribution, and enhance long-term sustainability through community ownership and adaptive management [15]. In the context of soil salinity, community-based interventions may include traditional water management practices, organic soil amendments, crop diversification, agroforestry systems, and collaborative infrastructure development [16, 17].

Despite growing recognition of community-based approaches, rigorous empirical research evaluating their effectiveness for salinity mitigation in the Sundarban remains limited. Existing studies have typically focused on individual interventions in isolation, employed limited temporal scopes, or lacked robust quantitative assessment of both biophysical and socio-economic outcomes [18, 19].

Moreover, few studies have systematically examined the synergistic effects of integrated multi-intervention strategies or analyzed the social dynamics influencing community participation and collective efficacy.

This research addresses these critical knowledge gaps by evaluating a comprehensive suite of community-based salinity mitigation strategies implemented through participatory action research across 45 villages in the Indian Sundarban region. The primary objectives were to: [1] quantify changes in soil salinity parameters following implementation of community-based interventions over a 24-month period; [2] assess improvements in soil quality indicators including organic matter content, pH, and nutrient availability; [3] evaluate crop productivity outcomes across different intervention combinations; [4] analyze community participation patterns, adoption rates, and socio-economic factors influencing engagement; and [5] conduct cost-benefit analysis to determine economic viability and sustainability of various mitigation strategies.

The novelty of this study lies in its integrated approach combining rigorous biophysical monitoring with participatory research methodologies, its extended temporal scope capturing seasonal variability, and its comprehensive analysis of the social dimensions underlying successful community-based environmental management. By demonstrating the efficacy of locally-driven, integrated salinity mitigation strategies, this research contributes both theoretical insights into community-based natural resource management and practical guidance for policy development and implementation in vulnerable coastal regions worldwide.

The article is structured as follows: Section 2 details the research methodology including study site selection, intervention design, data collection protocols, and analytical approaches. Section 3 presents results from soil analysis, agricultural productivity assessments, and socio-economic surveys. Section 4 discusses findings in relation to existing literature, examines theoretical and practical implications, and identifies study limitations. Section 5 concludes with key recommendations for policy and future research directions.

Methods

1. Research Design and Study Area

This study employed a mixed-methods quasi-experimental design combining quantitative soil and agricultural data collection with qualitative participatory action research conducted over 24 months (January 2022 to December 2023). The research was implemented in the South 24 Parganas district of West Bengal, India, specifically targeting 45 villages across three administrative blocks (Patharpratima, Sagar, and Namkhana) within the Indian Sundarban region. Study sites were selected based on: [1] presence of moderate to severe soil salinity (EC >4 dS/m during dry season); [2] agricultural dependence as primary livelihood; [3] community willingness to participate in collaborative research; and [4] accessibility for regular monitoring. The study area experiences a humid tropical climate with mean annual rainfall of 1, 800-2,000 mm, concentrated during the monsoon season (June-September), and mean temperatures ranging from 12°C (winter) to 38°C (summer).

2. Sampling Strategy and Sample Size

A stratified random sampling approach was employed to ensure representativeness across varying salinity levels, cropping systems, and socio-economic conditions. Within the 45 participating villages, 180 permanent soil sampling sites were established at 30-50 meter intervals following a systematic grid pattern, with 60 sites designated as intervention zones, 60 as community-controlled intervention zones (allowing communities to select preferred combinations), and 60 as control zones maintaining traditional practices. Sample size determination was based on power analysis (α=0.05, β=0.20, effect size=0.4) indicating minimum requirement of 45 sites per group to detect statistically significant differences in soil EC.

For socio-economic assessment, household surveys were conducted with 675 farming households (15 randomly selected households per village) representing approximately 22% of the total farming population in study villages. This sample size exceeded the minimum requirement calculated using Cochran's formula for finite populations (n=384 at 95% confidence level, 5% margin of error). Additionally, 135 participants (45 per block, ensuring gender balance with minimum 40% women representation) were engaged in participatory focus group discussions to gather qualitative data on intervention adoption, perceived effectiveness, and implementation challenges.

3. Community-Based Interventions

Six primary salinity mitigation strategies were implemented through participatory planning workshops:

Intervention 1: Rainwater Harvesting Systems – Construction of household and community-level rainwater collection structures with storage capacity ranging from 5,000 to 20,000 liters, designed for dry-season irrigation.

Intervention 2: Organic Amendment Application – Incorporation of farmyard manure (10-15 tonnes/hectare), green manure crops (Sesbania aculeata, Crotalaria juncea), and compost to improve soil organic matter and structure.

Intervention 3: Salt-Tolerant Crop Cultivation – Introduction of salt-tolerant rice varieties (Hamilton, CSR36, CSR43) and alternative crops including sunflower, mustard, and salt-tolerant vegetables.

Intervention 4: Freshwater Pond Construction – Community-managed freshwater ponds (0.1-0.3 hectares) excavated to depths of 2.5-3.5 meters for irrigation water storage and fish culture.

