

Technological solutions for saline soil environment restoration in aquaculture ponds in Dong Chau Commune, Hung Yen Province

Do Quy Manh^{1,*}, Nguyen Quoc Huy¹, Nguyen Minh Duc¹, Ha Tra My¹,
Le Anh Tuan¹, Nguyen Viet Duc¹, Nguyen Thanh Luan^{2,3}, Pham Ngoc Tu²

¹*Institute of Ecology and Works Protection (WIP),
No. 267 Chua Boc, Kim Lien Ward, Ha Noi, Viet Nam*

²*The Key Laboratory of River and Coastal Engineering (KLORCE),
No. 1, Alley 165 Chua Boc, Kim Lien Ward, Ha Noi, Viet Nam*

³*Thuyloi University, 175 Tay Son, Kim Lien Ward, Ha Noi, Viet Nam*

*Email: doquymanh@gmail.com

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Abstract. Conversion of mangrove forests to coastal aquaculture has led to severe saline soil degradation in the Red River Delta Biosphere Reserve, exemplified by the study area in Dong Chau commune, Hung Yen province. The persistent issue is the conversion resulting in deep water levels (averaging 0.65 m to 1.3 m), which prevents tidal exposure necessary for mangrove regeneration. To address this, we developed and applied an integrated technological solution package. This package included ecological engineering for embankment stabilization, ridge techniques to significantly raise the planting area elevation, and a controlled water regulation regime to ensure target tidal exposure. The integrated approach successfully lowered the local inundation degree at the planting zone and created suitable physical conditions for restoration. Consequently, the survival rate of planted mangroves was over 80 % in the model area, compared to under 30 % using conventional methods. These results demonstrate a robust scientific basis for developing stable, sustainable silvo-aquaculture models through the restoration of degraded saline soil environments in similar coastal areas across Viet Nam.

Keywords: aquaculture ponds, bio-engineering, water regulation, saline soil restoration, Red river delta biosphere reserve.

Classification numbers: 3.1, 3.4.

1. INTRODUCTION

Coastal saline environments and mangrove forests represent a vital ecosystem for coastal regions in tropical, subtropical countries, and certain temperate zones. These areas serve as nurseries, spawning grounds, and growth habitats for numerous economically valuable marine species and biodiversity, where they play crucial environmental, economic, and social roles and functions. According to the FAO's Global Forest Resources Assessment, compiled from 223 countries and territories, in 2020, there were 113 countries with mangrove forests worldwide. Globally, the estimated area of mangrove forests reaches 14.8 million hectares; Asia has the

largest area at 5.55 million hectares, followed by Africa, North and Central America, South America, and Oceania. However, the average annual rate of mangrove forest loss in Asia has increased significantly, from 1,030 hectares in the 1990s–2000 period to 38,200 hectares in the 2010s–2020 period. Indonesia-the country with the world's largest mangrove forest area-once lost 40 % of its coverage in just a few decades due to industrial shrimp farming. The government of this nation is currently implementing a program to restore 600,000 hectares of mangrove forests, viewing it as a vital solution to combat erosion and reduce greenhouse gas emissions [1]. The Philippines lost more than half of its mangrove forests in the 20th century, but following super typhoon Haiyan in 2013, the country has regarded mangrove planting and protection as a national security strategy to safeguard coastal populations [2]. In Mexico and Central America, land conversion to shrimp farming has devastated forests; now, these countries are applying the "Blue Carbon" mechanism, which provides payments for ecosystem services to communities, thereby protecting forests while generating additional income. The mechanism of paying communities to protect mangrove forests through carbon pricing is known as Payment for Ecosystem Services (PES), with Blue Carbon as a specific form. Mexico is one of the pioneering countries in applying PES to natural areas [3].

Viet Nam is a country with over 3,260 km of coastline, stretching from Quang Ninh province to An Giang province. Up to 2024, the mangrove area (RNM) in Viet Nam exceeds 160,000 ha [4], distributed across coastal regions. The area of mangrove forest and saline land environments have been converted mainly to aquaculture, cleared, and lacks natural recovery capacity. Saline land environments are very important, providing many useful products and services to coastal communities. Many benefits from mangroves include timber and non-timber forest products, fishery resources, recreational areas, ecotourism, biological filtration, coastal protection-especially protecting sea dikes, soil stabilization, carbon accumulation, and CO₂ absorption. The Red River Biosphere Reserve holds very important environmental, economic, and social values. It preserves rich biodiversity values with approximately 200 bird species, including nearly 60 migratory bird species, over 50 water bird species, especially rare species of international importance such as the Black-faced Spoonbill, Black-headed Ibis, Spoon-billed Sandpiper, and Eastern Great Egret [5]. This is a unique biosphere reserve with important national and global values.

The coastal saline land environment of Dong Chau commune, Hung Yen province (formerly as Thai Binh), once contained over 150.0 ha of mangroves crucial for coastal protection, livelihood generation, and ecosystem stability [6]. However, this area has continuously declined, with the study site now characterized by open water aquaculture [6]. This conversion, coupled with environmental degradation (storms, erosion, pollution), has led to the loss of thousands of hectares of mangrove forests, making natural regeneration impossible [7].

The importance of this saline environment lies in its role as a transitional habitat supporting high biodiversity and characteristic mangrove ecosystems (e.g., *Sonneratia caseolaris*, *Rhizophora stylosa*, *Avicennia marina*) [8–11]. The widespread degradation threatens valuable genetic resources and biodiversity [7].

