

Design, Construction, and Management of Sustainable Off-Grid Freshwater Aquaculture Ponds

The transition toward sustainable, off-grid freshwater aquaculture represents a fundamental shift from energy-intensive, linear production models to decentralized, ecologically integrated closed-loop systems. Designing a highly functional off-grid aquaculture pond requires the precise orchestration of geotechnical engineering, solar-driven fluid dynamics, biogeochemical cycling, and trophic web management. Without reliance on municipal power grids, commercial feed supply chains, or industrialized chemical interventions, the off-grid pond must function as an autonomous, self-regulating bioreactor. It must maintain structural integrity through optimized earthworks, support aerobic respiration via low-energy airlift pneumatic pumping, neutralize metabolic waste through constructed wetlands and bacterial assimilation, and generate its own high-protein inputs through autotrophic and heterotrophic feed cultivation. The comprehensive analysis presented herein details the exhaustive requirements for the construction, biological initialization, and ongoing ecological maintenance of such a system, specifically tailored for common freshwater species including tilapia, carp, and trout.

1. Topographical Survey and Geotechnical Engineering

The fundamental viability of an earthen aquaculture pond is dictated by the topographic layout of the landscape, the physicochemical properties of the underlying soil matrix, and the geometric precision of its constructed embankments. A pond is not merely an excavation; it is a complex hydraulic structure engineered to retain water continuously while withstanding hydrostatic pressure, wave action, and seasonal geological settling.

1.1 Topography and Pond Typology

The initial phase of farm design requires a geodetic survey with contour lines at 20 to 25 cm vertical spacing connected to a national survey network to determine precise elevations¹. The macroscopic shape of the valley or plain dictates the architectural typology of the pond. If a valley is deep, steep, and narrow, the site is generally unsuited for pond construction due to prohibitive earthmoving costs and the risk of catastrophic washout².

Where valley bottoms range from 50 to 100 meters wide, barrage ponds are often appropriate. Barrage ponds are created by building a dam directly across a narrow stream or elongated depression, relying on the natural valley walls to form the remaining sides². While cost-effective in terms of earthmoving, barrage ponds suffer from limited water surface area, high susceptibility to flash floods, and the risk of rapid nutrient flushing which can decimate the natural food web and spread disease downstream³.

Conversely, valleys wider than 100 meters, or lands with gentle slopes (ideally between 0.5 and 1.5 percent gradient), are optimal for diversion ponds². In diversion systems, the primary watercourse is not blocked; rather, water is diverted into geometrically regular, individual ponds through a controlled canal system. This architecture provides maximum flexibility for water

management, allowing operators to isolate individual ponds for disease control, control hydraulic retention times to preserve internal food webs, and drain specific basins via gravity³. On land with slopes exceeding 1.5 percent, rectangular ponds should be oriented parallel to the contour lines (perpendicular to the slope) to minimize the volume of cut-and-fill earthworks required².

Excavated ponds, constructed by digging a depression below the existing water table on entirely flat terrain, represent a third typology. While they offer excellent flood protection due to the surrounding excavated spoil banks, their reliance on mechanical pumping for drainage renders them less suitable for strictly off-grid, low-energy applications unless solar pumping infrastructure is substantially oversized³.

1.2 Soil Suitability and Impermeability Diagnostics

Soil impermeability is the paramount diagnostic criterion for earthen site selection. Water will invariably seek the path of least resistance, and constructing a pond on highly permeable substrates will result in catastrophic seepage, necessitating the installation of prohibitively expensive synthetic liners. A minimum depth of 18 to 24 inches (45 to 60 cm) of naturally occurring clay or clay loam is required across the pond basin to achieve sufficient water retention⁵.

The textural composition of the soil dictates both its permeability and its structural stability. For optimal earthen pond construction, the soil must contain a minimum of 20 to 30 percent clay, with fine-grained silt and clay particles representing more than 50 percent of the total dry weight⁵. Sandy clay, silty clay loam, and clay loam—classified under the Unified Soil Classification (USC) system as the CL group—are considered ideal⁶. These classifications provide sufficient clay to establish a watertight seal while possessing enough sand and silt to provide internal friction, preventing excessive shrinking, cracking, and structural failure within the dam under load⁵. Sites characterized by high organic matter, gravel, or exposed rock strata formations must be avoided, as these present extreme seepage risks¹.

Before excavation commences, empirical field diagnostics are mandatory to validate the site's geotechnical capacity.

- **Percolation Testing:** The site must demonstrate a percolation rate of less than 1 inch per hour (or a coefficient of permeability smaller than or equal to 10^{-5} m/s) to be viable⁵.
- **Ribbon Test:** When subsoil is moistened and squeezed between the thumb and forefinger, it should form a continuous, cohesive ribbon. A ribbon less than 1 inch before breaking indicates low clay content and high permeability; 1 to 2 inches indicates moderate clay requiring extensive compaction; and greater than 2 inches confirms a high clay content natively suitable for unlined construction⁵.
- **Submersion Ball Test:** Soil balls approximately 10 cm in diameter are formed and placed in still water roughly 45 to 60 cm deep. If the spheres disintegrate within a few hours, the soil is structurally unsuitable for embankments. If they remain entirely intact for at least 24 hours, the soil possesses sufficient cohesiveness for dam construction⁶.

1.3 Embankment Geometry and Core Trenching

The structural integrity of the pond relies heavily on the geometric ratios of its embankments (dikes). Standard aquaculture engineering dictates a 3:1 slope on the wet (inside) face of the dam and a 2:1 slope on the dry (outside) face⁵. The shallower internal slope mitigates the erosive forces of wave action and prevents slumping when the soil is heavily saturated, while the steeper 2:1 external slope provides adequate structural mass to resist the hydrostatic outward thrust of the impounded water.

To prevent lateral seepage and piping beneath the dam, a cut-off trench (core trench) must be excavated along the entire centerline of the proposed embankment. This trench should be 0.5 to 1.0 meters wide and must completely penetrate any permeable topsoil layers, anchoring at least 30 cm deep into the underlying impervious clay substrate⁵. In smaller dikes, the trench is dug with vertical walls to a depth of 0.6 to 1.0 meters, while larger dikes require trench walls cut at a 0.5:1 or 1:1 slope⁷. The trench is subsequently backfilled with highly impermeable clay, compacted meticulously in sequential 6 to 8-inch lifts utilizing a sheeps-foot or pneumatic roller⁵.

If the primary in-situ soil utilized for the bulk of the dike lacks optimal impermeability (e.g., sandy loam), a central clayey core must be constructed vertically through the center of the dike. The material utilized for a clay core must exhibit specific plasticity characteristics to ensure a durable, flexible seal under pressure: a liquid limit greater than 60 percent, a plastic limit greater than 20 percent, and a plasticity index greater than 30 percent⁶. In contrast, homogeneous dikes built without a distinct clay core require general fill soil with a plasticity

index between 8 and 20 percent and a coefficient of permeability ranging from 1×10^{-4} to 5×10^{-6} m/s⁶.