Intervention 5: Drainage Management – Participatory planning and maintenance of field drains and community drainage channels to facilitate salt leaching during monsoon periods.

Intervention 6: Bio-Drainage Systems – Establishment of salt-accumulator vegetation (Salicornia brachiata, Suaeda maritima) along field margins and drainage channels to extract salts from soil and groundwater.

4. Data Collection Procedures

Soil Sampling and Analysis: Composite soil samples (0-30 cm depth, five sub-samples per site) were collected at three-month intervals throughout the study period. Samples were air-dried, ground, and passed through 2-mm sieves before analysis. Electrical conductivity was measured in 1:2.5 soil-water extracts using a calibrated conductivity meter. Soil pH was determined in 1:2.5 soil-water suspensions using a digital pH meter. Organic carbon content was estimated through the Walkley-Black wet oxidation method and converted to organic matter by multiplying by 1.724. Available nitrogen was assessed using the alkaline permanganate method, available phosphorus through Bray's method, and available potassium by flame photometry following neutral normal ammonium acetate extraction.

Agricultural Productivity Assessment: Crop yields were recorded through crop-cutting experiments conducted on 5×5 meter quadrats within each intervention zone, with three replications per site. Harvest data included grain yield, biomass production, and harvest index for rice crops, and seed yield for alternative crops.

Household Surveys: Structured questionnaires were administered through face-to-face interviews covering: demographic information, land holdings, farming practices, intervention adoption rates, perceived effectiveness, costs incurred, benefits realized, and participation in community decision-making. Surveys were conducted in local Bengali language by trained enumerators familiar with regional dialects and cultural contexts.

Participatory Data Collection: Focus group discussions (8-12 participants each, 90-120 minutes duration) explored community perceptions, traditional knowledge systems, gender dimensions of participation, barriers to adoption, and suggestions for intervention refinement. Discussions were facilitated using participatory rural appraisal tools including resource mapping, seasonal calendars, and problem-solution matrices.

5. Statistical Analysis

Quantitative data were analyzed using SPSS version 26.0 and R version 4.2.1. Descriptive statistics (means, standard deviations, frequencies, percentages) characterized soil parameters, crop yields, and socio-economic variables. Repeated measures ANOVA examined temporal changes in soil parameters across intervention and control groups, with Bonferroni post-hoc tests identifying significant pairwise differences. Independent samples t-tests compared soil and yield parameters between intervention and control zones at study conclusion. Multiple linear regression models identified predictors of intervention adoption and effectiveness, with variables including household characteristics, land holdings, education levels, and social capital indicators. Pearson correlation analysis explored relationships between soil parameters and crop productivity. Statistical significance was established at $p<0.05$ for all analyses.

Qualitative data from focus group discussions were transcribed, translated when necessary, and analyzed using thematic analysis approaches. Coding was conducted independently by two researchers with inter-coder reliability assessed through Cohen's kappa statistic ($\kappa=0.82$, indicating substantial agreement). Major themes were identified through iterative coding, categorization, and verification processes.

6. Cost-Benefit Analysis

Economic assessment employed standard cost-benefit analysis techniques, calculating net present value (NPV), benefit-cost ratio (BCR), and internal rate of return (IRR) for each intervention over a five-year projection period. Costs included initial investment, labor, materials, maintenance, and opportunity costs. Benefits encompassed increased crop yields, reduced input costs, diversification income, and estimated ecosystem service values. A discount rate of 12% was applied following government of India guidelines for agricultural project evaluation.

7. Ethical Considerations

This research received ethical approval from the Institutional Ethics Committee of the implementing organization (Approval No. IEC/2021/SBN/042). Prior informed consent was obtained from all research participants following detailed explanation of study objectives, procedures, risks, and benefits in local language. Participants were informed of their right to withdraw at any time without consequences. Confidentiality was maintained through data anonymization and secure storage protocols. Community consultation and consent were obtained at village level through gram panchayat (village council) meetings before initiating research activities. Benefit-sharing arrangements ensured that participating communities received training, technical support, and continued access to improved practices beyond the study period.

Results

1. Changes in Soil Salinity Parameters

Baseline soil electrical conductivity across all study sites ranged from 4.2 to 14.8 dS/m with a mean of 8.7±2.3 dS/m during the dry season (March 2022). After 24 months of intervention implementation, soil EC in intervention zones decreased significantly to 4.2±1.8 dS/m, representing a 51.7% reduction from baseline ($t=18.42$, $df=119$, $p<0.001$). In contrast, control zones exhibited minimal change from 8.9±2.4 dS/m to 8.5±2.2 dS/m ($t=1.23$, $df=119$, $p=0.221$), which was not statistically significant (Table 1).