Previous research, both worldwide and in Viet Nam, emphasizes the importance of integrating mangrove restoration into aquaculture to rehabilitate saline soils, utilizing methods like Ecological Mangrove Restoration (EMR) and specific species selection [12–14]. These studies highlight the critical role of technical solutions, species appropriateness, and hydrological management [14, 15].

However, a critical gap remains: there is a lack of integrated technological solutions (combining irrigation, ecological engineering, and silviculture) designed specifically to overcome the initial physical barriers (deep water and low elevation) created by aquaculture conversion. Therefore, this study aims to investigate the environmental status and propose, implement, and verify such an integrated technological package to restore the saline soil environment in degraded aquaculture ponds, providing a scientific basis for wider application in Viet Nam.

2. RESEARCH MATERIALS AND METHODS

2.1. Method of synthesizing, analyzing and inheriting secondary documents

Scientific documents and reports from domestic and international projects and research programs were collected. These materials cover various management levels and focus on saline land environments in aquaculture ponds, and related applied technological solutions. Sources include local authorities and relevant functional agencies.

The collected data is compiled by content and subsequently analysed and evaluated against the research objectives. This includes statistics on research works regarding saline land environments in aquaculture ponds, technological solutions for restoring land and water environments, and current relevant regulations

The study specially inherits the research topics of Project DTDL.CN 16/22. This content includes: the current status of land and water environments in aquaculture ponds, the assessment and planning for mangrove planting land, and the scientific and technological solutions (irrigation and forestry) used to restore mangroves under different site conditions. This inheritance helped to determine research scope and locations, and for proposing technological solutions for saline land restoration in the typical area of Dong Chau commune, Hung Yen province.

2.2. Expert consultation method

To collect opinions from experts in the research field to ensure high scientific and practical value, avoiding duplication with existing studies, and effectively inherit previous research achievements.

The manner of expert consultation: seeking opinions, comments, and suggestions for constructing the research methodology, the method of collecting, analyzing, and processing documents, and multi-round consultations.

The number of experts: 3 experts in the fields of environment, hydrology, and saline soils.

2.3. Field investigation and survey methods

Field investigation location and coordinates: Aquaculture area of Dong Chau Commune, Hung Yen Province. Coordinates: X = 667840; Y = 2260068.

Survey scale: 4.0 ha of aquaculture ponds, with detailed investigation of factors such as measurements using RTK equipment (Hi-Target V30 GNSS RTK Receiver) to determine tidal flat elevations.

Soil sampling: Collecting 9 samples (1 kg/sample) from the bottom sediment of aquaculture ponds. Analysis of some indicators to assess mangrove soil characteristics (particle

size composition, pH_{kcl} , salinity, total and available NPK, calcium, magnesium) according to current Vietnamese standards.

Water sampling: Collecting 9 composite water samples (1 liter/sample) from 3 layers (surface layer, middle layer, and bottom layer) in aquaculture ponds, to determine some indicators (pH_{kcl} , salinity, turbidity, ammonia, mercury, lead, arsenic, total oil and grease, TSS) analyzed in the laboratory according to current Vietnamese standards.

Referring to 45 samples of saline soil and 45 samples of saline water from Project: DTDL.CN 16/22.

Vegetation survey: Overall investigation of the 4.0 ha area to determine the distribution, species composition of mangrove trees, shrubs, grasses, and their growth status.

Integrated evaluation: Laboratory analysis results of soil and water, along with expert consultation will be used to evaluate the status of land and water environments, and mangrove conditions.

2.4. Restoration engineering of saline soil in coastal aquaculture zones

Given the status of soil in aquaculture ponds that is continuously deeply flooded with poor regulation capacity, irrigation support solutions are required, such as water regulating sluices, bund raising, and embankment construction to elevate the tidal flat level, thereby creating a suitable living environment for mangroves in the aquaculture area.

Methods and techniques for constructing a model to rehabilitate the saline land environment aimed at restoring mangrove forests in aquaculture areas: Equivalent area of 2.0 ha.

Employing techniques to calculate the interaction between tidal flat elevation and exposure time in the aquaculture area to determine the bund elevation for digging and filling soil on bunds for mangrove restoration planting. Bund scale: length 200 m x width 10 m, filling height of approximately 0.3 m. Volume of soil digging and filling on bunds approximately 600 m³.

Bank Stabilization and Terracing Techniques: Employing techniques to calculate bank stability, creating terraces with bamboo fences to enhance bank stability and create space for mangrove restoration in aquaculture areas. Reinforcing fence scale: expected length 600 m, 6 stakes/1 m length, 2 rows of stakes, each stake 3 m long; distance between two rows of stakes 0.5 m, stuffed with branch bundles. Volume of soil digging and filling for terraces and embankments approximately 360 m³.

Mangrove Planting Techniques: Employing techniques for species selection, propagation, determining planting season, and solutions for planting to restore mangrove forests in aquaculture areas. Planting density 2,500 trees/ha, supporting 01 stake per tree; planting season: from July to October annually.