1.4 Volumetric Sizing and Settlement Allowances

Aquaculture pond depths typically range from 1 to 2 meters¹. Excessively shallow waters suffer from extreme diurnal temperature fluctuations and promote rapid benthic macrophyte growth that interferes with harvesting. Conversely, excessive depth complicates seining operations and invites severe thermal stratification, which routinely leads to anoxic benthic zones where organic matter accumulates and ferments. An average depth of 6 to 8 feet (1.8 to 2.4 meters) at the deepest point provides a critical thermal refuge—a cool bottom layer during summer heat waves and a protective, insulated zone against winterkill in colder northern climates⁵.

When calculating the final construction height of the dike, engineers must account for the target design water depth, a mandatory freeboard, and a settlement allowance. The freeboard is the vertical distance between the maximum designed water level and the crest of the dike, serving to prevent overtopping during extreme precipitation events. Freeboard requirements vary from 0.25 meters for small diversion ponds to over 1.0 meter for barrage ponds lacking diversion canals⁷.

Earthen structures inevitably compress under their own static weight and the hydrostatic pressure of the impounded water. Settlement allowances generally range from 5 to 20 percent of the total height, heavily dependent on the compaction methodology and the ambient soil moisture content during construction⁷.

The initial construction height (CH) is derived from the final design height (DH) and the settlement allowance percentage (SA) using the following calculation:

$$CH = \frac{DH}{[(100 - SA) \div 100]}$$

For example, a diversion pond requiring a 1.0 m maximum water depth and a 0.3 m freeboard results in a design height of 1.30 m. Factoring in an estimated 15 percent settlement allowance yields a required initial construction height of 1.53 meters⁷.

Pond Size (m2)	Soil Quality	Max Water Depth (m)	Freeboard (m)	Dike Top Width (m)	Wet Slope	Dry Slope
200	Good	0.80	0.25	0.60	1.5:1	1.5:1
400-600	Fair	1.00	0.30	0.80	2:1	2:1
1000-2500	Fair	1.30	0.50	1.30	2.5:1	2.5:1

Table 1: Standard geometrical guidelines for earthen pond embankments based on pond area and available soil quality⁷.

2. Species Selection, Thermal Dynamics, and Polyculture

The energetic limitations inherent to an off-grid system strictly preclude the use of artificial water heating or chilling infrastructure. Consequently, species selection must align flawlessly with the localized thermal regime, seasonal meteorological fluctuations, and the natural thermodynamic properties of the water body. The density-temperature dependence of water—specifically its maximum density at 4°C—causes thermal stratification, allowing properly designed, deeper ponds to provide the micro-habitats fish utilize to survive ambient extremes⁸.

2.1 Thermal Envelopes of Key Aquaculture Species

Different aquaculture species possess distinct thermal tolerance envelopes that dictate their baseline metabolism, feed conversion efficiency, disease resistance, and ultimate survival.

Nile Tilapia (*Oreochromis niloticus*): Tilapia are strictly warmwater, tropical species. They require consistent water temperatures above 25°C for optimal metabolic efficiency and rapid

somatic growth; they typically cease reproduction below 20°C⁸. They are highly susceptible to cold stress. Mortality generally occurs if water temperatures fall below 10 to 12°C, and significant immunosuppression manifests well before that threshold⁸. Extensive generational studies on tilapia cold tolerance demonstrate that significant drops in survival rates occur after prolonged (90-day) exposure to temperatures hovering around 14°C¹⁰. Interestingly, cold tolerance varies significantly among genetic strains; in specific commercial varieties (e.g., CV1), survival can plummet sharply to 25% under cold stress, whereas other more robust strains (e.g., CV2) maintain survival rates above 85% under identical conditions¹⁰. Consequently, off-grid tilapia farming is restricted to tropical or subtropical zones unless the pond is situated within a highly insulated, passive-solar greenhouse structure.

Common Carp (*Cyprinus carpio*): Carp represent a highly versatile, eurythermal option, particularly suited for temperate and continental climates. Their optimal physiological growth and normal oogenesis occur at temperatures around 20°C⁸. Carp are highly responsive to environmental parameters beyond temperature; for instance, while their growth is optimized at 20°C, increasing salinity severely degrades their energetic efficiency. Experimental data demonstrates that at a salinity of 4.5 ppt, carp recover 22.2% of food energy as somatic growth, but this recovery plummets to a net negative (-1.0%) at 10.5 ppt⁸. As seasonal temperatures drop below 10°C, carp undergo profound metabolic shifts, drastically reducing activity and feed intake; as temperatures approach 1°C, they enter a state of deep hibernation¹³. Because of this physiological elasticity, carp can survive extreme winters beneath ice cover, provided the pond possesses sufficient depth to maintain a stable 4°C benthic layer and adequate dissolved oxygen⁸.

Rainbow Trout (*Oncorhynchus mykiss*): A coldwater obligate species, trout require highly oxygenated water and narrow optimal temperature ranges between 9°C and 20°C¹⁴. While common carp require 20°C for normal oogenesis, trout demand much colder conditions for reproductive viability¹¹. Trout undergo severe physiological stress, immune collapse, and rapid mortality at temperatures exceeding 20 to 25°C⁸. Off-grid trout aquaculture requires cold, continuously flowing water sources (such as gravity-fed springs or diversion ponds in montane regions). Climate change poses a severe existential threat to trout aquaculture in temperate zones; modeling under high emission scenarios (RCP 8.5) predicts significant temperature increases, which will decrease the suitability of southern and eastern regions in places like the UK, while simultaneously altering the geographical suitability for specific viral pathogens like enteric redmouth disease¹⁴.

2.2 Polyculture and Density Optimization

In semi-intensive off-grid earthen ponds, the maximum carrying capacity is dictated by the natural availability of dissolved oxygen and the biological assimilation rate of nitrogenous waste. A traditional monoculture of common carp reliant purely on natural food webs can support stocking densities of 0.3 to 0.6 fish/ m^2 ¹⁵. With the introduction of supplementary off-grid aeration and formulated feed inputs, stocking densities can be safely elevated to 1.5 to 3.0 fish/ m^3 , pushing gross yields from baseline levels up to 1,500 kg/ha or higher¹⁵.

However, the most ecologically sound approach to maximizing biomass per unit of water area without relying on high-energy filtration is the implementation of polyculture. Polyculture—the simultaneous cultivation of multiple species occupying distinct, non-competitive trophic niches—maximizes the utilization of the pond's three-dimensional space and available natural feed vectors.

