



## Biological Processes Governing Advanced Treatment in Algal Pond Systems

Gauti Herlitz\*

*Department of Water and Environmental Studies, Linköping University, Linköping, Sweden*

### DESCRIPTION

High rate algal ponds have gained attention as an effective and sustainable approach for advanced wastewater treatment. These systems integrate biological nutrient removal with biomass production by combining algal photosynthesis and bacterial metabolism. In recent years, their application has expanded beyond secondary treatment to include tertiary and quaternary treatment stages, where the objectives include polishing of nutrients, reduction of organic residues, pathogen control, and improvement of effluent quality for reuse or safe discharge. Among the operational parameters that shape the performance of high rate algal ponds, hydraulic retention time plays a defining role in determining treatment efficiency, biomass dynamics, and system stability.

Phosphorus removal in high rate algal ponds is closely tied to algal growth and sedimentation processes. Algae assimilate phosphorus during cellular synthesis, while particulate phosphorus can settle along with biomass. Hydraulic retention time affects both processes by influencing growth cycles and settling velocity. Moderate retention times often support optimal phosphorus uptake and biomass formation, while shorter retention may limit assimilation due to insufficient contact time. Conversely, overly long retention may promote internal recycling of phosphorus from decaying biomass, which can reduce net removal in tertiary treatment scenarios.

Organic matter reduction during tertiary treatment is typically measured by parameters such as chemical oxygen demand or biochemical oxygen demand. Although much of the biodegradable organic load is removed in earlier treatment stages, residual compounds remain that can affect receiving waters. Retention time influences the extent to which heterotrophic bacteria degrade these compounds within algal ponds. Adequate retention supports bacterial activity and oxygen production from algae, facilitating further oxidation of organic matter. Short retention periods may result in incomplete treatment, while very long periods may yield diminishing returns due to low substrate availability.

When high rate algal ponds are applied for quaternary treatment, the focus shifts toward polishing effluent quality to meet stringent reuse or discharge standards. This stage may involve pathogen reduction, removal of trace nutrients, and stabilization of effluent characteristics. Hydraulic retention time plays a key role in pathogen inactivation through prolonged exposure to sunlight, elevated oxygen levels, and biological antagonism. Longer retention times generally enhance pathogen reduction by increasing exposure to ultraviolet radiation and oxidative conditions. However, excessive retention can lead to biomass accumulation that reduces light penetration, potentially counteracting disinfection effects.

Biomass dynamics within high rate algal ponds are closely connected to hydraulic retention time. Short retention periods tend to favor fast-growing algal species that can reproduce rapidly, while longer retention allows slower-growing but potentially more resilient species to establish. Changes in community structure can affect treatment performance, settling characteristics, and downstream processing of biomass. In tertiary and quaternary treatment systems, maintaining a stable and harvestable algal population is important for both nutrient removal and operational efficiency. Retention time adjustments must therefore balance treatment goals with biomass management considerations.

Operational stability is another aspect influenced by hydraulic retention time. Fluctuations in influent quality, temperature, and light availability can challenge system performance. Retention time acts as a buffering factor, smoothing short-term variations and supporting consistent treatment outcomes. Longer retention provides greater resilience against shock loads or transient changes, while shorter retention increases sensitivity to influent variability. In advanced treatment applications, where effluent quality requirements are strict, this buffering capacity becomes particularly relevant.

Energy efficiency is another factor indirectly affected by hydraulic retention time. High rate algal ponds rely primarily on natural sunlight and biological processes, making them attractive for low-energy treatment. However, extended retention times

**Correspondence to:** Gauti Herlitz, Department of Water and Environmental Studies, Linköping University, Linköping, Sweden, E-mail: gauti.herlitz@hjl.gu.se

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may require additional mixing or harvesting efforts to prevent biomass overgrowth and maintain performance. Shorter retention times may reduce these demands but risk insufficient treatment. Finding an appropriate retention window supports energy-efficient operation while meeting treatment objectives.

Environmental conditions such as temperature and solar radiation interact with hydraulic retention time to shape system behavior. In warmer climates with high light availability, shorter retention times may still support effective tertiary and quaternary treatment due to rapid algal growth and metabolic activity. In cooler or less sunny regions, longer retention may be necessary to compensate for reduced biological rates. Seasonal variation further complicates retention time optimization, suggesting that flexible or adaptive operation may improve year-round performance.

Evaluation of hydraulic retention time effects requires integrated monitoring of physical, chemical, and biological parameters. Measuring nutrient concentrations, organic matter indicators, biomass density, and microbial composition provides insight into how retention influences treatment processes. Such

assessments support evidence-based adjustments and inform design guidelines for advanced algal pond systems. Comparative studies across different retention regimes have shown that no single value is universally optimal, emphasizing the need for site-specific evaluation.

In conclusion, hydraulic retention time is a central operational factor governing the performance of high rate algal ponds used for tertiary and quaternary wastewater treatment. It influences nutrient removal, organic matter reduction, pathogen control, biomass dynamics, and system stability. While longer retention generally supports more complete treatment, excessively extended periods may introduce challenges related to biomass decay, land use, and diminishing returns. Conversely, very short retention can compromise effluent quality and operational resilience. Effective assessment and optimization of retention time require consideration of treatment objectives, environmental conditions, and practical constraints. Through informed design and adaptive management, high rate algal ponds can serve as efficient and sustainable solutions for advanced wastewater treatment applications.