3. RESULTS AND DISCUSSION

3.1 Status of some saline soil environmental factors in the study area

3.1.1. Status of aquaculture area in the study area

According to the Statistical Yearbook of Thai Binh Province (now Hung Yen Province), the total aquaculture area was approximately 15,268 hectares in 2021. Over the nearly past

decade, the province has expanded significantly. For instance, the aquaculture area was below 15,000 hectares between 2012 and 2018, but reached the peak of 16,114 hectares in 2020 [27, 28]. This expansion resulted from the conversion of historically ineffective salt production and rice cultivation land into brackish and saltwater aquaculture. Aquaculture has become a key economic sector, particularly in coastal areas, accounting for 26 % to 33 % of the total provincial aquaculture area due to favorable natural conditions. The farming objects here are also very diverse such as giant tiger prawn, white leg shrimp, seaweed, sea bass, grouper, blue crab, clam, etc. Currently, the aquaculture practices in Dong Chau commune are oriented toward improved extensive farming combined with natural capture fisheries; additionally, some households continue to maintain intensive and semi-intensive farming methods.

3.1.2. Current status of mangrove forest area in the aquaculture area

The survey results indicate that most of the study area in Dong Chau Commune has been converted to enclosure farming, resulting in a landscape dominated by numerous aquaculture ponds of various sizes (Figure 1). The remaining mangrove area and species composition in the aquaculture area are sparse, with no true mangrove groups encountered. Instead, the flora consists mainly of mangrove-associated plant groups from families such as *Casuarina* (specially *Casuarina equisetifolia*), *Fimbristylis*, *Glinus oppositifolius*, *Alternanthera philoxeroides*, and other species such as *Dialium cochinchinense*, *Pandanus tectorius*, *Passiflora foetida*, *Phyllanthus urinaria*, and *Solanum spp.* These species primarily function in soil fixation and protection around the pond banks [16].



Figure 1. Status of survey and investigation locations for some environmental factors in aquaculture ponds.

Mangrove vegetation in the coastal area of Dong Chau commune currently occupies approximately 120.4 hectares, and forms several high-density communities, including Pure *Avicennia marina* community, *Avicennia marina* dominant community - *Aegiceras corniculatum*, and Pure *Sonneratia caseolaris* community. The *Avicennia marina* dominant community is characterized by the dominant species *Avicennia marina* interspersed with *Aegiceras corniculatum* planted in 1992 and 2008. Trees in the community are tall with an average height of 0.8–2.5 m. Pure *Sonneratia caseolaris* community has an average height of 5–8 m, and was established during planting years 1997 and 2003.

Overall, the demand for economic development, particularly driven by the enclosure farming of aquatic and marine species, has led in a clear decline in the mangrove area and a reduction in species richness within the planned aquaculture zones. The species composition in these impacted zones is now impoverished, dominated primarily by shrubby groups exhibiting poor growth. True mangrove plant communities in Dong Hoang commune are only narrowly distributed and concentrated along the coast, exhibiting low species diversity focused on groups of *Avicennia marina*, *Sonneratia caseolaris*, and *Aegiceras corniculatum*. Despite the threats, these stands with planting timelines forming long-term communities (over 30 years), serve as pioneer population units [17]. They play a crucial role in the formation, maintenance, and stability of mangroves ecosystems [18], contributing significantly to climate regulation, soil retention, protection, and creation of living environments for associated organisms [5].

3.1.3. Current status of tidal flat elevations in aquaculture ponds

The topographic survey results for the 4.0 ha aquaculture area in Dong Chau commune, were mapped at a scale of 1/200 with a basic contour interval of 1.0 m. The pond bottom exhibits the lowest elevation of -0.25 m, with pond bottom elevations quite uniform at many locations and gradually increasing from the center of the pond to the edges. The outer pond embankment elevations range from +1.7 m to +2.5 m, while the seaside soil embankment is lower. The inner pond embankment has an elevation of approximately +1.5 m. The current embankments ensure water retention capacity.

The current water regulating sluice combined with the water channel has a bottom elevation of -0.1 m, brick-type sluice, with unstable regulation capacity. The current status of the research area is completely flooded land with a water depth of 0.6-0.7 m, always maintained with water for year-round aquaculture. Water sources are only adjusted during harvest or when water is insufficient in the ponds.

This is one of the important reasons why mangroves cannot regenerate and grow in conditions of complete flooding with an average elevation of 0.65 m, lacking photosynthesis and respiration capacity for the trees. Therefore, technical solutions to improve the tidal flat elevations in aquaculture ponds are essential.

3.1.4. Characteristics of the soil environment in the aquaculture area

The particle size composition reveals that the sand ratio accounts for 48.45 % (max: 80.56 %, min: 16.34 %), silt averages 35.97 % (max: 58.80 %, min: 14.8 %), and clay averages 19.07 % (max: 34.99 %, min: 6.39 %). These proportions closely approach the characteristic values of loam soil group according to the Soil Survey Staff, 1975 [11]. The saline soil here can be classified as soil with a high sand particle ratio, requiring technologies to remediate and increase the silt content.

The pH_{KCl} of the soil in the aquaculture area has an average value of 7.82 (max: 8.05, min: 7.66), not exceeding the recommended limits (6.5–9) [19]. Compared to the study by Do Quy Manh (2018) [20] in the coastal saline land area of Thai Binh Province, where soil pH_{KCl} ranged from 5.16–6.51, the pH value recorded in the aquaculture area with an average of 7.82 is relatively high, thereby indicating alkaline properties.

The average salinity in the aquaculture area is 31.06 ± 4.35 ‰ (0-20 cm soil layer) and 32.19 ± 3.71 ‰ (20-60 cm soil layer). This result is quite consistent with most salinity values of mangrove soils in many areas worldwide, which typically fluctuate above 30 ‰ [21].