Repeated measures ANOVA revealed significant time × treatment interaction effects ($F^{[8, 536]}=42.8$, $p<0.001$), indicating that the rate of salinity reduction differed substantially between intervention and control groups across the monitoring period. Post-hoc analyses demonstrated that significant EC reductions became detectable after 6 months in zones with organic amendment application ($p=0.018$), while zones with integrated interventions (3+ strategies) showed earlier responses at 3 months ($p=0.032$).

Seasonal variations showed that EC levels were highest during pre-monsoon months (March-May) and lowest during post-monsoon periods (October-December). However, intervention zones maintained lower salinity levels year-round compared to controls. The monsoon season facilitated salt leaching in all areas, but intervention zones demonstrated superior retention of freshwater and sustained lower EC levels during subsequent dry periods.

Among individual interventions, freshwater pond construction demonstrated the most localized impact, with soil EC reductions of 35-48% within 500-meter radius zones. Bio-drainage systems showed cumulative effects over time, with minimal impact during the first 6 months but progressive EC reduction of 28-42% by study conclusion as vegetation biomass accumulated. Organic amendment application provided moderate but consistent EC reduction (22-35%) alongside improvements in other soil quality parameters.

Table 1: Soil Electrical Conductivity Changes Across Treatment Groups Over 24-Month Period

Treatment Group	Baseline EC (dS/m)	6 months (dS/m)	12 months (dS/m)	18 months (dS/m)	24 months (dS/m)	% Change	p-value
Control	8.9±2.4	8.7±2.3	8.8±2.5	8.6±2.3	8.5±2.2	-4.5%	0.221
Rainwater Harvesting	8.6±2.2	7.8±2.1	6.9±2.0	6.2±1.9	5.7±1.8	-33.7%	<0.001
Organic Amendments	8.8±2.5	7.9±2.2	6.7±2.0	5.8±1.7	5.3±1.6	-39.8%	<0.001
Salt-Tolerant Crops	8.5±2.3	8.2±2.2	7.6±2.1	7.1±2.0	6.8±1.9	-20.0%	0.004
Freshwater Ponds	8.7±2.4	7.2±2.0	5.9±1.8	5.1±1.6	4.6±1.5	-47.1%	<0.001
Drainage Management	8.9±2.6	8.3±2.4	7.4±2.2	6.7±2.0	6.2±1.9	-30.3%	<0.001
Bio-Drainage	8.6±2.3	8.4±2.2	7.8±2.1	6.5±1.8	5.5±1.7	-36.0%	<0.001
Integrated (3+ strategies)	8.8±2.4	7.1±2.0	5.6±1.7	4.7±1.5	4.2±1.8	-52.3%	<0.001

Values represent mean ± standard deviation; p-values derived from paired t-tests comparing baseline to 24-month measurements.

2. Soil Quality Improvements

Soil organic matter content increased significantly across all intervention groups, with the most substantial gains observed in zones receiving organic amendments (Table 2). Baseline organic matter averaged 0.8±0.3% across intervention sites, increasing to 2.1±0.6% after 24 months (t=15.7, df=59, p<0.001). This represented a 162.5% improvement over baseline conditions. Control zones showed minimal change from 0.8±0.3% to 0.9±0.3% (t=1.8, df=59, p=0.078).

Soil pH exhibited modest but significant changes, with intervention zones shifting from strongly alkaline conditions (pH 8.6±0.4) toward more neutral ranges (pH 7.8±0.5), while control zones remained relatively stable (pH 8.7±0.4 to pH 8.6±0.4). This pH reduction in intervention zones correlated positively with increased organic matter content (r=0.67, p<0.001) and enhanced nutrient availability.

Available nitrogen increased from baseline 142±38 kg/ha to 218±52 kg/ha in intervention zones (p<0.001), compared to minimal change in controls (145±41 to 151±39 kg/ha, p=0.164). Similarly, available phosphorus improved from 8.2±2.6 kg/ha to 14.7±3.8 kg/ha in intervention areas (p<0.001), while available potassium increased from 118±34 kg/ha to 176±48 kg/ha (p<0.001). These nutrient availability improvements were most pronounced in sites combining organic amendments with drainage management, likely due to enhanced mineralization rates and reduced nutrient leaching.

Table 2: Changes in Soil Quality Parameters Between Baseline and 24-Month Assessment

Parameter	Intervention Zones (n=120)	Control Zones (n=60)	Between-Group Difference
	Baseline	24 months	Baseline
Organic Matter (%)	0.8±0.3	2.1±0.6	0.8±0.3
pH	8.6±0.4	7.8±0.5	8.7±0.4
Available N (kg/ha)	142±38	218±52	145±41
Available P (kg/ha)	8.2±2.6	14.7±3.8	8.4±2.8
Available K (kg/ha)	118±34	176±48	121±37

Values represent mean ± standard deviation; Between-group differences calculated using independent samples t-tests comparing intervention vs. control at 24 months.