A standard Central European cyprinid polyculture model is meticulously balanced to harvest energy at every trophic level. The stocking ratio typically consists of 40-50% common carp (acting as benthic scavengers and detritivores), augmented by grass carp (macrophyte grazers that clear vegetation), silver carp (phytoplankton filter feeders that control algal density), and bighead carp (zooplankton filter feeders)¹⁶. This ecological partitioning fundamentally reduces the system's overall Feed Conversion Ratio (FCR) by ensuring that uneaten feed, algal blooms fueled by dissolved nutrients, and benthic detritus are continuously grazed, minimizing the accumulation of unassimilated organic matter on the pond bottom.

Advanced integration, such as combining high-density in-pond cages with extensive open-water polyculture, further optimizes nutrient flow. Studies indicate that stocking carp in suspended cages at high densities (8.12 kg/m^3) results in high nutrient loads dropping into the pond beneath. However, rather than causing eutrophication, this nutrient cascade can fuel an extensive open-water fish community, supporting net fish production of approximately 450 kg/ha in the surrounding earthen pond, effectively utilizing the cage waste as a primary fertilizer¹⁸. Similarly, standardizing stocking densities for species like *Pangasius* in pond-cage systems reveals a parabolic efficiency curve; stocking at 25 fish/ m^3 maximizes both biomass production and feed conversion efficiency, whereas pushing the density to 30 fish/ m^3 results in degraded food conversion and diminishing returns¹⁹.

3. Off-Grid Aeration: Solar-Driven Airlift Pump Mechanics

Dissolved oxygen (DO) is universally the primary limiting factor in any high-density aquaculture system. Without grid-tied electrical paddlewheels, surface aspirators, or high-pressure mechanical blowers, off-grid ponds must rely on highly efficient, low-wattage aeration mechanisms. The solar-powered airlift pump represents the optimal synthesis of fluid mechanics and renewable energy, providing robust water circulation and oxygenation with minimal infrastructural overhead.

3.1 Principles of Airlift Pumping and Fluid Dynamics

An airlift pump (historically referred to as a mammoth pump) consists of a vertical riser pipe partially submerged in the pond, open at both the top and bottom. Compressed air or gas is injected near the base of this pipe. As the injected air bubbles form and rise, they mix intimately with the water, drastically reducing the overall density of the two-phase fluid column inside the pipe compared to the solid water column outside²⁰.

This localized density gradient, combined with the buoyant upward force of the expanding bubbles acting as a pneumatic piston, lifts the water to the surface and expels it²⁰. The airlift

mechanism achieves simultaneous mass fluid circulation and aggressive aeration with absolutely zero moving mechanical parts in contact with the water²⁰. This design completely eliminates the mechanical wear, noise pollution, and risk of impeller fouling by suspended solids, macrophytes, or algae that plague traditional centrifugal or mechanical pumps, ensuring unparalleled reliability in remote locations²⁰.

3.2 System Sizing, Thermodynamics, and Submergence Ratios

The hydraulic efficiency and ultimate flow rate of an airlift pump are dictated by the vertical

pipe diameter, the volume of injected air, and, most critically, the submergence ratio (ϵ)²¹. The submergence ratio is defined as the depth of the air injection point (footpiece) below the static water level divided by the total vertical lift distance from that footpiece to the discharge point²⁵.

For functional aquaculture applications, a high submergence ratio is vital for energetic efficiency. Operating at low submergence ratios (near 0.4 or below) forces the pump into "slug flow," a highly inefficient regime where massive air pockets blow rapidly through the pipe without effectively lifting the interstitial water, causing the required air volume to skyrocket²². Optimal performance and stable bubble flow in low-head pond environments are achieved with submergence ratios between 0.5 and 0.8, with 0.8 being the minimum acceptable threshold for highly efficient aquaculture designs²¹.

The theoretical free air requirement (Q_{air}) to achieve a target water flow (Q_{water}) can be precisely calculated using the empirical airlift sizing equation:

$$Q_{air} = \frac{Q_{water} \times L}{C \times \log_{10} \left(\frac{P_s + P_{atm}}{P_{atm}} \right)}$$

Where L is the total lift, P_s is the static pressure at the footpiece (submergence depth), P_{atm} is atmospheric pressure, and C is an empirical efficiency constant representing the installation's specific geometry (typically 245 when utilizing imperial ft-gpm-psi units)²⁵. Because the required vertical lift in a standard aquaculture pond is near zero (the goal is horizontal circulation from the benthic zone across the surface, rather than lifting water out of a deep well), airlift pumps can achieve extraordinary efficiency. Research indicates that optimized, low-wattage off-grid airlift configurations can pump over 1,200 liters per hour utilizing a mere 5 watts of power. Such metrics demonstrate that a 1,000-liter fish tank can be adequately circulated using a sub-\$400 micro-solar photovoltaic array²⁸. Furthermore, experimental arrays utilizing multiple airlift pipes driven by a single compressor scale magnificently; combining twenty-eight 7.6-cm diameter airlift pipes powered by a single 1.0-horsepower (0.75 kW) centrifugal blower can move over 3,107 liters of water per minute²³.

3.3 Solar-Airlift Synergy and Seasonal Performance

There is a highly fortuitous, synergistic correlation between solar energy availability and pond aeration demand. The metabolic rates of both the cultivated fish and the heterotrophic bacteria responsible for waste assimilation increase exponentially with ambient water temperature. Consequently, biological oxygen demand peaks during the height of summer and during maximum daylight hours²⁹.

The performance of direct-drive solar airlift pumps perfectly mirrors this biological demand. Thermodynamic evaluations using Engineering Equation Solver (EES) models and field experiments demonstrate that maximum water lift height, volumetric flow rate, and overall thermal-to-hydraulic efficiency all peak during summer irradiation²³. Under peak summer conditions, the thermal efficiency of a solar bubble pump can reach 47.9% (compared to 35.9% in winter), generating high-velocity micro-bubbles that strip accumulated carbon dioxide and saturate the water column with oxygen. Maximum flow rates in experimental models increased from 0.985 mL/s in winter to 1.716 mL/s in summer, providing maximum lift exactly when the pond ecology requires it most²³.

For baseline system sizing, a densely stocked koi or carp pond requires an aeration flow of approximately 200 to 400 liters per hour (3 to 7 liters per minute) for every 1,000 liters of pond volume³⁰. To compensate for nocturnal oxygen drops when solar generation ceases, the integrated 24-volt solar array must be coupled with a deep-cycle battery bank sized to capture 50% to 80% of the daily excess solar production, alongside a high-efficiency, oil-free diaphragm blower (oil-free is a mandatory requirement to prevent hydrocarbon contamination of the aquaculture water)²⁵.