The levels of total macronutrients are rated as moderate with nitrogen (N) averages 0.1 % (max 0.24 %, min 0.03 %); phosphorus (P) averages 0.16 % (max 0.21 %; min 0.1 %) and potassium (K) averages 1.95 % (max 2.17 %; min 1.32 %). Available K_2O and P_2O_5 components, calcium, magnesium have average values of 69.3 mg/100g, 57.98 mg/100g, 7.39 cmol/kg, and 7.41 cmol/kg, respectively. The analysis results show that the nutrient composition in the soil of the research area is at a moderate to rich level.

Based on the analysis, the soil environmental characteristics in the research area, a preliminary assessment indicates that this soil type has a higher sand ratio compared to silt and clay components, with pH belonging to the alkaline type. The aquaculture soil can be classified as having a high sand particle ratio, requiring technological solutions for improvement. Although the values do not achieve the quality of tidal flat loam soil, some indicators of physical and chemical soil properties are suitable for the growth and development of basic mangrove species in the research area.

3.1.5. Characteristics of the water environment in the aquaculture area

The water environment in the research area is a saline water environment influenced and regulated by tides, sharing common characteristics of the Gulf of Tonkin sea with a predominantly semi-diurnal tidal regime, occurring on most days of the month (an average month has 2 spring/neap tidal periods, each approximately 14 days). The average tidal fluctuation amplitude ranges from 1.0 to 2.0 m, minimum from 0.2 to 0.5 m. The maximum tidal fluctuation ranges from 3.0–3.5 m and is often active in months 1, 6, 7, and 12, with the highest water level possibly reaching 4.0 m and the lowest 0.02 m.

The water environment is characterized by a water pH that fluctuates in the range of 5.5–6.3; Salinity from 12.9 ‰ to 23 ‰; DO values in the aquaculture area from 8.5 to 10 mg/l; Turbidity from 19.5 to 378.4 NTU. The salinity value range in the aquaculture area fluctuates from 7.9 ‰ to 17.8 ‰; Ammonia values from 0.03 to 0.13 mg/l; Mercury concentrations from 3×10^{-4} to 7×10^{-4} mg/l.

The sample analysis results show that the concentrations of lead (Pb), arsenic (As), and total oil and Grease do not exceed QCVN 10-MT:2015/BTNMT, specifically Pb concentrations are all lower than 0.001 mg/l, As lower than 0.002 mg/l, and total oil and Grease lower than 0.3 mg/l. Based on the principal component analysis (PCA) method, it is evident that water sample quality is greatly influenced by factors such as total suspended solids (TSS), turbidity, and ammonia [22]. However, these results indicate that the water sample quality in the research area is quite suitable for mangrove growth according to QCVN 10-MT:2015/BTNMT [23].

The operation process for water source regulation in the research area is as follows: According to the main objective of aquaculture, water is always maintained in the ponds to ensure optimal growth and development of aquatic species. Water is only supplemented during the farming phase (farming time approximately 3 months for shrimp and 6 months for marine crab). The process of regulating seawater into shrimp and crab farming ponds in the Red River coastal area is a critical technical procedure. It is heavily influenced by the semi-diurnal tidal regime and salinity fluctuations due to freshwater from rivers. Farmers must time the high tide (rising water) to intake water, ensuring water levels and especially achieving optimal salinity, avoiding low-salinity water during the rainy season. Seawater is supplied to the ponds through sluice systems and intake channels, often directly into the ponds.

Periodic water exchange (typically 10-30 % of water volume) is necessary to remove accumulated toxins such as NH_3 and replenish dissolved oxygen, helping maintain a healthy

living environment for shrimp and crabs. During the rainy season, a major challenge is the sudden drop in salinity, forcing farmers to stop water intake and adjust by draining surface water. Conversely, in the dry season, increased water exchange is needed to lower temperature and compensate for evaporation.

Wastewater discharge must occur during low tide (ebb tide) and be routed through settling ponds to prevent re-pollution of the intake water source. Currently, many households are adopting integrated mangrove aquaculture (Silvo-aquaculture) models. This leverages the natural water filtration capacity of mangroves to reduce reliance on chemicals, promote sustainable production, and minimize environmental impacts on the coastal environment.

3.2. Technological solutions for restoring saline soil environments in aquaculture ponds

3.2.1. Principles for arranging technological solutions to rehabilitate saline soil environments

Principles for arranging saline soil environmental rehabilitation solutions:

For embankments, they must be sufficiently high with a solid base plane and require reinforcement for stability; must be easy to construct and repair, prioritize the utilization of local materials, and leverage existing structures wherever possible.

For the water supply and drainage system, solutions were selected based on the topographic conditions and tidal water levels of the area to utilize self-flowing water supply solutions into the model area. Water must be sourced from nearby creeks and unpolluted sources. The water intake time depends on each area's position (varying tidal water levels), type of water intake, water source quality (salinity, quality), and actual intake time. The water intake time will be inversely proportional to the water supply coefficient (scale of water supply works), possibly during peak high tide or during peak high tide and rising tide phases.

The scale of water supply and drainage sluices is calculated based on the required water volume, typically fully drained within one tidal cycle (according to ebb tide time), using locally available sluice apertures. The minimum number of sluices is 2 sluices; the intake creek must ensure an elevation that creates appropriate flow, facilitating easy and thorough water exchange, and ensuring drainage during the lowest ebb tide.

