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Water retention strategies for drought-prone aquaculture ponds: Technologies, effectiveness, challenges, and future prospects

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ABSTRACT

Water scarcity threatens earthen pond aquaculture's viability and profitability. Drought, variable rainfall, rising air and water temperatures, decreased groundwater availability, and inadequate pond soils deplete stored water through evaporation, seepage, and operating losses. This review synthesises drought-prone pond water retention solutions from engineering, hydrological, aquaculture, and climate-adaptation literature. It covers diagnostic water-balance methods, site selection, soil compaction, compacted clay, bentonite-amended soil, geomembranes, composite liners, evaporation-suppression technologies, rainfall harvesting, reuse, and recirculation, and sensor-assisted water management. The research suggests starting seepage management with a soil and construction diagnosis because a solution that works in silty soil may fail in coarse sand, fractured expanding clay, or a pond with deficient embankments. Compacted soil and locally available clay are smallholders' first-line options. However, sodium bentonite can improve finer sandy and silty materials when evenly combined and compacted at the proper moisture content. Geomembranes are the best barrier in extremely permeable soils, but they cost more, require subgrade preparation, seaming, UV and puncture protection, and end-of-life planning. Aquaculture requires partial coverage and water-quality monitoring because floating or suspended covers limit reservoir evaporation. Complete coverage may restrict light, gas exchange, and primary productivity. The best results across methods come from diagnosis, structural sealing, rainfall capture, reduced discharge, aeration, and routine monitoring. Low-cost field validation, locally modified liner specifications, farmer finance, and life-cycle environmental evaluation are crucial for drought-prone South Asia, especially Bangladesh's Barind Tract. No universal liner exists; the ideal solution is the lowest-cost combination that meets a site-specific water-balance target without ecological or management risks.

Keywords: Drought, Seepage control, Geomembrane, Bentonite, Climate resilience, Bangladesh

1. Introduction

The global aquatic food chain relies heavily on aquaculture. Aquaculture raised 94.4 million tons of aquatic animals in 2022, surpassing capture fisheries for the first time. This shows the importance of water- and climate-resilient farming systems (FAO, 2024) [3]. Earthen ponds are essential because they are easy to build, can be integrated with crop and livestock activities, and are accessible to family farms. Their apparent simplicity masks a crucial dependency: a pond is productive only if it can hold enough quality water.

Water supply impacts almost every pond biological and economic process. Falls in water levels diminish habitat capacity, concentrate fish and metabolites, increase daily temperature variation, and lower nocturnal dissolved oxygen. Farmers may pump groundwater, harvest before market size, reduce stocking, or accept increased mortality. Every answer raises production costs or loses income. Pumping can move the problem from the pond to the aquifer regionally, increasing competition between home supplies, irrigation, aquaculture, and environmental needs (Boyd *et al.*, 2000; Symeonidou *et al.*, 2024) [4, 5].

This susceptibility is increased by climate change. The IPCC concludes that due to changes in precipitation, drought, heat, and evapotranspiration, climate change has changed the global water cycle and increased risks associated with water. Due to a combination of climatic and non-climatic factors, around half of the world's population faces acute water scarcity at least part of the year (IPCC, 2022a, 2023). Higher temperatures, decreased water availability, salinity changes, infrastructure damage, and changed disease dynamics are among the direct effects on aquaculture; higher pumping energy costs, water competition, and unstable feed and market systems are among the indirect effects (De Silva *et al.*, 2009; Maulu *et al.*, 2021; Abisha *et al.*, 2022) [1, 2, 6].

This review evaluates practical methods for minimizing water loss and enhancing pond aquaculture drought resilience. It prioritizes water retention over supply. When the root causes of water loss are not addressed, adding water may temporarily restore pond depth but become economically and environmentally unsustainable. Thus, a retention-first approach examines water loss pathways, identifies losses that can be realistically reduced, evaluates technologies suitable for soil type, farm scale, and management capacity, and considers the secondary effects of each intervention on water quality, fish welfare, and the environment.

The review addresses hydrology, soil engineering, geosynthetics, pond management, and climate adaptation. Small-scale farms in drought-prone and seasonally dry areas like South Asia and sub-Saharan Africa, where capital, technical services, and replacement materials are scarce, are prioritized. Main point: technology should not be prioritized by theoretical impermeability. They should be assessed as management systems that consider construction quality, maintenance, water-quality compatibility, farmer skills, life-cycle cost, and local water governance.