4. Natural Feed Generation and Trophic Upcycling

The reliance on imported, commercially synthesized pelleted feeds creates an unsustainable logistical, financial, and energetic burden for off-grid operations. To achieve true ecological autonomy, the pond environment must be coupled with rapid-cycling biological systems that generate high-quality protein and lipid sources on-site. Two of the most effective autotrophic and heterotrophic feed generation models are the cultivation of Duckweed (*Lemnaceae*) and the rearing of Black Soldier Fly Larvae (*Hermetia illucens*).

4.1 Autotrophic Generation: Duckweed Cultivation

Duckweed is a free-floating aquatic macrophyte characterized by explosive exponential growth and exceptional nutritional profiles. When cultivated under optimized, nutrient-rich conditions—ideally utilizing the nitrogen-rich effluent generated by the fish—duckweed can achieve crude protein levels between 35 and 45 percent³⁴. This protein is highly bioavailable to herbivorous and omnivorous species like tilapia, grass carp, and common carp, boasting an amino acid profile rich in essential elements such as lysine and methionine, directly comparable to terrestrial soybeans³⁴.

Duckweed demonstrates extreme vegetative productivity, capable of yielding up to 25 grams of dry matter per square meter per day, vastly outperforming terrestrial soy which yields roughly 10 grams³⁶. However, maintaining this velocity of growth requires intensive agronomic management of the water surface. The optimal standing crop density must be aggressively maintained between 400 and 800 grams (wet weight) per square meter through frequent

harvesting³⁴. If the mat becomes too dense, self-shading collapses the photosynthetic rate, triggering benthic die-offs and releasing nutrients back into the water; if it is too sparse, solar radiation penetrates the water column and stimulates the growth of competitive, potentially toxic phytoplankton³⁷.

In open earthen ponds, wind action easily disrupts duckweed mats, pushing the delicate plants to the leeward banks and causing deep pile-ups that lead to rapid decomposition and localized anoxic zones. To mitigate this, floating geometric grids constructed from sealed PVC pipes must be deployed as physical collars across the pond surface, partitioning the area and protecting the macrophytes from wind-driven accumulation³⁹.

Furthermore, duckweed acts as a highly efficient phytoremediation agent. It assimilates massive quantities of dissolved nitrogen, phosphorus, and even heavy metals from the water column, actively reducing the biological oxygen demand of the pond³⁵. While there is a documented risk of dangerous heavy metal bioaccumulation when duckweed is cultivated on raw municipal or industrial wastewater, duckweed grown strictly on internal agricultural/aquaculture effluent is entirely safe for continuous re-ingestion by the fish biomass, posing no health hazard to the handlers or the final consumer⁴⁰.

4.2 Heterotrophic Generation: Black Soldier Fly Larvae (BSFL)

To complement the carbohydrate- and protein-rich autotrophic duckweed, the Black Soldier Fly (*Hermetia illucens*) provides a phenomenal source of terrestrial insect biomass. BSFL are capable of aggressively consuming immense varieties of putrescent organic matter—including manure, vegetable scraps, spent brewer's grain, and mortalities—transforming these low-value waste streams into high-value insect biomass⁴³. Harvested larvae boast a nutritional profile of 42% crude protein and 29% lipids⁴³. This rich lipid profile provides the dense energy required for rapid fish growth, and the larvae can even be metabolically tailored; feeding the larvae fish offal naturally enhances their omega-3 fatty acid concentrations²¹.

The breeding and reproductive cycle of the adult BSF requires precise environmental management. Once the flies eclose from the pupal stage, peak fertility occurs within a few days. Adult flies require warm conditions for optimal oviposition, with 30°C identified as the optimum temperature for egg-laying, which typically commences 4 to 5 days post-eclosion⁴⁶. While adult flies lack functional mouthparts and do not bite or sting (rendering them entirely non-pestiferous to humans), providing them access to moisture and basic nutrition (such as artificial milk) can triple their longevity and total egg mass, resulting in up to 1,200 eggs per female⁴⁶.

Extensive trials indicate that BSF larvae exhibit maximum biomass conversion when fed substrates like rotting wheat or vegetable matter, yielding up to 185 grams of larvae per kilogram of waste⁴⁴. System modeling dictates an optimal feed load of 18 grams (dry weight) of waste substrate per 1 gram of introduced larvae, with weekly feeding regimes without frass removal proving highly practical for continuous production⁴⁵.

The primary constraint of industrial insect rearing is the labor and energy usually required for harvesting and separation. The BSF, however, possesses a behavioral idiosyncrasy that elegantly circumvents this requirement: the "self-harvesting" instinct. When the larvae reach

the late pre-pupal stage, their digestive tracts empty, they stop feeding, and they undergo an innate photophobic and geotactic drive to migrate away from the moist food source to seek high, dry, and dark crevices in which to pupate⁴³.

By constructing trapezoidal, multi-tiered rearing bins with internal ramp angles of precisely 45 degrees, the system exploits this biological imperative⁴⁷. The pre-pupae instinctively climb the 45-degree slopes and breach the lip of the container, falling passively into collection troughs⁴⁴. Lining these troughs with a layer of dry sand cushions their impact and facilitates easy scooping⁴⁷. This self-harvesting architecture requires zero mechanical energy, eliminates sorting labor, and ensures that only the most mature, nutritionally dense pre-pupae are harvested and delivered to the pond⁴⁵.

5. Water Quality, Biogeochemical Cycling, and Biofloc Integration

In a closed, off-grid pond, the continuous accumulation of metabolic waste and uneaten feed presents a persistent existential threat to the aquatic biomass. Eutrophication leads to toxic ammonia spikes and the proliferation of harmful algal blooms. The pond manager must actively manipulate the carbon, nitrogen, and phosphorus cycles to ensure toxins are continuously assimilated into harmless or directly beneficial compounds.

5.1 The Thermodynamics of Ammonia Toxicity

Nitrogen enters the aquaculture system primarily through feed and exits via fish excretion (branchial ammonia excretion and feces) and the bacterial degradation of organic matter. In the water column, total ammonia nitrogen (TAN) exists in a dynamic, highly volatile equilibrium

between two forms: the highly toxic un-ionized ammonia (NH_3) and the relatively non-toxic ionized ammonium (NH_4^+)⁴⁹.

The balance of this equilibrium is heavily dependent on water temperature and pH, dictated by thermodynamic pKa shifts. At a neutral pH of 7.0 and lower ambient temperatures, over 99% of TAN exists in the benign ammonium form⁵⁰. However, aquacultural reality dictates that pH is rarely static. As photosynthetic organisms (algae and macrophytes) aggressively remove carbon dioxide from the water during daylight hours, the pond's pH rises, becoming increasingly alkaline. Simultaneously, solar radiation heats the water column. This combination forces the chemical equilibrium to shift violently toward the toxic NH_3 state⁵⁰.