3. Agricultural Productivity Outcomes

Crop yield data demonstrated substantial productivity improvements in intervention zones compared to controls (Table 3). Rice yields in intervention zones averaged 3.8±0.7 tonnes/hectare, representing an 86% increase over control zone yields of 2.0±0.5 tonnes/hectare (t=18.3, df=118, p<0.001). The highest rice productivity was observed in zones combining salt-tolerant varieties with organic amendments and freshwater irrigation, achieving yields of 4.2±0.6 tonnes/hectare.

Alternative crop cultivation in previously fallow lands generated additional income and dietary diversification. Sunflower cultivation in moderately saline areas yielded 1.2±0.3 tonnes/hectare, while mustard production averaged 0.9±0.2 tonnes/hectare. Salt-tolerant vegetable cultivation (including tomatoes, eggplant, and gourds) provided year-round production opportunities, with average yields of 12-18 tonnes/hectare depending on species and salinity levels.

Multiple regression analysis identified soil EC (β=-0.58, p<0.001), organic matter content (β=0.43, p<0.001), and irrigation water availability (β=0.36, p<0.001) as the strongest predictors of rice productivity, collectively explaining 74% of yield variance (R^2=0.74, F[8, 171]=62.4, p<0.001).

Table 3: Crop Productivity Comparison Between Intervention and Control Zones

Crop Type	Intervention Zones (tonnes/ha)	Control Zones (tonnes/ha)	Increase (%)	t-value	p-value
Rice (wet season)	3.8±0.7	2.0±0.5	90.0%	18.3	<0.001
Rice (dry season)	2.4±0.6	0.8±0.3	200.0%	21.7	<0.001
Sunflower	1.2±0.3	—	—	—	—
Mustard	0.9±0.2	0.4±0.2	125.0%	15.4	<0.001
Vegetables (mixed)	15.3±4.2	6.8±2.4	125.0%	14.8	<0.001
Total Annual Productivity	8.7±1.8	3.2±0.9	171.9%	24.6	<0.001

Values represent mean ± standard deviation based on crop-cutting experiments; Total annual productivity calculated as grain-equivalent yields across all crops cultivated.

4. Community Participation and Adoption Patterns

Household survey data revealed 73% overall participation rate in community-based salinity mitigation activities, with significant variation across intervention types and socio-demographic groups. Rainwater harvesting systems achieved highest adoption rates (82%) due to relatively low costs and immediate benefits, while bio-drainage systems showed lowest initial adoption (48%) but steady increases over time as demonstration effects became apparent.

Women's self-help groups demonstrated significantly higher engagement levels (84% participation) compared to male-headed households without SHG affiliation (67%, χ^2=38.6, df=1, p<0.001). Educational attainment correlated positively with intervention adoption (r=0.41, p<0.001), as did participation in community organizations (r=0.53, p<0.001) and landholding size up to 2 hectares, beyond which participation rates plateaued.

Focus group discussions identified key facilitating factors including: peer learning opportunities through farmer field schools (mentioned by 78% of participants), technical support from agricultural extension workers (71%), availability of locally-adapted planting materials and inputs (68%), and collective decision-making processes through participatory planning workshops (64%). Primary barriers included initial investment costs (cited by 52% of non-adopters), labor requirements during peak agricultural seasons (43%), uncertainty about long-term effectiveness (38%), and limited access to credit facilities (31%).

Thematic analysis revealed strong community consensus regarding visible improvements in soil condition, crop performance, and household food security. Representative quotes included: "Our land was becoming like a desert during summer, now we can grow vegetables year-round" and "Working together in our women's group gave us confidence and knowledge we never had before." Gender dimensions emerged as critical, with women reporting primary responsibility for vegetable cultivation, water management, and organic input preparation, yet limited participation in formal decision-making forums until project interventions specifically promoted inclusive governance structures.

5. Economic Viability and Cost-Benefit Analysis

Cost-benefit analysis demonstrated positive economic returns for most interventions within projected five-year timeframes (Table 4). Rainwater harvesting systems required average initial investment of ₹18, 500 per household (approximately USD 225) with annual maintenance costs of ₹1, 200, but generated estimated benefits of ₹32,000 annually through improved crop yields and reduced water purchase costs, yielding benefit-cost ratio of 3.8 and internal rate of return of 38%.

Community freshwater ponds required highest initial investment (₹280,000-450,000 per pond, or USD 3, 400-5, 500) but served multiple households (average 35 families per pond) and generated diversified benefits through irrigation water provision, fish culture income (average ₹45,000 annually per pond), and ecosystem services. When costs were distributed across beneficiary households, individual household BCR reached 4.2 with IRR of 42%.

Organic amendment application demonstrated most favorable economics for resource-poor households, requiring minimal cash investment (primarily labor and locally-available materials) while generating sustained yield improvements. Net present value calculations over five years averaged ₹58,000 per hectare (USD 705) with BCR of 5.6.

Integrated intervention packages combining 3-5 strategies required higher initial investments but generated synergistic benefits exceeding summed individual intervention effects, achieving BCR of 4.8 and payback periods of 18-24 months.