Climate-to-production pathway in drought-prone pond aquaculture

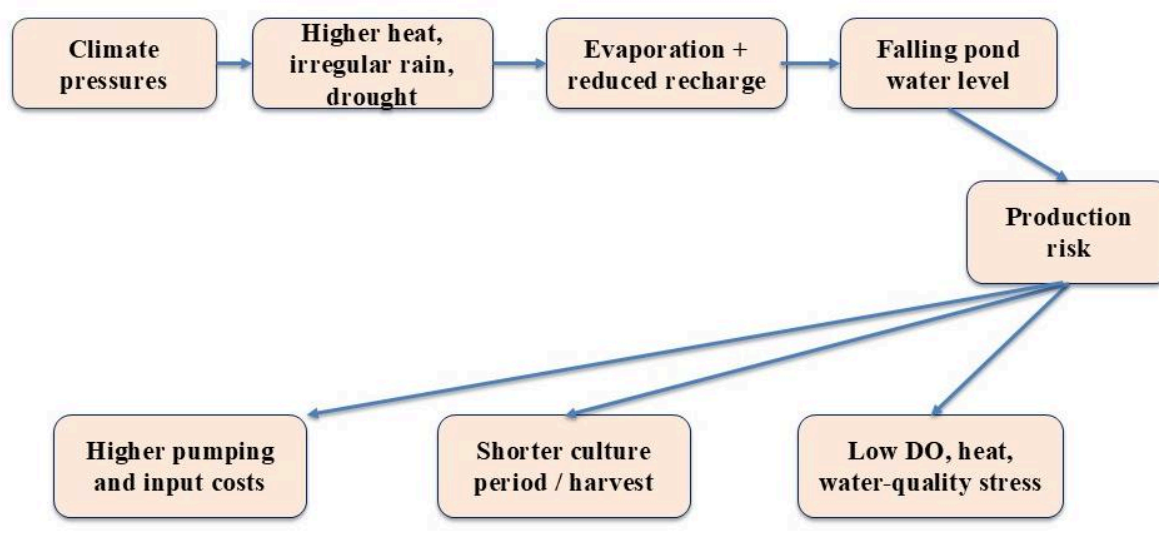


Figure 1. Drought-prone pond aquaculture climate-to-production route. Author synthesis from IPCC (2022a, 2023), De Silva and Soto (2009)^[1], and Maulu *et al.* (2021)^[2]

2. Review approach and scope

This narrative review is structured. Peer-reviewed studies on pond water budgets, water use, liners, soil sealing, evaporation suppression, climate impacts, and aquaculture adaptation; FAO and USNRCS technical manuals and standards; and recent global and Bangladesh-focused climate and aquaculture reviews provided evidence. Sources reporting field or controlled experimental performance, engineering methods, or reproducible design guidelines were prioritized. We only utilized direct numerical comparison where research reported comparable findings because language and measurement methods differ between professions.

Freshwater and low-salinity earthen pond aquaculture are the focus, but reservoir and irrigation-pond studies are included when applicable. Recirculating aquaculture systems cannot replace ponds, although partial reuse, sludge-water integration, and low-exchange management minimize make-up water. It avoids showing a universal percentage of pond water lost to seepage or evaporation. Climate, soil, pond age, water level, and construction affect the prevailing pathway in published water budgets. In dry-tropical research ponds evaluated by Green *et al.* (1995)^[7], evaporation accounted for 70% of total loss, while Indian pond budgets showed considerable and spatially varied contributions from both evaporation and seepage (Sharma *et al.*, 2013; Adhikari *et al.*, 2017)^[9, 8].

This paper applies ordinal and decision-oriented comparative ratings, not *meta-analysis*. They show average performance when a technology is properly designed and installed. Before investing, site-specific lab testing, trial sections, contractor competency, and local cost data are needed. When seams leak, the subgrade settles, animals breach the surface, or the farm cannot maintain the system, a technically superior material can operate poorly.

3. Mechanisms and diagnosis of water loss

Retention planning starts with pond water balance. The change in stored water over time is rainfall, runoff, surface inflow, and pumped supply minus evaporation, seepage, overflow, drainage, and operating withdrawals. The balance is $\Delta S = P + R + I - E - Q_s - D$, where ΔS is the storage change, P is direct precipitation, R is runoff, I is managed inflow, E is evaporation, Q_s is seepage, and D is discharge and withdrawals. The calculation is straightforward, but it requires continuous water-level records, rainfall data, knowledge of deliberate additions and removals, and attention to pipe, gate, and embankment leaks (Yoo *et al.*, 1994; Boyd *et al.*, 2000)^[10, 4].

The practical assessment begins on numerous rain-free days without water addition or removal. A fixed staff gauge measures daily water-level drop. Next, local pan evaporation or a reliable weather estimate is used to estimate evaporation. The remaining decline estimates seepage and unreported leakage. Seepage can decrease as pores clog with fine silt or rise as fractures, burrows, roots, or structural faults occur, therefore measuring at different seasons and water levels is important. Wet places outside the dike, localized settlement, pipe penetrations, animal holes, degraded slopes, and downstream toe seepage should be checked together with water-level monitoring.

Hydraulic gradient, wetted area, soil and liner hydraulic conductivity control seepage. Without imported fines, bentonite, or a barrier, coarse sands and gravels have huge linked pores and are hard to close. Silts can break or dissolve despite appearing tight. Clay-rich soils have lesser permeability but can leak if dry, compacted poorly, built in thick lifts, contaminated with roots or organic materials, or desiccated. FAO soil-engineering guidelines emphasize cohesive materials, careful placement, and compaction, while NRCS criteria demand investigated subgrade, liner material, compaction, and protection from desiccation, wave action, animal activity, and penetrations (FAO, 1992; USDA-NRCS, 2016)^[11, 12].

Evaporation transfers surface energy and mass based on solar radiation, air and water temperature, humidity, wind, and surface area. It cannot be eradicated from an open aquaculture pond, and surface heat and gas exchange is helpful. However, pond architecture, wind management, and partial surface covers can decrease excessive evaporation. Deepening a pond increases storage per unit surface area if embankment stability, excavation expense, groundwater conditions, and fish-management requirements allow. Though narrow windbreaks might lessen local wind exposure, thick trees around the pond can shade excessively, drop organic materials, undermine banks with roots, and compete for water.