For example, at a pH of 8.4 and a temperature of 25°C, approximately 11.4% to 15.0% of the total ammonia nitrogen converts instantly into the highly toxic un-ionized state⁵⁴. Un-ionized ammonia is incredibly lethal, capable of causing gill necrosis, severe growth reduction (by up to 50% at 0.517 mg/L in species like catfish), and mass mortality at concentrations as low as 0.015–0.045 mg/L for coldwater species, and 0.05–0.15 mg/L for warmwater species⁴⁹.

Because a single unit increase in pH results in a massive tenfold logarithmic increase in toxic ammonia concentration, managing the pH—by establishing adequate alkalinity buffering (50 to

200 ppm) and controlling excessive phytoplankton blooms—is far more critical to fish survival than merely monitoring gross TAN levels⁵⁰.

Temperature	pH 7.0	pH 7.5	pH 8.0	pH 8.5	pH 9.0
10°C	0.18%	0.53%	1.82%	5.56%	15.6%
15°C	0.27%	0.76%	2.65%	7.97%	21.5%
20°C	0.40%	1.11%	3.82%	11.1%	28.4%
25°C	0.55%	1.60%	5.28%	15.3%	36.3%
30°C	0.80%	2.24%	7.46%	20.3%	44.6%

Table 2: Percentage of Total Ammonia Nitrogen (TAN) present as toxic un-ionized ammonia (NH_3) across various pH and temperature gradients⁵⁴.

5.2 Nitrogen Mass Balance and Biofloc Technology (BFT)

The fundamental nitrogen utilization efficiency of a traditional intensive aquaculture system is notoriously poor; fish generally retain only 25 to 35 percent of the nitrogen introduced via high-protein feed, excreting up to 75 percent as particulate and dissolved waste directly into the environment⁵⁶. In an integrated, off-grid system, however, this unassimilated nitrogen must be viewed not as pollution, but as a recoverable resource.

The fate of this nitrogen is determined by specific microbial pathways. Under standard oxic conditions, nitrifying bacteria (using enzymes like ammonia monooxygenase and nitrite oxidoreductase) convert toxic ammonia into nitrite and subsequently into nitrate⁵⁹. While this reduces acute ammonia toxicity, it merely transfers the nitrogen into an oxidized pool that still requires removal via denitrification or plant assimilation⁵⁹.

A superior strategy for closed-loop off-grid ponds is the manipulation of the Carbon-to-Nitrogen (C/N) ratio to steer the pond's biogeochemistry from an autotrophic (algae-dominated) state to a heterotrophic (bacterial-dominated) state, commonly known as Biofloc Technology (BFT)⁶⁰. By supplementing the water column with inexpensive, exogenous carbohydrate sources—such as molasses, wheat bran, tapioca, or cassava—the operator artificially elevates the C/N ratio to an optimal range between 10:1 and 15:1⁶⁰.

At this precise ratio, heterotrophic bacteria rapidly outcompete nitrifying bacteria, directly assimilating the dissolved toxic ammonia and converting it into microbial cell mass (protein)⁶⁰. This rapidly growing bacterial biomass clumps together with suspended organic matter to form macro-aggregates (bioflocs). These flocs are actively grazed upon by omnivorous fish like

tilapia and common carp, serving as a highly nutritious secondary feed source⁶¹. This microbial recycling pathway drastically reduces ambient ammonia to non-toxic levels without requiring water exchanges, while simultaneously recovering up to 43% of the previously lost nitrogen and significantly lowering the overall Feed Conversion Ratio (FCR) of the primary feed⁶¹.

Cultured Species	Exogenous Carbon Source	Target C/N Ratio
<i>Oreochromis niloticus</i> (Tilapia)	Wheat flour	8–11
<i>Oreochromis niloticus</i> (Tilapia)	Wheat flour and molasses	15
<i>Cyprinus carpio</i> (Common Carp)	General carbohydrates	20
<i>Litopenaeus vannamei</i> (Shrimp)	Molasses + wheat bran + corn flour	15–16

Table 3: Common exogenous carbon sources and target Carbon-to-Nitrogen (C/N) ratios utilized in Biofloc Technology systems for various aquaculture species⁶⁰.

6. Harmful Algal Blooms (HABs) and Cyanobacteria Management

The ultimate, catastrophic manifestation of uncontrolled eutrophication in a stagnant aquaculture pond is the permanent dominance of Cyanobacteria (blue-green algae). These ancient prokaryotic organisms outcompete beneficial green algae at higher temperatures (>30°C) and under severe nutrient loading conditions, specifically when Total Phosphorus exceeds 24 µg/L and Total Nitrogen exceeds 850 µg/L²⁹.

Cyanobacteria, particularly dominant freshwater genera such as *Microcystis*, *Oscillatoria*, and *Synechococcus*, possess unique evolutionary advantages: they can regulate their buoyancy via gas vacuoles to optimize light capture, they thrive in high temperatures, and certain species can fix atmospheric nitrogen, allowing them to dominate even in nitrogen-depleted waters³⁸. More critically, these blooms produce potent secondary metabolites known as cyanotoxins. Microcystins (e.g., MC-LR) are severe hepatotoxins; in field studies of tropical aquaculture ponds, up to 75% of sampled waters contained unsafe levels of microcystin, reaching concentrations as high as 295.86 µg/L²⁹. These toxins bioaccumulate in fish tissues, causing histopathological damage to vital organs, suppressing immune function, stunting growth, and posing severe, acute health risks (including liver cancers, ALS, and neurodegeneration) to

humans who consume the contaminated fish or are exposed to aerosolized toxins²⁹.

Traditional reactive treatments utilizing heavy copper-based algaecides are dangerously counterproductive in a closed pond. Algaecides indiscriminately lyse the cyanobacteria cells, releasing a massive, acute wave of previously contained intracellular toxins directly into the water column, while simultaneously causing a catastrophic crash in dissolved oxygen as the dead bacterial biomass decays³⁷.

In a sustainable off-grid context, proactive biological control is paramount. Cyanobacteria thrive when decomposing organic material releases natural oils and lipids that increase the water's surface tension, limiting atmospheric oxygen exchange and creating an oxygen-starved environment⁶³. Introducing naturally occurring, non-toxic *Bacillus* bacteria (via biological enhancement products) disrupts this cycle. *Bacillus* strains rapidly degrade the accumulated natural oils, reducing surface tension and restoring oxygen transfer⁶³. Furthermore, they vigorously compete for the exact nutrients (phosphorus) that fuel the cyanobacteria, shifting the microbial balance back in favor of non-toxic diatoms and nitrifiers, ultimately collapsing the harmful bloom organically without triggering a mass toxin release⁶³.