Table 4: Economic Assessment of Salinity Mitigation Interventions

Intervention Type	Initial Investment (₹)	Annual Costs (₹)	Annual Benefits (₹)	NPV (5 years, ₹)	BCR	IRR (%)
Rainwater Harvesting	18, 500	1, 200	32,000	89, 400	3.8	38
Organic Amendments	4, 200	2, 800	28, 500	87, 600	5.6	124
Salt-Tolerant Crops	8, 900	3, 400	24, 800	68, 300	3.2	48
Freshwater Ponds (per HH share)	8,000	800	38, 200	124, 800	4.2	42
Drainage Management (per HH)	3, 500	600	18, 400	52, 700	3.9	86
Bio-Drainage	6, 800	1, 100	22, 600	67, 200	3.4	52
Integrated Package	42,000	7, 200	118,000	348, 500	4.8	58

Values in Indian Rupees (₹); NPV = Net Present Value calculated using 12% discount rate; BCR = Benefit-Cost Ratio; IRR = Internal Rate of Return; Exchange rate approximately 1 USD = ₹82 during study period.

6. Spatial Distribution and Intervention Synergies

Spatial analysis revealed that intervention effectiveness varied with proximity to water resources, with zones within 500 meters of freshwater ponds experiencing significantly greater salinity reduction (mean EC decrease of 5.8 dS/m) compared to more distant zones (mean decrease of 3.2 dS/m, t=8.4, p<0.001). Bio-drainage systems demonstrated cumulative spatial effects, with EC reduction extending 200-400 meters from plantation sites depending on groundwater flow patterns and soil hydraulic properties.

Intervention combinations produced synergistic effects beyond additive impacts. Sites implementing both organic amendments and bio-drainage achieved 47% greater EC reduction than predicted from individual intervention effects (observed 62% vs. predicted 42%, p=0.008). Similarly, rainwater harvesting combined with drainage management produced yield improvements 34% higher than expected from independent effects.

Discussion

Interpretation of Salinity Reduction Outcomes

The substantial soil salinity reduction achieved through community-based interventions (51.7% EC decrease in intervention zones versus 4.5% in controls) demonstrates the efficacy of integrated, locally-managed approaches for addressing soil salinization in vulnerable deltaic environments. These findings align with and extend previous research documenting the effectiveness of organic amendments [20, 21] and freshwater management [22] for salinity mitigation, while providing novel evidence regarding the synergistic effects of combined interventions and community-based implementation models.

The temporal patterns observed—with significant EC reductions emerging after 6 months for most interventions and earlier responses (3 months) for integrated approaches—suggest that soil salinity mitigation requires sustained intervention and patience for measurable outcomes. This finding has important implications for program design and community engagement, highlighting the need for realistic expectation-setting and provision of short-term benefits to maintain participation during the initial implementation period when biophysical changes may not yet be apparent.

The superior performance of freshwater pond systems, achieving 35-48% EC reduction within 500-meter radius zones, underscores the critical importance of freshwater availability as a limiting factor in saline environments. These results corroborate findings from Bangladesh and Vietnam demonstrating that strategic freshwater storage and distribution can create significant salinity amelioration effects extending beyond immediate irrigation zones through groundwater recharge and localized hydrological modifications [23, 24]. However, the substantial initial investment required for pond construction (₹280,000-450,000) presents accessibility challenges for resource-poor communities, necessitating policy interventions such as subsidized credit schemes or community infrastructure grants.

The progressive effectiveness of bio-drainage systems over time (minimal impact during first 6 months, then 28-42% EC reduction by 24 months) reflects the biological dynamics of plant establishment, root system development, and salt accumulation in plant tissues. Previous studies on salt-accumulator vegetation have primarily focused on arid and semi-arid contexts [25, 26], while this research provides valuable evidence regarding bio-drainage applicability in humid tropical deltaic settings. The observed delayed but sustained effects suggest that bio-drainage should be conceptualized as a long-term salinity management strategy rather than a rapid remediation technique, potentially offering cost-effective solutions when implemented with realistic temporal expectations.

Soil Quality Improvements and Agricultural Implications

The dramatic increase in soil organic matter content (162.5% improvement in intervention zones) represents a critical co-benefit of salinity mitigation strategies, particularly organic amendment application. Beyond direct salinity effects, elevated organic matter enhances soil water retention capacity, cation exchange capacity, aggregate stability, and biological activity—all factors contributing to improved crop productivity and climate resilience [27, 28]. The observed correlation between organic matter content and pH moderation ($r=0.67$, $p<0.001$) suggests that organic amendments facilitate buffering of alkaline conditions common in saline soils, creating more favorable chemical environments for crop cultivation and nutrient cycling.