Operational losses are typically overlooked. Farmers may exchange water without measuring water quality, bypass the pond with inflow water, drain too much water after harvest, or leave pipes and tanks leaking. Banks and liners can be damaged by livestock. Aquatic weeds transpire and inhibit management, but their total pond water loss varies. Repairing these losses is cheaper than lining. Thus, before choosing a material solution, a retention program should repair structures, calibrate water additions, remove unneeded exchange, and start a water-level log.

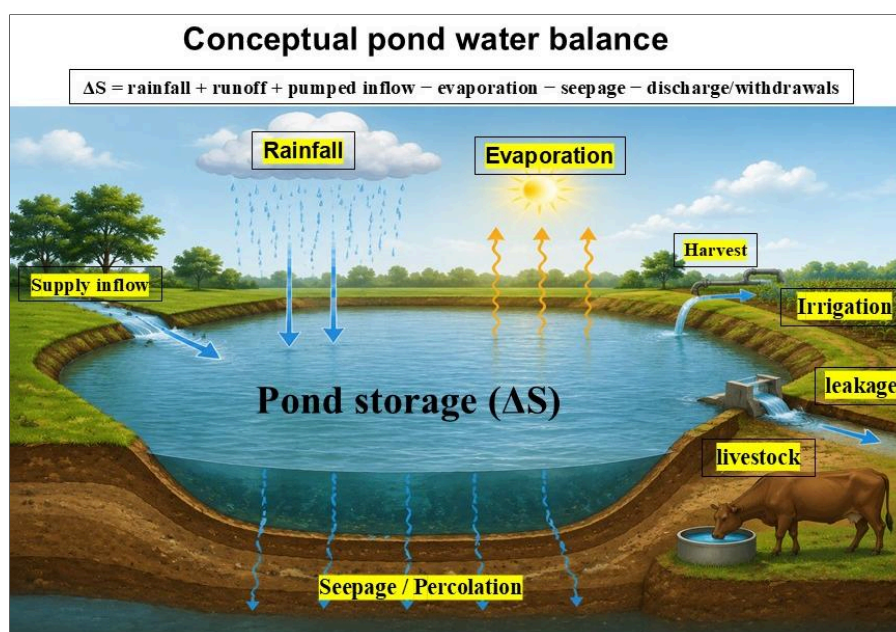


Figure 2. Aquaculture pond water balancing concept. Source: Author synthesis based on Yoo *et al.* (1994) [10], Boyd *et al.* (2000) [4], and FAO water-budget guidance.

Table 1. Major pond water-loss pathways, field indicators, and first responses.

Loss pathway	Field indicators	Simple diagnostic approach	Priority response
Seepage through bottom/sides	Persistent decline during rain-free periods; wet soil outside dike; loss greater at high water level	Daily staff-gauge record minus estimated evaporation; inspect downstream toe and penetrations	Repair localized leaks; compact soil; add clay/bentonite; consider geomembrane
Evaporation	Loss tracks hot, dry, windy weather; no external wet spots	Use pan/weather estimate and compare seasonal decline	Increase depth-to-area ratio where feasible; partial shade/cover; wind management
Structural leakage	Flow near outlet, monk, pipe, spillway, cracks or animal burrows	Visual inspection; dye test; isolate pipe or gate	Repair structures and penetrations before lining
Operational withdrawals	Pump or exchange records exceed water-quality need; livestock access; harvest drainage	Audit pump runtime, exchange volume and management routines	Reduce unnecessary exchange; repair valves; fence livestock; improve harvest practice

4. Technologies for improving pond water retention

Prevention through site selection and construction, corrective pond bottom and side sealing, and atmospheric or operational loss reduction are water-retention technologies. Using the simplest measure to fulfill the goal is optimal. A farmer should not buy a geomembrane to fix a leaking outlet pipe or use bentonite to seal a pond built on open gravel or broken rock without plan.

4.1 Site selection, pond geometry, and soil compaction

Properly treated native soil is the cheapest liner. Site study should reveal soil texture with depth, permeable lenses, bedrock fissures, organic layers, and seasonal groundwater. Cohesive soil without roots and debris should form embankment cores. Instead of running equipment over dry fill, compact in thin lifts near optimal moisture.

Moisture rearranges particles and diminishes linked pores; excessively wet soil pumps and deforms; dry soil remains cloddy and may not attach between lifts. FAO guides and NRCS practice standards emphasize moisture control, lift thickness, and surface preparation for low-permeability construction (FAO, 1992; USDA-NRCS, 2016) [11, 12].

The bottom of existing ponds is drained, dried for equipment access, stripped of soft sludge, scarified, adjusted to suitable moisture, and compacted. Dike-bottom intersections, pipes, and former stream courses demand special attention. When the soil has adequate particles, compaction works best. In extremely sandy material, it can increase density but raise hydraulic conductivity too much for drought-prone aquaculture. Low material cost, local familiarity, and no plastic waste are its key benefits. Machinery, operator competence, weather, and soil suitability limit it.

4.2 Compacted clay blankets

Over permeable subgrades, imported clay can produce a low-permeability blanket. Characterize, distribute, and compact clay in multiple lifts. Where fish, harvesting nets, tractors, or cattle could disturb the sealing zone, a strong protection layer may be needed. Smallholders like local clay since it's cheap and easy to repair. Transport can be expensive, and highly flexible clay can shatter during drying. A pond that empties fully each dry season may need a surface protection layer, quick refilling, or a composite system.