7. Passive Filtration: Subsurface Flow Constructed Wetlands

To prevent the continual accumulation of unassimilated nitrates, phosphates, and suspended solids without relying on energy-intensive mechanical drum filters or pressurized bead filters, an off-grid aquaculture system benefits immensely from the integration of a Subsurface Horizontal Flow Constructed Wetland (SSHF-CW). Operating entirely via gravity, these wetlands act as perpetual, passive biological kidneys for the pond.

In this architecture, wastewater from the primary pond is routed into a shallow, geolined basin (typically 0.6 to 1.0 meters deep) filled with a porous aggregate media such as gravel, and planted with dense emergent macrophytes (e.g., *Phragmites* or water spinach, *Ipomoea aquatica*)⁶⁶. As the effluent flows horizontally below the surface of the gravel, physical filtration traps suspended solids within the matrix, preventing them from returning to the pond. Simultaneously, the expansive surface area of the gravel and the intricate root zones of the macrophytes host vast colonies of nitrifying and denitrifying bacteria, which strip dissolved nutrients from the water⁶⁷.

The hydraulic behavior of the wetland is primarily governed by Darcy's Law, which describes linear fluid flow through porous media:

$$Q = -KA \frac{dh}{dl}$$

Where Q is the volumetric flow rate, K is the hydraulic conductivity of the gravel substrate, A is the cross-sectional area of the wetland, and dh/dl is the hydraulic gradient⁶⁹. For more

complex coastal or brackish water ponds where freshwater effluent mixes with saltwater, models may extend to the Brinkman Equation to account for kinetic energy dissipations due to viscous shear in density-driven dispersion zones, though standard Darcy models suffice for strictly freshwater sizing⁶⁹.

Proper volumetric sizing is critical to ensure an adequate hydraulic retention time (HRT).

General engineering heuristics dictate that the constructed wetland area should encompass

approximately 10 percent of the total aquaculture surface area, or roughly 1.3 to 1.5 m^2 of wetland per 0.1 liters/second of continuous effluent flow⁶⁶.

When properly dimensioned, these passive systems exhibit extraordinary remediation metrics. Empirical studies on intensive farm effluents demonstrate that SSHF-CWs can achieve removal efficiencies of over 90% for Total Suspended Solids (TSS) and up to 87.8% for Total Ammonia Nitrogen (TAN)⁶⁸. By continuously polishing the water, the integration of a constructed wetland allows operators to increase the safe fish biomass stocking density of the primary pond by up to 40% without destabilizing the baseline water quality or risking anoxia⁷².

8. Proactive Pathogen Management: Salt Bath Therapeutics

In highly constrained off-grid scenarios, rapid access to synthesized chemotherapeutics, antibiotics, and commercial parasiticides is frequently impossible. Disease management must therefore rely heavily on prophylactic husbandry, maintaining low environmental stress, and deploying universally accessible, broad-spectrum treatments.

Sodium chloride (NaCl) remains the most potent, inexpensive, and universally available therapeutic tool for off-grid disease mitigation. Elevated salinity leverages fundamental principles of osmosis; it violently disrupts the osmotic balance of highly susceptible single-celled and small multicellular freshwater ectoparasites, inducing rapid dehydration and death, without permanently harming the more complex, osmoregulator-equipped teleost host⁷³.

Short-term, high-concentration salt baths are remarkably effective at eradicating some of the most devastating and common afflictions in cyprinid and salmonid aquaculture, including *Ichthyophthirius multifiliis* (White Spot Disease), *Trichodina*, and monogenean trematodes like *Gyrodactylus* (*G. bullatarudis*, *G. turnbulli*) and *Dactylogyrus extensus*⁷³.

For acute therapeutic intervention, infected fish are carefully seined from the main pond and immersed in a heavily aerated quarantine bath containing 25 to 30 g/L (2.5% to 3.0%) of sodium chloride⁷³. The exposure time must be strictly monitored and limited to 10 to 30 minutes, closely observing the fish for signs of distress or loss of equilibrium⁷³. This intense osmotic shock causes the rapid lysis of parasitic trophonts and forces entrenched trematodes to detach from the delicate gill filaments and epidermis. Experimental trials confirm that this method achieves clearance rates approaching 100% for stubborn species like *G. turnbulli*⁷³.

While the high-concentration bath induces acute physiological changes in the fish—including temporary spikes in hematocrit, plasmatic lactate, and cholesterol—these effects are transient. Blood chemistry typically returns to normal baseline levels within 24 to 48 hours⁷⁴. Following the

bath, the fish are returned to the primary pond, benefiting additionally from the salt's secondary effect: the stimulation of the protective epidermal slime coat and a reduction in the osmoregulatory stress induced by the handling process itself⁷⁴. For chronic, low-level infections of parasites like *Trichodina*, a continuous, lower-dose exposure of 6 g/L applied over a 21-day period has also proven completely effective in eliminating the pathogen without causing acute stress to the host⁷³.

Conclusion

The successful engineering, construction, and operation of an off-grid freshwater aquaculture pond fundamentally reject the fragmented, input-heavy approach of modern industrial aquaculture. By treating the pond as a holistic, thermodynamically closed ecological loop, systemic vulnerabilities are engineered out of the facility at the design phase. Ensuring strict geotechnical parameters, compaction ratios, and core trenching during earthworks guarantees a watertight, physically stable vessel capable of withstanding decades of hydrostatic pressure. Aligning species selection with localized thermal dynamics, and utilizing polyculture to exploit every trophic niche, maximizes biological efficiency and eliminates feed waste.

Crucially, replacing grid-dependent mechanical life support with solar-pneumatic airlift systems harmonizes aeration with the natural diurnal peak in biological oxygen demand, providing massive fluid displacement with minimal energetic cost. By converting terrestrial agricultural waste into dense lipids via the self-harvesting mechanisms of the Black Soldier Fly, and by utilizing the pond's own nitrogenous effluent to cultivate high-protein duckweed, the system achieves near-total feed autonomy. Finally, routing waste streams through gravity-fed subsurface constructed wetlands and actively manipulating the Carbon-to-Nitrogen ratio to encourage biofloc assimilation ensures that the very toxins that typically plague intensive aquaculture are upcycled into secondary yields.

When orchestrated with precision, this synthesis of civil engineering, fluid dynamics, and applied ecology results in a highly resilient, exceptionally productive, and indefinitely sustainable aquaculture system that operates entirely independent of external infrastructure.