Principles for arranging planting technologies: Technical planting solutions must be implemented after completing the saline soil environmental rehabilitation technologies designed to support mangrove growth. The selection of mangrove species is based on native species in the research area, with an important principle of "right tree for the right land". Selection standards for planting stock, planting techniques (planting density, pit digging technique, planting method), care, and protection of mangroves must be comply with relevant regulations such as: Decision No. 5365/QĐ-BNN-TCLN [24]; 1205/QĐ-BNN-TCLN [25], and Decision No. 4147/QĐ-BNN-TCLN [26].

3.2.2. Technological solutions for rehabilitating saline soil environments in aquaculture ponds

The model construction site is the area adjacent to mangrove forests and sea dikes, where aquaculture-related activities are organized. Historically, these areas possessed mangrove forests which were subsequently cleared for aquaculture purposes. Currently, due to water retention in the ponds for aquaculture purposes, the soil in the ponds is continuously deeply flooded, leading to almost unsuccessful mangrove regeneration and inability to plant forests

using conventional silvicultural solutions. The current status of the aquaculture pond area has no mangrove plantings, only water surface and embankments. Therefore, researching and selecting irrigation solutions for water regulation, bund raising, and embankment construction for mangrove planting is essential. Additionally, dividing site types to select species, planting solutions, and mangrove care in aquaculture ponds based on supportive irrigation solutions is an appropriate approach to restore this degraded ecosystem.

Given the current status of soil in aquaculture ponds continuously flooded over 0.65 m with poor regulation capacity, technological support solutions are needed, such as embankment stabilization, increasing tidal flat elevation through bund raising, improving soil quality by using fertile soil for bund raising, water regulating sluices, to create a suitable living environment for mangroves in the aquaculture area.

(1) Embankment stabilization using ecological engineering technology with organic bamboo fencing materials

Embankments are constructed to protect aquaculture areas, maintain the desired and stable water level in the ponds, and prevent water seepage. Since aquaculture ponds are often located near river mouths and coastal areas, embankment alignment selection must meet requirements. The embankment alignment should pass through areas with high topography, good geology, tight connection to stable positions, and convenience for auxiliary works. The embankment alignment should be straight, avoiding bends. Existing embankments can be utilized and improved. Embankments are built using on-site soil in the model area (Figure 2). The research area's embankment dimensions are determined as 600 m in length, 3.0 m in width, and 0.2 m in filling height. Existing embankments were utilized existing embankments for improvement and filling to an elevation of +2.0 m. For the implementation sub-area and control area, embankments were newly constructed and filled to an elevation of +0.7 m.

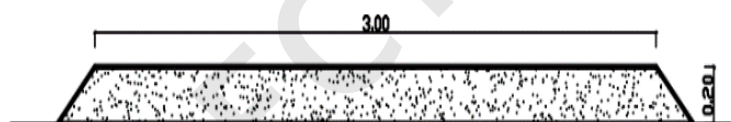


Figure 2. Schematic cross-section of the model embankment.

Employing techniques to calculate embankment stability (Figure 3), creating terraces and steps with bamboo fencing to enhance embankment stability and create space for saline soil environmental restoration (water, soil, and restored mangrove forest ecosystem in the aquaculture area). The reinforcing fence for stability has a length of 600 m, with a staking density of 6 stakes per 1 m length, comprising 2 rows of stakes, each stake 3 m long. The distance between two rows of stakes is 0.5 m, and the space is stuffed with branch bundles.

Since the model construction area is within aquaculture ponds with minimal wave and current impacts, and the bamboo fence's primary function is embankment reinforcement, the key parameters were defined: the stake driving depth was selected as 2.0 m and the fence height as 1.0 m. The final fence parameters include: Stake top elevation: +1.3 m, fence height: 1.0 m, and stake driving depth: 2.0 m. The pond embankment design ensures stability, good impermeability, convenience for management and care, low cost, easy construction and repair, and utilizes local materials. It employs organic materials such as bamboo, reeds, sedges, wood, branch bundles as bamboo branch bundles, casuarina branch bundles. They are environmentally friendly materials and leveraging existing structures.

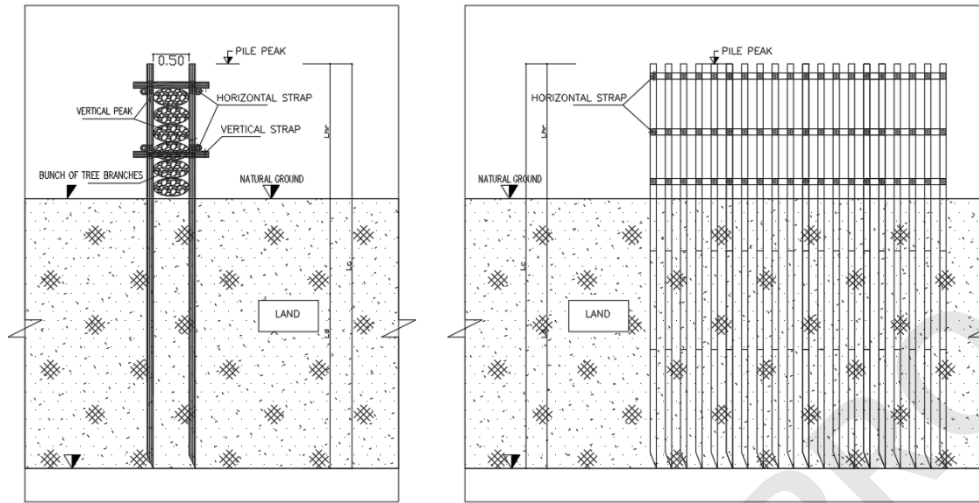


Figure 3. Schematic diagram of bamboo fence for enhancing embankment stability.