4.3 Bentonite-amended soil

Sodium bentonite's swelling smectite minerals absorb water, expand, and block soil pores. Mixing it with silts, silty sands, or sands without clay works best. Material must be evenly dispersed, moisture-conditioned, compressed, and mixed to depth. Bentonite may help some leaky ponds, but it may not reach or seal the passage. NRCS advice specifies sodium bentonite quality and uses greater minimum treatment rates as soils become more pervious, showing why a single rate should not be used everywhere (USDA-NRCS, 2016) [12].

Bentonite bridges native-soil compaction and synthetic lining. It does not form a continuous plastic layer and can be laid with standard earthwork equipment. In locations without stable suppliers, it is not always cheap. Mixing, confining pressure, water chemistry, and wet-dry cycling affect performance. Divalent cations and saline water limit swelling compared to fresh water, and unprotected layers can erode or split. Thus, field trial panels and laboratory permeability tests are better than generic application rate tables.

4.4 Chemical dispersants and biological sealing

Dispersants based on sodium can deflocculate clay soils so tiny particles fill pores during compaction. NRCS recognizes certain dispersants under regulated design settings, but soil mineralogy and water chemistry determine applicability. Handling them requires laboratory testing and worker protection. For food-production ponds, consider water chemistry and downstream flow before use. Historically, manure, crop leftovers, and induced gley formation were used to close pores. Although locally economical, decomposition can use oxygen, release nutrients, increase methane production, and produce unpredictable outcomes. Instead of commercial aquaculture suggestions, such approaches should be managed niche possibilities.

4.5 Geomembrane liners

Geomembranes are sheets made of polymers characterized by little permeability, offering an immediate physical obstruction. Examples of widely used materials are polyvinyl chloride, ethylene propylene diene monomer, linear low-density polyethylene, and high-density polyethylene (HDPE). HDPE is valued for its welded seams and chemical durability; nevertheless, more flexible polymers may possess varying features regarding plasticizers, UV resistance, puncture strength, and installation yet can more readily accommodate irregular subgrades. The selection process should factor in water chemistry, projected temperature, slope, exposure, accessible welding tools, fish-production techniques, and the ability to mend damage (Koerner, 2012) [13].

Successful lining starts under the sheet. The subgrade must be smooth, stable, and free of stubble, sharp stones, roots, and rapid settlement zones. Protective soil or geotextile cushion may be needed. We must test seams, design anchors, detail penetrations, and deploy panels without strain. On exposed side slopes, UV radiation, wave action, vandalism, birds, rodents, animals, and harvesting may destroy the liner. Covering geomembrane protects but complicates inspection and maintenance. An empty lined pond with high groundwater can

float or wrinkle if water collects beneath it, therefore uplift pressure must be assessed.

Where soils are coarse, water is expensive, and contractors are trusted, geomembranes control seepage best. Acidic, saline, or polluted subsoil can be isolated from culture water. Capital cost, quality assurance, puncture risk, and end-of-life plastic management are the main drawbacks. A site-specific durability plan that specifies exposure circumstances, cover, inspection frequency, repair materials, and removal or replacement is more beneficial than a notional service-life assurance.

4.6 Geosynthetic clay and composite liners

Geosynthetic clay liners combine clay swelling with artificial homogeneity by adding a thin bentonite layer between geotextiles. They are prevalent in environmental containment but rare in small pond aquaculture. Geomesh over compacted clay or geosynthetic clay liners provide redundancy and decrease leakage through isolated flaws. It is primarily relevant to high-value production, permeable foundations, deeper storage, or environmental protection locations. Cost and installation difficulties tend to discourage smallholder adoption.

4.7 Evaporation-control technologies

Surface covers limit sun and wind-driven vapor exchange. Depending on coverage fraction, material, environment, and geometry, reservoir and evaporation pan experiments have shown moderate to over 90% suppression. For all floating coverings evaluated, Shalaby *et al.* (2021) [14] found 27.7–96.8% suppression. Later studies showed suppression of 43–53% for modular bottles or discs and 95% under complete continuous covering. Aminzadeh *et al.* (2018) [15] and Mady *et al.* (2021) [16] found considerable suppression in controlled and field settings for self-assembling discs and spheres.

Such findings will not aid fish ponds without ecological certification. Full covers can alter temperature stratification, limit feeding and aeration, reduce photosynthesis, atmospheric reaeration, and wind mixing, and complicate harvesting. Plastics on the water might accumulate rubbish or break down into microplastics. For aquaculture, partial shade structures, modular covers over specified zones, or shade cloth for access may work better. Any cover should be checked with continuous dissolved oxygen and temperature monitoring, especially at night and in calm hot weather.

4.8 Rainwater collection, repurposing, and low-exchange control

Water capture should depend on retention technology. If runoff quality is good and erosion is managed, diversion drains, silt traps, roof runoff, and properly sized catchments can fill ponds during wet times. Treatment and sedimentation can be done in storage ponds before use. Lowering normal water exchange reduces make-up demand and effluent emissions, making it a good conservation measure (Boyd *et al.*, 2000) [4]. Once salinity and nutrient compatibility are confirmed, water can be recycled for crops, turning outflow into input for integrated farming. Reuse should not recycle infections or collect harmful metabolites.

4.9 Smart monitoring and adaptive operation

Low-cost pressure sensors, ultrasonic gauges, meteorological data, and mobile alerts may turn water management into a plan. A good system monitors water level, rainfall, pump runtime, temperature, dissolved oxygen, conductivity, and salinity. Early detection of aberrant decline, aeration risk, liner damage, or ineffective pumping is the goal, not technology. When regular measurements are tied to decisions, a manual staff gauge and journal can be beneficial.