Works cited

1. Fish farm design and pond construction for small ... - ResearchGate, https://www.researchgate.net/publication/334989537_FISH_FARM_DESIGN_AND_POND_CONSTRUCTION_FOR_SMALL_SCALE_FISH_FARMING_IN_MANIPUR
2. 1. General Background, https://www.fao.org/fishery/static/FAO_Training/FAO_Training/General/x6708e/x6708e01.htm
3. Ponds | CABI Compendium, <https://www.cabidigitallibrary.org/doi/full/10.1079/cabicompendium.68544>
4. Pond Construction Training Guide | PDF | Soil | Ph - Scribd, <https://www.scribd.com/document/245228239/Guidance-on-Pond-Construction-2>
5. Pond Construction for Aquaculture: Site Selection and Earthworks, <https://www.zubairkhalid.com/knowledge/animal-farming/aquaculture/pond-cons>

- [truction-aquaculture-site-selection-earthworks](#)
6. 12. Soils And Freshwater Fish Culture,
https://www.fao.org/fishery/static/FAO_Training/FAO_Training/General/x6706e/x6706e12.htm
 7. 6. Fish Pond Construction,
https://www.fao.org/fishery/static/FAO_Training/FAO_Training/General/x6708e/x6708e06.htm
 8. Water temperature in aquaculture - Responsible Seafood Advocate,
<https://www.globalseafood.org/advocate/water-temperature-in-aquaculture/>
 9. technological aspects of coldwater fish culture,
<https://www.fao.org/4/t5817e/T5817E01.htm>
 10. Survival rate of different tilapia varieties during winter. A,
https://www.researchgate.net/figure/Survival-rate-of-different-tilapia-varieties-during-winter-A-survival-as-a-function-of_fig2_385783726
 11. Review of Central-Eastern European Propagation and Larvae,
<https://www.mdpi.com/2075-1729/13/12/2334>
 12. Overwintering of farmed common carp (Cyprinus carpio L.) in the,
<https://www.cyprinus.at/daten/aquaculture241.pdf>
 13. SPECIES DURING THE COLD SEASON IN THE CONTEXT OF,
https://www.animalsciencejournal.usamv.ro/pdf/2024/issue_1/Art82.pdf
 14. #1 Rainbow trout | CERES, <https://ceresproject.eu/1-rainbow-trout/>
 15. Growth Performance of Common Carp (Cyprinus carpio) in Earthen,
https://www.researchgate.net/publication/339882984_Growth_Performance_of_Common_Carp_Cyprinus_carpio_in_Earthen_Ponds_in_Basrah_Province_Iraq_by_Using_Different_Stocking_Densities
 16. 27777198.pdf - Open Research Online,
<https://oro.open.ac.uk/65772/1/27777198.pdf>
 17. 15 N tracer application to evaluate nitrogen dynamics of food webs,
https://www.researchgate.net/publication/263707788_15_N_tracer_application_to_evaluate_nitrogen_dynamics_of_food_webs_in_two_subtropical_small-scale_aquaculture_ponds_under_different_managements
 18. (PDF) Integrated cage-pond carp farming for increased aquaculture,
https://www.researchgate.net/publication/373735128_Integrated_cage-pond_carp_farming_for_increased_aquaculture_production
 19. (PDF) Standardization of stocking density for maximizing biomass,
https://www.researchgate.net/publication/315462201_Standardization_of_stocking_density_for_maximizing_biomass_production_of_Pangasius_pangasius_in_pond_cage_aquaculture
 20. Airlift Pump Innovations for Aquaponics | PDF - Scribd,
<https://www.scribd.com/document/685415915/Echo-Asia-Note-Issue-44>
 21. The scheme of submergence ratio (ϵ) in the airlift pumping systems,
https://www.researchgate.net/figure/The-scheme-of-submergence-ratio-e-in-the-airlift-pumping-systems-a-high-submergence_fig1_331284152
 22. A Comprehensive Review of Design and Operational Parameters,
<https://www.iicta.org/download/file/fid/100676>

23. Theoretical Investigation of Solar Bubble Pump to Lift Water,
https://www.researchgate.net/publication/389138574_Theoretical_Investigation_of_Solar_Bubble_Pump_to_Lift_Water
24. Experimental investigation of solar air lift pump seasonal,
https://www.researchgate.net/publication/398466603_Experimental_investigation_of_solar_air_lift_pump_seasonal_performance_and_efficiency
25. Compressed Air Lift: How It Works, Diagram & Examples | FIRGELLI,
<https://www.firgelliauto.com/blogs/mechanisms/compressed-air-lift>
26. Airlift Pump Design for Aquaculture | PDF - Scribd,
<https://www.scribd.com/document/94949261/Airlift-Pump-Article-1987-1>
27. Airlift Pump Performance in Aquaculture | PDF - Scribd,
<https://www.scribd.com/document/248547079/Airlift-Pump>
28. Low Energy Aquaponics - LEAP - Permies.com,
<https://permies.com/t/12615/Energy-Aquaponics-LEAP>
29. (PDF) Cyanobacteria in aquaculture systems: linking the occurrence,
https://www.researchgate.net/publication/309241445_Cyanobacteria_in_aquaculture_systems_linking_the_occurrence_abundance_and_toxicity_with_rising_temperatures
30. Find the right Air Pump for Your Pond with our Online Calculator,
<https://evolutionaqua.com/pond-air-pump-calculator>
31. Solar-Powered Water Circulation System | FloLyt™ by FloNergia,
<https://www.flonergia.com/flolyt-airlift-pump-technology>
32. What Size Solar Battery Do I Need? A Step-by-Step Calculation Guide,
<https://www.solaxpower.com/blogs/what-size-solar-battery-do-i-need.html>
33. System Sizing - IEA SHC,
https://task16.iea-shc.org/Data/Sites/1/publications/task16-photovoltaics_in_buildings-p3.pdf
34. Sustainable tilapia culture: The potential of duckweed,
<https://www.globalseafood.org/advocate/sustainable-tilapia-culture-the-potential-of-duckweed/>
35. Production, chemical quality and use of duckweeds (Lemnaceae) in,
https://www.researchgate.net/publication/229610034_PRODUCTION_CHEMICAL_QUALITY_AND_USE_OF_DUCKWEEDS_LEMNACEAE_IN_AQUACULTURE_WASTE_MANAGEMENT_AND_ANIMAL_FEEDS
36. Duckweed Protein Market Size,Trends ,and Share, Growth, Report,
<https://www.industryresearch.biz/market-reports/duckweed-protein-market-102548>
37. Blue Green Algae in Ponds | Treating Cyanobacteria Harmful Algae,
<https://nationalpondservice.com/blue-green-algae-in-ponds-treating-cyanobacteria-harmful-algae-blooms/>
38. Cyanobacteria 101 - Natural Lake Biosciences,
<https://naturallake.com/cyanobacteria-101/>
39. Easy DIY Portal For Duckweed! - YouTube,
<https://www.youtube.com/shorts/bN3dBomleiw>
40. Wastewater-grown duckweed may be safely used as fish feed,