(2) Technology to improve tidal flat elevation (increasing saline soil elevation to counteract tidal flooding when accumulating water in aquaculture ponds)

Improving soil quality is essential. Analysis and assessment of soil environmental quality indicate that the basic indicators and nutrient content of saline soil in aquaculture ponds in Dong Chau commune, Hung Yen province, and adjacent areas are relatively high, making them generally suitable for mangrove species. However, the sand ratio is quite high (over 50 %). Therefore, improvement is needed by supplementing and enhancing the research area's saline soil quality with saline soil having a sand ratio below 30 %.

Techniques were employed to calculate the interaction between tidal flat elevation and tidal exposure time in the aquaculture area to determine bund elevation. Soil was then filled onto these bunds to improve saline soil elevation in the ponds (Figure 4). The bund scale is of 200 m (length) x 10 m (width) with a total of 10 bunds/ridges, and the filling height is approximately 0.3 m.

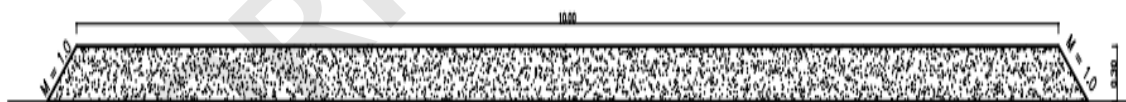


Figure 4. Schematic cross-section of bund for improving saline soil elevation in the pond.

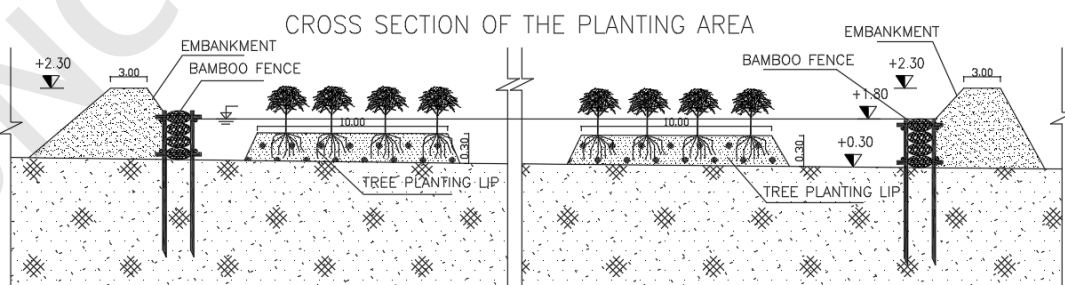


Figure 5. Schematic cross-section of the area for improving saline soil environment in the pond.

(3) Regulating water sources in aquaculture ponds

The water intake time depends on each area's position (varying tidal water levels), water intake type, water source quality (salinity, quality), and actual intake time. The water intake time will be inversely proportional to the water supply coefficient (scale of water supply works), possibly during peak high tide. To obtain good quality water, currently, intake is during the day's peak high tide and during spring tide periods (mid or late lunar month). Based on tidal amplitude, salinity from the supply source and required salinity for aquatic species, water quality, self-flow capacity (if self-flowing supply), and depending on each position and region, the start time for water intake will vary.

The intake creek before the sluice is improved and ensures channel bed elevation is suitable for the regulating sluice. This design must facilitate an appropriate flow, allowing for easy and thorough water intake and drainage, and ensuring discharge capability during the lowest ebb tide.

Tidal water regulation operation process to improve flooding degree in the pond

Step 1: Arrange a reasonable water supply and drainage system with sluices; The channel system, regulating sluice system, intake sluice, drainage sluice, farming ponds (nursery pond, stocking pond, settling pond) must have circulating water. Stabilize pond banks using technological solutions like bamboo stake revetments and reeds.

Step 2: Clean, dredge, and expand the channel system from the sea to increase supply and drainage flow for the farming area. Conduct dredging during the dry season (October of the previous year to January of the following year), drain and flush the farming pond for 10-15 days. Apply lime for sterilization and pond improvement, CaCO_3 lime at dosage 15-20 kg/1,000 m^3 water. During early rainy season storms, apply 15-20 kg/1,000 m^2 to prevent acid sulfate runoff lowering pond water pH.

Step 3: Regulate water according to farming cycles, 3-6 months, following monthly tidal schedules (14 days per tidal cycle). Ensure water level approximately 30-40 cm above the flat surface, tidal exposure time approximately 5-8 hours/day/night for plants from 1 month to 6 months old. Maintain water level in the surrounding creeks at approximately 1.3 m, with a creek width of 6.0 m.

(4) Technology for mangrove restoration in aquaculture ponds

Species analysis and selection: Restoration prioritizes native species with competitive advantages suitable for the specific site conditions. These species must be capable of restoring degraded mangrove forests, creating necessary environments and habitats for local fauna, and enhancing mangrove conservation effectiveness. The selected species must be compliant with the list of mangrove species for planting as Decision No. 5365/QĐ-BNN-TCLN; 1205/QĐ-BNN-TCLN and Decision No. 4147/QĐ-BNN-TCLN [24–26]. Based on some common native mangrove species already planted in the research area, the potential species include *Aegiceras corniculatum*, *Rhizophora stylosa*, *Sonneratia caseolaris*, and *Kandelia obovata*.