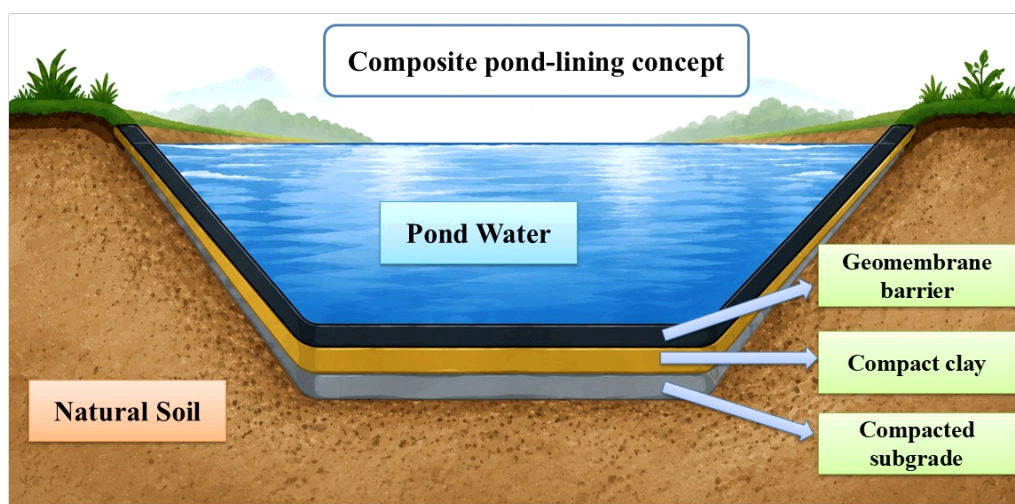


Figure 3. Composite pond-lining concept showing prepared subgrade, compacted mineral layer, and geomembrane barrier. Source: Author illustration based on USDA-NRCS (2016) [12] and Koerner (2012) [13].

Table 2. Properties and application contexts of major pond-retention materials and systems.

Material/system	Typical mechanism	Strengths	Main limitations	Best-fit context
Compacted native soil	Reduces pore volume and connectivity	Low material cost; repairable; familiar	Requires suitable fines, correct moisture and equipment	New or renovated ponds with clayey/silty soils
Compacted clay blanket	Provides thicker low-permeability mineral layer	Local material; robust under protective cover	Transport cost; cracking during drying; variable quality	Permeable subgrade with nearby clay source
Bentonite-amended soil	Swelling clay fills pores and lowers conductivity	Effective for marginal silty/sandy soil; conventional earthwork	Uniform mixing essential; cost and chemistry sensitivity	Small/medium ponds where native soil can form stable matrix
Geomembrane (HDPE/LLDPE/PVC/EPDM)	Continuous polymer barrier	Very high seepage control; immediate performance	Capital cost; seam/puncture risk; plastic end-of-life	Highly permeable soils, expensive water, high-value culture
Composite liner	Redundant barrier: membrane plus clay/GCL	Low leakage and higher reliability	Highest complexity and cost	High-consequence or environmentally sensitive sites
Partial floating/suspended cover	Reduces radiation and wind exchange	Can strongly reduce evaporation; may reduce heat load	May impair DO, access, mixing and primary production	Evaporation-dominated systems with monitoring and aeration

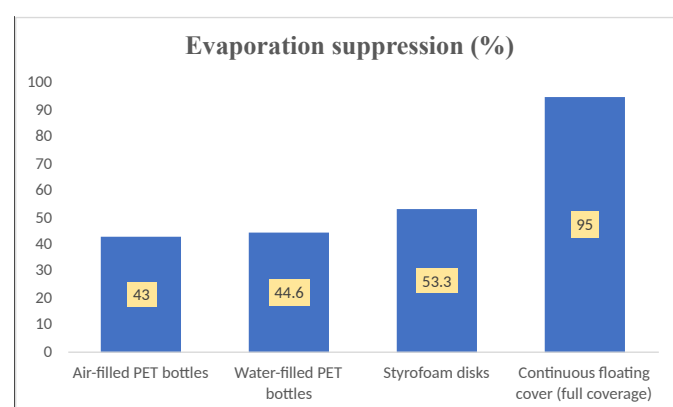


Figure 4. Reported evaporation suppression in controlled floating-cover experiments. Values are from Shalaby *et al.* (2024) [17]; they should not be interpreted as guaranteed fish-pond performance.

5. Comparative evaluation and technology selection

A performance goal, such as maintaining a minimum depth during a predetermined dry time with no more than a certain amount of make-up water, should be the first step in the technology selection process. The goal is then converted into a storage need and an acceptable seep-

age rate. Without this step, farmers can underinvest in a treatment that can't meet demand during the drought season or overinvest in an expensive barrier. Soil, pond area, depth, side slopes, anticipated wet-dry cycle, water value, crop value, contractor availability, and failure repercussions should all be taken into account.

Compaction and repaired clay work well for smallholders in suitable soil. They are repairable, employ local materials, and can be included into ongoing pond maintenance. When native soil is marginal but can produce a stable compacted matrix, bentonite is attractive. Geomembranes are justified when seepage is severe, imported clay is expensive, water is scarce, or production value supports higher capital. Evaporation-control coverings supplement seepage barriers. They are most useful when evaporation dominates the water balance, but aquaculture requires more careful design than irrigation reservoirs due to their ecological and operational impacts.