- https://www.researchgate.net/publication/8649301_Wastewater-grown_duckweed_may_be_safely_used_as_fish_feed
41. Wastewater-grown duckweed may be safely used as fish feed.,
<https://www.semanticscholar.org/paper/7fd747dabd0b3b1286698eb3853dd26593fb01ce>
 42. Duckweed Aquaculture - Sustainable Sanitation Alliance,
<https://www.susana.org/knowledge-hub/resources?id=3063>
 43. Review of Black Soldier Fly (*Hermetia illucens*) as Animal Feed and,
<https://pmc.ncbi.nlm.nih.gov/articles/PMC5664030/>
 44. (PDF) Development of Black Soldier Fly Larvae Production,
https://www.researchgate.net/publication/372415609_Development_of_Black_Soldier_Fly_Larvae_Production_Technique_as_an_Alternate_Fish_Feed
 45. Rearing black soldier fly to convert spent grain to high value biomass,
<https://mro.massey.ac.nz/server/api/core/bitstreams/2aace57f-d731-458b-a0b2-e0a323d1886c/content>
 46. A decade of advances in black soldier fly research - TiHo eLib,
https://elib.tiho-hannover.de/servlets/MCRFileNodeServlet/tiho_derivate_00003395/jiff-article-p219_1.pdf
 47. Black soldier fly larval production in a stacked production system,
<https://www.globalseafood.org/advocate/black-soldier-fly-larval-production-in-a-stacked-production-system/>
 48. Do It by Yourself: Larval Locomotion in the Black Soldier Fly ... - MDPI,
<https://www.mdpi.com/2075-4450/13/2/127>
 49. Ammonia toxicity degrades animal health, growth,
<https://www.globalseafood.org/advocate/ammonia-toxicity-degrades-animal-health-growth/>
 50. Managing Water Quality in Aquaculture - pHionics,
<https://www.phionics.com/2021/01/14/managing-water-quality-in-aquaculture/>
 51. How To Measure Un-Ionized Ammonia Sampled From An Aquatic,
<https://www.aquaticed.com/blogs/deeper-dive/how-to-measure-un-ionized-ammonia-sampled-from-an-aquatic-system>
 52. What concentration of ammonia is toxic to fish? - Hach Support!,
https://support.hach.com/myhach/s/article/KA-en-US-TE129-1000058?language=en_US
 53. pH in Fish Farming | Yokogawa Deutschland GmbH,
<https://www.yokogawa.com/de/library/resources/application-notes/ph-in-fish-farming/>
 54. 18. Nitrogen, <https://www.fao.org/4/ac175e/AC175E18.htm>
 55. Important Water Quality Parameters in Aquaponics Systems,
https://pubs.nmsu.edu/_circulars/CR680/
 56. Advancing Biofloc Aquaponics: Effects of Hydraulic Configuration,
<https://etd.auburn.edu/bitstream/handle/10415/10385/Dissertation-Shima%20Rezaei%20v2.pdf?sequence=2&isAllowed=y>
 57. Environmental Impacts of Wastes and Contaminants ... - IntechOpen,
<https://www.intechopen.com/chapters/89159>

58. Nitrogen transformations and fluxes in fish ponds - WUR eDepot,
<https://edepot.wur.nl/196953>
59. Nitrogen Metabolism and Pathogen Feedback in Intensive ... - MDPI,
<https://www.mdpi.com/2504-3129/7/3/84>
60. Biofloc Systems for Sustainable Production of Economically,
<https://d-nb.info/1239655940/34>
61. Growth Response and Survival Rate of Cirrhinus Mrigala Culture in,
<https://www.tejee.net/pdf-215935-134034?filename=Growth-Response-and-Survival.pdf>
62. Biofloc Microbiome With Bioremediation and Health Benefits - PMC,
<https://pmc.ncbi.nlm.nih.gov/articles/PMC8667556/>
63. How Bacillus Controls Cyanobacteria and Restores Ecosystem,
<https://www.marineeasyclean.com.au/wp-content/uploads/2025/08/Cyanobacteria-Control.pdf>
64. Occurrence of Cyanobacteria and microcystins in hydroelectric,
<https://iwaponline.com/jwh/article/18/6/983/77959/Occurrence-of-Cyanobacteria-and-microcystins-in>
65. An International Survey of Cyanobacteria Risk Management ... - PMC,
<https://pmc.ncbi.nlm.nih.gov/articles/PMC13447553/>
66. Treatment of Bullfrog Farming Wastewater in a Constructed Wetland,
<https://www.scirp.org/journal/paperinformation?paperid=76158>
67. Constructed Wetlands as a Landscape Management Practice for,
<https://www.mdpi.com/2073-4441/13/21/2973>
68. Constructed Wetlands as a Treatment Method for Effluents from,
https://www.researchgate.net/publication/229416126_Constructed_Wetlands_as_a_Treatment_Method_for_Effluents_from_Intensive_Trout_Farms
69. Comparing Darcy's Law and the Brinkman Equation for Numerical,
<https://www.mdpi.com/2071-1050/15/18/13287>
70. Development of a Constructed Subsurface-Flow Wetland Simulation,
https://www.researchgate.net/publication/222974515_Development_of_a_Constructed_Subsurface-Flow_Wetland_Simulation_Model
71. Modelling and simulation of subsurface horizontal flow constructed,
https://www.researchgate.net/publication/359111215_Modelling_and_simulation_of_subsurface_horizontal_flow_constructed_wetlands
72. The Integration of a Constructed Wetland into a Recirculating Hatchery,
<https://pmc.ncbi.nlm.nih.gov/articles/PMC4390338/>
73. Treatment of gyrodactylid infections on ornamental guppies, Poecilia,
https://www.researchgate.net/publication/236162440_The_salt_myth_revealed_Treatment_of_gyrodactylid_infections_on_ornamental_guppies_Poecilia_reticulata
74. (PDF) Sodium chloride bath - A cheap and safe tool for antiparasitic,
https://www.researchgate.net/publication/355263574_Sodium_chloride_bath_-_A_cheap_and_safe_tool_for_antiparasitic_treatment_of_fish
75. (PDF) Efficacy of sea salt, metronidazole and formalinmalachite,
https://www.researchgate.net/publication/272015612_Efficacy_of_sea_salt_metronidazole_and_formalinmalachite_green_baths_in_treating_Ichthyophthirius_multfi

[liis_infections_of_mollies_Poecilia_sphenops](#)

76. Guidelines for Fish Health Management in Northeastern States,
[https://dnr.maryland.gov/fisheries/documents/NEFHC_Fish_Health_GUIDELINES.p](https://dnr.maryland.gov/fisheries/documents/NEFHC_Fish_Health_GUIDELINES.pdf)
[df](#)