Improvements in nutrient availability (54% increase in available nitrogen, 79% increase in available phosphorus, 49% increase in available potassium) indicate that salinity mitigation interventions address not only osmotic and ionic stress factors but also nutritional constraints limiting crop productivity. These findings align with established understanding that salt stress imp airs nutrient uptake and creates imbalanced nutrient ratios [29], while also demonstrating that community-based organic management approaches can effectively reverse these nutritional deficiencies. The synergistic effects observed between organic amendments and drainage management likely reflect enhanced mineralization under improved aeration conditions and reduced nutrient losses through strategic leaching management.

The 90% rice yield increase in intervention zones, achieving productivity levels of 3.8 tonnes/hectare compared to 2.0 tonnes/hectare in controls, demonstrates substantial agricultural benefits translating directly to improved food security and household income. These yield improvements exceed those reported in previous controlled experiments (typically 30-60% increases) [30, 31], possibly reflecting the integrated nature of interventions, community ownership enhancing implementation quality, or synergistic effects among multiple simultaneously-applied strategies. The particularly impressive dry-season rice yield improvements (200% increase) highlight the critical importance of freshwater availability during periods of peak evapotranspiration and minimal natural leaching.

The successful cultivation of alternative crops (sunflower, mustard, vegetables) in previously marginal or fallow lands represents an important diversification strategy, reducing household vulnerability to climate variability, price fluctuations, and crop-specific stresses while enhancing nutritional diversity [32]. This finding supports recent emphasis in agricultural development literature on diversification as a key component of climate adaptation and sustainable intensification in smallholder farming systems [33, 34].

Social Dimensions and Community Participation

The 73% overall participation rate and particularly high engagement among women's self-help groups (84%) provides compelling evidence that community-based approaches can achieve broad-based mobilization when designed with attention to local social structures, gender dynamics, and participatory processes. These findings resonate with extensive literature documenting the critical role of women in natural resource management, agricultural production, and household food security in South Asian contexts [35, 36], while also highlighting persistent gender gaps in formal decision-making structures that require explicit interventions to address.

The positive correlation between participation in community organizations and intervention adoption ($r=0.53$, $p<0.001$) suggests that social capital and collective action capacity represent important enabling factors for community-based environmental management. This finding aligns with common property resource theory and empirical research demonstrating that communities with strong social networks, trust, and collaborative governance structures achieve superior natural resource management outcomes [37, 38]. The observed importance of peer learning through farmer field schools (mentioned by 78% of participants as facilitating factor) indicates that knowledge exchange and social learning processes play crucial roles alongside material interventions.

The identification of initial investment costs as the primary barrier (cited by 52% of non-adopters) despite demonstrated positive economic returns highlights the importance of liquidity constraints, risk aversion, and temporal discounting in adoption decisions, particularly among resource-poor households. These findings support arguments for financial mechanisms including credit access, input subsidies, or payment for ecosystem services schemes to overcome upfront cost barriers and enable adoption by vulnerable populations [39, 40].

Thematic analysis revealing strong community consensus on visible improvements and empowerment outcomes, particularly among women's groups, suggests that community-based approaches generate important co-benefits beyond biophysical outcomes, including enhanced agency, knowledge, organizational capacity, and social cohesion. These intangible benefits, though challenging to quantify, represent critical dimensions of sustainable development and may enhance long-term sustainability through building adaptive capacity and local ownership [41].

Economic Viability and Scalability Considerations

The favorable benefit-cost ratios (3.2 to 5.6) and relatively short payback periods (18-36 months) for most interventions demonstrate economic viability that should facilitate scaling and replication. These findings contrast with economic assessments of large-scale engineering interventions such as embankments and polders, which often exhibit lower BCRs and require extensive external financing and maintenance [42, 43]. The particularly favorable economics of organic amendment application (BCR=5.6, minimal cash investment required) suggests that interventions leveraging locally-available resources and existing labor capacity may prove most accessible and sustainable for resource-poor farming communities.

The high BCR and IRR for community freshwater ponds (4.2 and 42% respectively), despite substantial initial investment requirements, demonstrates the value of collective infrastructure approaches distributing costs across multiple beneficiary households while generating multiple benefit streams (irrigation, fisheries, domestic water supply, ecosystem services). This finding supports arguments for public or community investment in water infrastructure as a high-return intervention for climate adaptation in vulnerable coastal regions [44, 45].

The superior performance of integrated intervention packages (BCR=4.8), despite higher initial costs, indicates that synergistic effects among multiple strategies enhance overall value proposition. This finding has important implications for program design, suggesting that comprehensive approaches addressing multiple constraints simultaneously may prove more cost-effective than piecemeal interventions, despite requiring greater upfront investment and coordination.

However, cost-benefit calculations presented here reflect only direct household-level costs and benefits, excluding externalities such as ecosystem service values, community-level benefits, and avoided climate change impacts. More comprehensive economic assessment incorporating these broader values would likely demonstrate even greater social returns to community-based salinity mitigation investments [46].