Important to consider life-cycle costs. The initial material price should include excavation, transport, machinery, installation supervision, protective layers, downtime, maintenance, pumping savings, projected service period, and residual or disposal cost. Repairing a low-cost clay treatment after every major dry-out may cost more than a protected membrane. A farmer may face long output delays if a geomembrane cannot be welded or repaired locally. Therefore, sensitivity analysis should consider high and low water prices, drought frequency, liner life, and productivity response.

As vital is risk. Slowly failing soil liners through cracks, erosion, or small permeable zones allow monitoring and earthwork repair. Small geomembrane faults can be hydraulically significant, and the sheet may disguise subgrade movement. Gas exchange restrictions from

covers can cause quick dissolved-oxygen difficulties. Water-level thresholds, emergency aeration, spare patch material, access routes, and draining/restocking criteria should be included in technology packages.

Table 3. Qualitative comparison of water-retention options. Ratings are context-dependent and assume correct design and construction.

Option	Seepage control	Evaporation control	Capital intensity	Maintenance demand	Smallholder suitability
Improved compaction	Moderate	None	Low	Moderate	High where soil is suitable
Local clay blanket	Moderate–high	None	Low–medium	Moderate	High if clay is nearby
Bentonite amendment	High in suitable matrix	None	Medium	Moderate	Medium–high with technical support
Geomembrane	Very high	Minimal direct effect	High	Moderate–high	Medium; depends on finance and installers
Composite liner	Very high	Minimal direct effect	Very high	High	Low for most small farms
Partial cover/shade	None	Low–high depending on coverage	Low–high	High in storm/debris areas	Context-specific
Rainwater capture + low exchange	Indirect	Indirect	Low–medium	Low–moderate	High

6. Impact on water quality and fish production

Improving retention mostly boosts output by stabilizing habitat volume. Depth reduces congestion, heat, and drought adaptation time for farmers. It can extend fish culture to market size and reduce emergency harvest at unfavorable prices. Refilling less often reduces pumping costs and the risk of predators, pathogens, pollutants, and water-quality changes.

If water stagnates or nutrient loading is high, retention is not beneficial. Pond silt collects feed wastes, excrement, plankton biomass, and decreased compounds. Reduced exchange increases oxygen demand and residence time. A clean synthetic bottom can initially sustain less natural production in lined ponds, which may have less soil contact to buffer chemical shifts. Better feed control, aeration, sludge removal, alkalinity management, and planned partial exchange may be needed. The goal should be consistent, efficient water use, not zero exchange everywhere (Boyd *et al.*, 1998) [18].

Evaporation controls need care. Sun radiation reduction can reduce nuisance algae and midday heat stress, but it also reduces daytime oxygen generation and photosynthesis. Under continual coverings, low-oxygen zones and temperature stratification may increase. Modular designs that leave open water for feeding, gas exchange, and paddlewheel circulation may work better for fish production. Monitoring dawn dissolved oxygen, afternoon temperature, pH range, ammonia, fish behavior, and water movement spatial pattern.

Building materials affect water quality. Fresh concrete raises pH, some flexible polymers contain additives, exposed clay increases turbidity, and poorly designed geotextiles trap organic waste. If available, use potable or food-production water materials, and remove installation residues before stocking. Bentonite and fine clay can temporarily increase suspended particles, therefore ponds should settle and water-quality conditions checked before adding fish.

7. Life-cycle and environmental sustainability considerations

The main environmental benefit of water retention is reduced fresh water demand. In groundwater-refilled ponds, lower seepage and evaporation reduce pumping, energy use, and aquifer pressure. Reduced overflow and exchange lower wastewater volume while controlling pollutant concentration. Each eliminated unit is worth more in integrated farms since retained water can irrigate crops and raise fish. Other technology may have detrimental effects. Transporting and excavating imported clay could damage the earth and utilize fuel. Bentonite mining and processing affect soil and water chemistry, and

dispersants may change them. Geomembranes made of fossil-based polymers degrade and can break under ultraviolet or mechanical stress. Floating coverings add a huge plastic surface to the air–water contact. Life-cycle assessment should consider water conserved, energy used, production gained, and trash generated, not just impermeability (Boyd *et al.*, 2007; Symeonidou *et al.*, 2024) [19, 5].

Sealing ponds changes local hydrology. Pond seepage normally reduces productivity, although in some environments it replenishes shallow groundwater or sustains vegetation. Lining many ponds may diminish local recharge, whereas sealing ponds may reduce downstream flows. Site-specific and frequently tiny at farm scale, these effects matter in cumulative watershed planning. Increased runoff capture must not harm downstream consumers or increase flood risk through poorly planned embankments.

End-of-life planning should be part of procurement. Reworking soil liners is usually achievable, but dirty or saline layers may need to be managed. Geomembranes need repair compatibility documentation and retrieval and disposal methods. Farmers require polymer type and thickness instead of an unknown sheet. Liners provided by public assistance programs should contain installation instructions, replacement supplies, instruction, and a damaged goods approach.

8. Adoption challenges, economics, and governance

Small-scale farmers sometimes have problems synchronizing costs and benefits. Liner costs are paid before stocking, whereas water and survival advantages accumulate throughout production cycles. Credit shortages or short-term terms may deter farmers from leasing ponds. Adoption can rise with longer payback terms, results-based incentives, matching grants, and group procurement. Subsidies should not favor one material regardless of site. Diagnostics, quality assurance, and the liner should be funded.