Applying expert consultation methods for criteria per species and selecting promising planting species. Planting method was determined to be mixed-species mangrove planting. Planting stock standards align with Decision 1205/QĐ-BNN-TCLN on issuing technical guidelines for planting forests of species: *Kandelia obovata*, *Aegiceras corniculatum*, *Lumnitzera racemosa*, *Bruguiera sexangula*, and *Sonneratia caseolaris*, and Decision No. 4147/QĐ-BNN-TCLN with 4 mangrove species: *Rhizophora mucronata*, *Nypa fruticans*,

Rhizophora stylosa, and *Avicennia marina* applicable to site type III (deep tidal flooding base, base mixed with much sand subsidence < 5 cm, sand mixed 65.25 to 88.13 %). The planting stock standards are: *Aegiceras corniculatum* trees (trees >12 months old, height >0.6 m, root collar diameter > 0.6 cm, good growth, no pests/diseases), and *Rhizophora stylosa* trees (trees > 12 months old, height > 0.6 m, root collar diameter >0.6 cm, good growth, no pests/diseases). The model construction site has site type III conditions (base mixed with much sand subsidence < 5 cm), so suitable planting density is 2,500 trees/ha. The planting spacing is 2 m x 2 m. The *Aegiceras corniculatum* planting area is 0.5 ha. The *Rhizophora stylosa* planting area is 1.5 ha. The number of *Aegiceras corniculatum* trees is 1,250 and the number of *Rhizophora stylosa* trees is 3,750 (excluding 10 % replanting rate). Regarding the planting technique, the arrangement of tree planting is as follows: Before planting, position the planting location for each tree. Arrange mixed species planting in rows, using a zigzag sole planting to maximize spatial nutrient utilization for mangroves. Seedlings 7-10 days before planting should be brought ashore to dry the soil in the root ball, helping it firm up and stabilize during transport from the nursery to the planting site. After transport from the nursery to the assembly point, seedlings can be planted immediately or assembled at a convenient location for transport to the planting site. Note that the seedling assembly flat should have daily tidal rise and fall or maintain water level at root ball level, with protective netting fences around the assembly flat to prevent tree tipping/breaking and livestock damage. Transporting seedlings from the assembly point to planting holes: Options include using styrofoam floats, bamboo baskets, boards, boats to transport seedlings. Best practice is to use 1.5 x 2 m styrofoam floats, place seedlings on the float, then use a boat to move seedlings to planting positions. Digging holes: 30x30x30 cm. Tear the root ball casing, place the tree in the center of the hole, keep the tree upright, root ball surface 5-7 cm lower than the hole surface, mound all surface mud to fill the hole, compact soil around to keep the tree stable (ensuring not to break or damage the root system). Staking trees: Since newly planted mangroves have low vitality, they are often susceptible to fouling by algae/debris causing stem breakage. However, in aquaculture ponds without tidal/wave impacts, only one stake is required per tree. Staking standards: Diameter 1.5 cm, length 1.0 m, sharpened, driven at 45° toward the wave impact direction, nylon rope tied to secure stem at 2/3 height from ground (stake protruding ~10 cm just enough to tie to stem). The stake depth is 0.6 m, with 0.4 m protruding above ground. Replanting: Check trees after 1 month. If mortality is ≤ 10 % (under 3 consecutive trees), and scattered, replanting is not necessary. If mortality exceeds 10 % (3 or more consecutive dead trees) or dead trees are concentrated, replant to ensure designed density. Expected replanting rate is 10 % of main planting trees. Planting season: After surveying and analyzing natural factors, the most favourable time for mangrove planting is months 6, 7, 8, 9, and 10, when salinity is lowest in the year, air temperature is favourable for mangrove development. Plant care: Must be implemented immediately in the first year. During the first 3 months after planting, check monthly, re-stake and re-tie if necessary. Thereafter, check quarterly and upright tipped trees. If pests are detected, use appropriate biological measures to care for mangroves. Tree protection: Post warning signs strictly prohibiting exploitation and fishing activities that could be affect newly planted trees in the first 2 years. Prevent damage from humans and livestock (buffalo, cattle, goats, etc.).

3.3. Discussion

3.3.1. Identifying saline soil constraints in aquaculture ponds

The saline soil environment that was once under mangrove canopies is now a saline soil and water environment resulting from the conversion of mangrove forests and their associated

land and water for aquaculture. Consequently, hundreds of thousands of hectares of mangroves were completely destroyed to create open water surfaces for aquaculture purposes. The surface water in these aquaculture ponds originates from coastal seawater, which is introduced into the ponds according to tidal cycles and aquaculture periods. These ponds typically maintain a stable water volume to sustain the cultured stock, meaning the flats (culture beds) and canals are constantly inundated. This creates adverse conditions for the restoration of the mangrove environment within the aquaculture ponds. Because the saline soil area has been modified and degraded, it cannot recover naturally; specifically, the mangrove ecosystem is unable to regenerate and recover according to natural successional processes as the conditions for its survival and growth no longer exist.