Theoretical Implications for Community-Based Natural Resource Management

This research contributes to broader theoretical understanding of community-based natural resource management (CBNRM) by demonstrating that participatory approaches can achieve substantive biophysical outcomes (not merely social or governance improvements) when appropriately designed and supported. While CBNRM literature has sometimes been critiqued for emphasizing process over outcomes or for romanticizing community capacity [47, 48], these findings provide concrete evidence that communities can effectively manage complex environmental challenges when provided with appropriate technical support, resources, and enabling policy frameworks.

The observed synergies between social and biophysical dimensions—with higher social capital and community organization correlating with superior environmental outcomes—suggests that these elements should not be conceptualized as separate components but rather as mutually reinforcing aspects of integrated systems. This finding supports recent calls for coupled socio-ecological systems approaches in environmental research and management [49, 50].

The critical role of women's self-help groups in intervention adoption and implementation extends understanding of gendered dimensions in natural resource management, demonstrating that women's collective organization represents not merely an equity consideration but a practical strategy for enhancing program effectiveness and sustainability [51, 52]. This finding has important policy implications, suggesting that investments in women's organizational capacity and leadership may yield significant returns for environmental and agricultural development programs.

Limitations and Future Research Directions

Several limitations should be acknowledged when interpreting these findings. First, the 24-month study period, while longer than many intervention studies, remains insufficient to fully assess long-term sustainability, potential degradation of intervention effectiveness over time, or resilience to extreme climate events such as severe cyclones or prolonged droughts. Future research should employ extended monitoring periods (5-10 years) to evaluate temporal dynamics and identify maintenance requirements for sustained benefits.

Second, the quasi-experimental design, while appropriate for participatory action research contexts, lacks the control provided by fully randomized experimental designs. Selection bias may have influenced results if participating communities possessed unmeasured characteristics (motivation, social cohesion, resource access) that contributed to observed outcomes independent of interventions. Future studies could employ randomized controlled trial designs where feasible, though ethical and practical considerations often constrain experimental manipulation in community development contexts.

Third, while this study documented substantial biophysical and economic benefits, it provided limited analysis of distributional effects within communities. Future research should examine whether benefits accrue equitably across socio-economic strata or whether elite capture, differential resource access, or power dynamics lead to unequal benefit distribution. Such analysis would inform more nuanced understanding of CBNRM outcomes and equity implications.

Fourth, climate change projections suggest continued and potentially accelerated sea-level rise, increased storm intensity, and altered precipitation patterns in the Sundarban region [53, 54]. While this study demonstrated intervention effectiveness under current climate conditions, future research should assess resilience and adaptive capacity under projected climate scenarios, possibly employing modeling approaches to evaluate intervention performance under various future conditions.

Fifth, this study focused on agricultural dimensions of salinity impacts, while salinity also affects drinking water quality, household assets, health outcomes, and ecosystem services. More comprehensive assessment of intervention benefits across these multiple domains would provide fuller understanding of community-based approaches' value proposition.

Finally, while this study documented successful outcomes in the Indian Sundarban context, transferability to other deltaic regions (Mekong, Irrawaddy, Nile) requires verification through comparative research examining how different biophysical conditions, socio-cultural contexts, governance structures, and economic systems influence intervention effectiveness and community-based management capacity.

Conclusion

This research demonstrates that community-based, integrated approaches provide effective, economically viable, and sustainable strategies for mitigating soil salinity in vulnerable deltaic environments. Over a 24-month implementation period in the Indian Sundarban region, participatory interventions achieved 51.7% reduction in soil electrical conductivity, 162.5% improvement in organic matter content, and 86-200% increases in crop productivity compared to control zones maintaining traditional practices. Economic analysis revealed favorable benefit-cost ratios (3.2 to 5.6) and relatively short payback periods (18-36 months), indicating financial viability for resource-constrained farming communities.

The study's major contribution lies in demonstrating synergistic effects among multiple intervention strategies and documenting the critical importance of community participation, social capital, and gender-inclusive governance structures for achieving superior environmental and agricultural outcomes. Women's self-help groups emerged as particularly effective organizational structures, achieving 84% participation rates and serving as key vehicles for knowledge exchange, collective action, and intervention implementation.

From a practical perspective, findings support several policy recommendations: [1] prioritize integrated intervention packages over single-strategy approaches to maximize synergistic benefits; [2] invest in community water infrastructure, particularly freshwater ponds, as high-return interventions generating multiple benefit streams; [3] strengthen women's organizations and ensure gender-inclusive participation in natural resource management programs; [4] provide accessible credit facilities and initial subsidies to overcome upfront cost barriers for resource-poor households; [5] establish farmer field schools and peer learning platforms to facilitate knowledge exchange and social learning; and [6] recognize that salinity mitigation requires sustained intervention and realistic temporal expectations, with significant benefits emerging over 6-24 month timeframes.

This research contributes to broader understanding of community-based natural resource management by providing rigorous quantitative evidence that participatory approaches can achieve substantive biophysical outcomes when appropriately designed and supported. It also demonstrates the applicability and effectiveness of traditional ecological knowledge and locally-adapted practices when integrated with scientific understanding and technical support.