Limited technical capacity is common. Bentonite requires uniform mixing, soil compaction demands moisture and lift control, and geomembranes require qualified welders and tested seams. A farmer may receive high-quality material yet leak because to improper subgrade preparation or wind or rain installation. Extension initiatives need demonstration ponds, simple acceptance checklists, and post-construction monitoring. Contractor payment can be based on inspection milestones, not completed area.

Decision-making is also limited by information shortages. A farmer may know a pond loses water, but not whether from evaporation, seepage, a leaking building, or unlawful use. Demonstrations should include water-level data, soil characteristics, costs, maintenance histories, and production results, not just before-and-after photos.

Extension personnel should offer treatments based on soil and climate rather than anecdote using local performance databases.

Drought makes water governance crucial. When pond farmers compete with drinking-water and irrigation users, pumping may be restricted. Retention investment reduces conflict but may stimulate pond extension beyond sustainable water supply. Thus, licensing, watershed allocation, and drought strategies should encourage efficiency and limit extraction. Climate-resilient aquaculture involves collaboration across fisheries, agriculture, water, environment, and local government.

9. Application to drought-prone regions and Bangladesh

Soil, water, farm scale, and culture species vary in drought-prone places, hence adaption packages should be localized. Lined rain-fed ponds can store seasonal runoff and feed tilapia or catfish in semi-arid Africa, but protracted dry seasons may require low stocking density, partial harvest, and emergency aeration. Dense pond networks, monsoon rainfall, high summer heat, and widespread groundwater pumping in South Asia allow rainwater capture and reuse but also compete for dry-season water. High evaporation, expensive water, and tougher environmental restrictions may favor designed liners and partial coverings in high-value activities in Mediterranean systems.

Bangladesh is a large pond-aquaculture nation with different climate concerns. Northwestern districts confront heat, unpredictable rainfall,

and water stress, while coastal farmers face saline intrusion and hurricanes. Recent Bangladesh fisheries and aquaculture evaluations identify drought, temperature, changing precipitation, salinity, and extreme events as interrelated challenges needing infrastructure, species, water, information, and institutional adaptation (Haque *et al.*, 2025) [20].

One of the country's most water-stressed agricultural regions, the Barind Tract is important. Water retention is important due to its older alluvial soils, seasonal dryness, and groundwater dependency. A World Bank study of Barind's development underlines the region's long-standing water restrictions and the economic importance of water-management organizations (World Bank, 2020) [21]. Renovation of old ponds and khals, catchment improvement, dike repair, staff-gauge monitoring, and testing compacted clay or bentonite on suitable soils are good starting points for pond aquaculture. Geomembranes may be suitable for tiny, high-value ponds, nurseries, or extremely permeable areas where water savings justify expense.

Bangladesh-specific field testing should evaluate technology over numerous wet-dry cycles. Trials must record seepage reduction, installation cost in local currency, labor demand, fish growth, dissolved oxygen, sediment management, maintenance frequency, farmer acceptability, and make-up water amount and source. Such evidence would be better than industrial reservoir service-life or cost assertions. Local universities, the Department of Fisheries, agricultural engineering schools, and farmer groups might build standard test ponds and training modules.

Table 4. Example site-based technology packages and upgrade triggers.

Site condition	Recommended first package	Upgrade trigger
Clayey pond with moderate seasonal loss	Repair structures; scarify and compact; protect slopes; monitor level	Persistent decline exceeds evaporation estimate
Silty/sandy pond with identifiable permeable layer	Targeted clay or bentonite-amended liner; compact in lifts; protect surface	Trial section fails or water value is high
Clean sand/gravel or fractured foundation	Engineered geomembrane or composite liner; drainage/uplift check	High consequence of failure or repeated puncture
Evaporation-dominated pond	Increase depth where safe; windbreak set back from dike; partial cover trial; aeration	DO or temperature targets not met; cover damage
Water-stressed smallholder cluster	Shared diagnosis, bulk procurement, contractor QA, rainwater capture, finance	Expansion threatens local water allocation

10. Integrated decision framework

Integrated strategies have six steps. Start with loss measurement. Two to four weeks of water-level, rainfall, and pumping records during a dry season are recommended, along with structural leakage check. Second, assess site soil texture, simple field permeability testing, topography, groundwater, and management access. Third, set minimum operating depth, replenishment frequency, and drought duration.

Fourth, evaluate viable technologies. Repair outlet or dike for structural leaks. Rework and compact native soil. If soil is marginal, add clay or bentonite. If the foundation is leaky or failure is likely, consider geomembrane or composite lining. Improve depth-to-area ratio, wind exposure, and partial cover while protecting oxygen dynamics if evaporation prevails. Fifth, evaluate life-cycle cost, environmental impact, and repairability. Sixth, build quality and evaluate performance after filling.

The framework should create a package, not a material. Smallholder packages may include restored dikes and pipes, compacted bottom soil, narrow bentonite treatment along a sandy lens, runoff diversion through a silt trap, reduced interchange, and a staff gauge. A high-value nursery may use a geomembrane, roof-water harvesting, backup storage, mechanical aeration, and level alarms. Reliable output with water demand within local supply constraints makes both systems climate-resilient.