Saline soils typical of *Aegiceras* and *Rhizophora* mangrove communities: These soils are concentrated in the coastal areas of aquaculture ponds, with the largest areas found along the coast of Southern Viet Nam, particularly in Ca Mau province. The soil is tidally influenced daily and is typically liquid mud, swampy, highly saline, with a neutral pH and high humus content from decomposed leaves and roots. The salinity in these coastal soils is caused by NaCl from seawater brought in by tides, river overflow into the ponds, or by capillary rise from saline groundwater during the dry season. Saline soils often have a total soluble salt content > 0.5 % and a Cl^- content of 0.40-0.50 %. The Cl^- content is frequently many times greater than that of SO_4^{2-} , classifying them as chloride saline soils. The electrical conductivity is usually greater than 4 mmhos/cm at 25 °C. Base saturation is high, and the pH is generally neutral. Physically, due to the effect of Na^+ ions, saline soils are often dispersed, structureless, very plastic and sticky when wet, and shrink and crack when dry, with salt efflorescence appearing on the surface, turning it white. The primary solutions for this type of soil have traditionally been hydrological measures: constructing dikes to prevent saltwater intrusion, severing the connection between leached areas and adjacent areas with saline groundwater, and introducing freshwater to leach the salt, dilute it, and wash it deeper into the soil profile to prevent it from rising to the surface.

Due to high clay content and waterlogging, the soil is constantly anaerobic (lacking oxygen), and reduction processes dominate, leading to gleying, which gives the soil a bluish gray (steel-blue) color. If the soil has a relatively high organic matter content, a grayish-blue color may appear. The decomposition of organic matter proceeds relatively slowly in saline soils, leading to the gradual accumulation of organic matter.

Studies on the mangrove soil environment in the South Central Coast region show that the saline soils in aquaculture ponds are formed mainly by the action of currents transporting estuarine and coastal sediments, which are then deposited into the ponds by wind, waves, and tides through water regulation systems. Located downstream at river mouths and adjacent areas, the primary deposits are fine particles of mud, clay, or sand in varying proportions. These soils have different levels of maturity, salinity, and texture, and support pioneer species adapted to saline conditions, such as *Avicennia marina*, *Rhizophora stylosa*, *Rhizophora apiculata*, *Sonneratia caseolaris*, and *Kandelia obovata*. Depending on the soil properties in each region, mangrove soils can be classified as having potential acid sulfate properties or not, and as being in high, medium, or low tidal inundation zones. They may also have varying levels of salinity and uneven fertility.

The saline soil environment within the ponds-also referred to as the substrate, sediment, or pond bottom-is where aquaculture activities take place under conditions of periodic or permanent tidal inundation. Spatially, saline soil is understood as degraded mangrove soil

within aquaculture areas that are zoned as forestry land. Identifying mangrove soil types involves classifying them according to site conditions, such as the aquaculture area, the mangrove forest area, and accreting mudflats. Each soil type has distinct characteristics and properties, thus requiring different scientific solutions for improvement.

3.3.2. *Appropriate scientific solutions for improving the mangrove soil environment*

Most current aquaculture ponds were created on deforested mangrove lands, resulting in constantly deep-water conditions that make forest restoration by conventional silvicultural methods difficult. To overcome this, it is necessary to implement integrated hydrological solutions, such as constructing sluice gates, building embankments, and creating raised beds (mounds) for planting. Embankments must be designed according to current standards, selecting routes with high topography and stable geology, and utilizing existing structures where possible. They should also be reinforced with bamboo fences to prevent erosion and create favourable conditions for forest restoration. The system of intake and drainage sluices must be flexible and compatible with the tidal regime, salinity, and water quality, with the optimal time for water intake being at high tide to ensure the best quality. Furthermore, the creation of raised beds for planting must be based on the site elevation and required tidal exposure time to ensure the growth of mangrove trees. For areas with high sand content, the sandy soil in planting holes should be replaced with mud to improve nutrient content and moisture retention. These solutions are expected to create a suitable environment for planting and caring for mangrove trees, contributing to the restoration of degraded coastal ecosystems.

The solution of planting mangroves in aquaculture ponds to improve soil quality and restore the ecosystem is based on selecting species appropriate for local site conditions that can regenerate the degraded forest. A proactive seedling supply is necessary, prioritizing native species such as *Aegiceras corniculatum*, *Rhizophora stylosa*, *Sonneratia caseolaris*, and *Kandelia obovata*. The appropriate planting density is 2,500 trees/ha, with a 2m x 2m spacing in a mixed-species, staggered (quincunx) pattern. Seedlings should be acclimatized for 7–10 days before planting and transported to the site using styrofoam rafts or boats. The planting technique requires digging 30x30x30cm holes, removing the polybag, placing the seedling upright, backfilling with mud, and compacting the soil firmly. To support the trees, each should be staked with a peg driven 0.6m deep at a 45° angle and tied securely to the stem. Replanting is carried out if the mortality rate exceeds 10 %, with a supplementary planting of about 10 % of the total number of trees. The most suitable planting season is from June to October when salinity is low and temperatures are favourable. Maintenance includes regular inspections, pest and disease control, and protecting the newly planted forest using biological measures. Simultaneously, this should be combined with a sustainable aquaculture model under the forest canopy, based on an improved-extensive system, to enhance both ecological and economic efficiency.

4. CONCLUSION

The study confirmed that the degradation of the saline soil environment, driven by coastal aquaculture conversion, resulted in key physical and environmental constraints, including inadequate planting bed elevation, unstable embankments, and insufficient water regulation.

Integrated technological solutions were successfully analyzed, selected, and implemented for the reclamation and restoration of these aquaculture ponds. This package combined: bio-engineering technology for embankment stabilization (using organic bamboo fencing);

mounding techniques to increase planting elevation and counteract tidal inundation; and a targeted water resource regulation process.

The effectiveness of this integrated model is demonstrated by a high mangrove survival rate of over 80 % after one year of planting, with the restored stands showing good and stable initial growth. This provides an evidence-based silvicultural and engineering approach for the sustainable conversion and restoration of degraded saline soil aquaculture environments.

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