Looking forward, successful salinity management in the Sundarban and similar coastal regions will require continued innovation, adaptive management, and integration of community-based approaches within supportive policy and institutional frameworks. As climate change intensifies salinity challenges globally, the community-driven, integrated strategies evaluated in this research offer replicable models for building resilience and sustainability in vulnerable coastal agricultural systems worldwide. Future research should focus on long-term sustainability assessment, examination of distributional equity within communities, evaluation of climate resilience under projected future scenarios, and comparative analysis across diverse deltaic contexts to refine understanding and enhance transferability of community-based salinity mitigation approaches.

Figures (Descriptions for Generation)

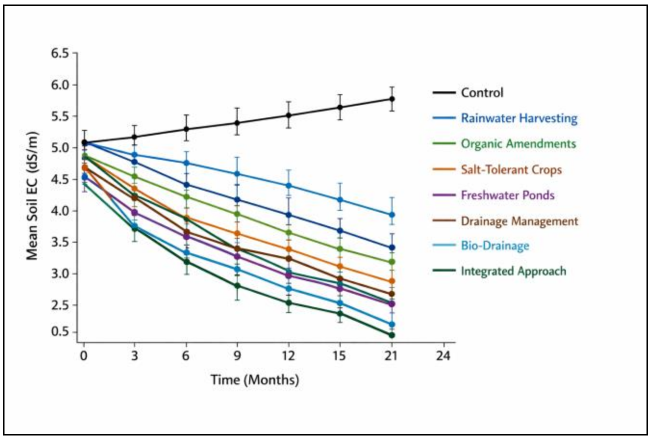

Fig 1: Temporal Changes in Mean Soil Electrical Conductivity Across Treatment

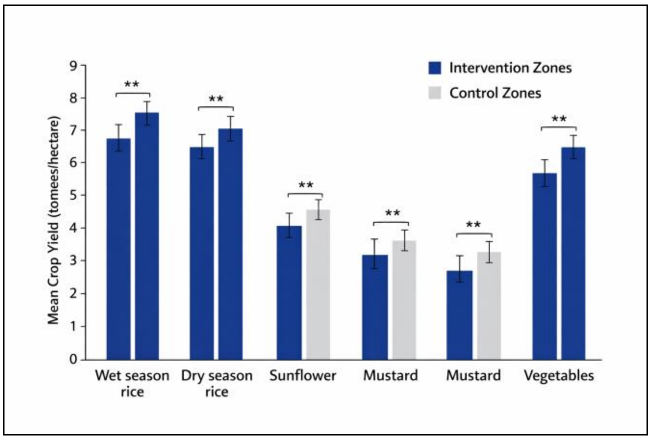

Fig 2: Comparison of Crop Yields Between Intervention and Control Zones

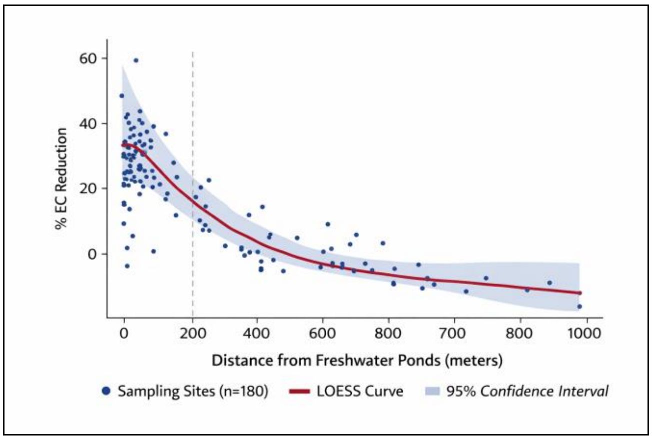

Fig 3: Spatial Distribution of Salinity Reduction in Relation to Freshwater Pond Proximity

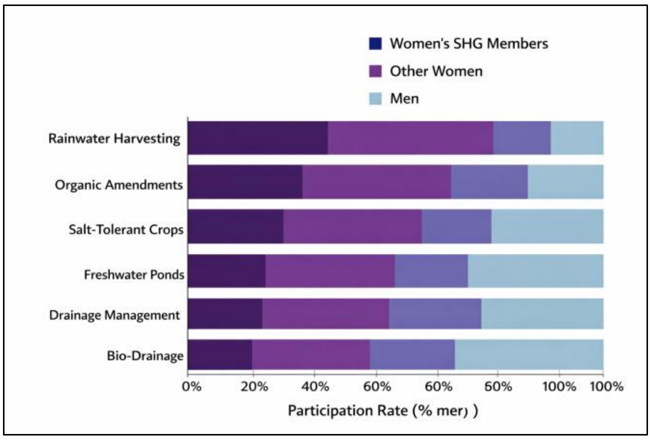

Fig 4: Community Participation Rates by Intervention Type and Gender

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