Site-specific decision pathway for pond water-retention investment

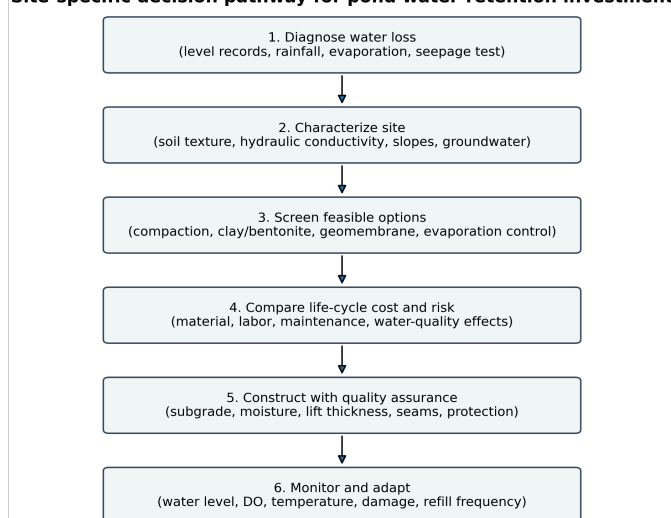


Figure 5. Site-specific decision pathway for pond water-retention investment.

11. Research gaps and future prospects

Comparing field performance over time is the first research gap. While farms suffer settlement, burrowing animals, harvesting equipment, algae, silt deposition, and recurrent drying, many research test

one material for a short time. Multi-year studies should evaluate hydraulic performance and fish output under realistic management. Initial soil parameters, liner thickness, compaction energy, moisture content, seams or joints, cover quality, rainfall, evaporation, water additions, and damage should be reported.

Development is needed for economical sustainable materials. Biopolymer membranes, natural-fiber-reinforced composites, safe recycled polymer sheets, and locally made geosynthetic clay products could save cost and travel. Biodegradability isn't always desirable in an intact liner, as recycled materials may include additives or varied strength. Research must balance permeability, durability, repairability, ecotoxicity, and end-of-life recovery. Third, aquaculture-specific evaporation-control research is needed. Reservoir studies determine cover physical potential, but fish ponds need oxygen, primary production, feeding, aeration, and harvesting. Partial coverage patterns, cover height, materials, and paddlewheel/diffuser compatibility should be tested. Not just millimeters of water conserved, outcomes should include diel oxygen, temperature stratification, plankton, ammonia, fish behavior, growth, and plastic degradation.

Farmer validation of low-cost monitoring and decision support is fourth. Sensors require accurate calibration, minimal power, easy interfaces, and service networks. Instead of dashboards farmers can't understand, algorithms should translate data into actions like 'inspect for leakage', 'start aeration', or 'delay stocking'. Manual monitoring is significant since it may be more sustainable than technology in distant areas. Fifth, prioritize economics and social inclusion. Adoption studies should identify owner-operated ponds from leased ones, household farms from commercial farms, and farmers with unequal credit, groundwater, labor, and extension. Pond management generally involves women, yet capital investment may be less theirs. Distributional effects and technical efficiency should be assessed for financing schemes, collective contracting, and public initiatives. Finally, watershed and climate planning should include water-retention research. Drought could affect rainfall capture and groundwater refill. Historical average-based designs can fail after protracted drought spells. Aquifer trends, fish tolerance, market risk, and expected heat and rainfall should be considered in scenario analysis. Adaptive design ponds with modular measures that can be improved as climate and water prices change is most promising.

Table 5. Research gaps and minimum outputs for future studies.

Research priority	Why it matters	Minimum recommended outputs
Multi-year liner trials	Short tests miss cracking, settlement, puncture and maintenance	Seepage, water additions, damage, cost, fish yield, water quality for ≥ 3 wet-dry cycles
Aquaculture-specific evaporation covers	Reservoir results may not protect fish welfare	Diel DO/temperature, plankton, fish behavior, growth, water saved, plastic condition
Low-cost sustainable materials	Current liners may be expensive or create waste	Permeability, strength, ecotoxicity, repairability, life-cycle assessment
Farmer finance and adoption	Capital barriers can outweigh technical merit	Cash flow, tenure, gender, willingness to pay, subsidy and credit performance
Climate and watershed integration	Historical water supply may not represent future drought	Scenario-based water balance, aquifer effects, downstream impacts, adaptive triggers

12. Conclusion

Drought-resistant pond aquaculture requires water retention. Before treatment, a water-balance diagnosis must distinguish seepage, evaporation, and unnecessary operational discharge. Good site selection, moisture-controlled compaction, sound embankments, and leak-free structures are the first defense. Sealing using compacted clay and bentonite-amended soil is inexpensive when materials and equipment are available. Geomembranes are the most reliable barrier in highly permeable soils, although subgrade preparation, seam quality, protection, inspection, and end-of-life management affect their effectiveness. Evaporation covers save water, but aquaculture must protect gas exchange, primary productivity, access, and fish welfare. Each technology has pros and cons. An integrated, site-specific package of structural retention, rainfall capture, efficient operation, aeration, and monitoring is best. Life-cycle cost and environmental performance should replace initial price in evaluation. In water-stressed locations like northwestern Bangladesh, pond diagnosis, water body rehabilitation, local field trials of clay, bentonite, and protected geomembranes, farmer training, and building quality funding are essential priority. Investment in water-retention can extend culture periods, reduce emergency pumping and harvest, conserve aquifers, and make pond aquaculture a more reliable climate-resilient food system component.

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