Wastewater Pond Technology

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Introduction

Waste stabilisation ponds (WSP) are widely used around the world to treat biodegradable wastewaters using natural processes. The main variants of stabilisation ponds are anaerobic and facultative ponds, which aim primarily at organic matter removal, and maturation ponds, whose main target is the removal of pathogenic microorganisms. Facultative and maturation ponds rely upon the production of oxygen by algae during photosynthesis, and the utilisation of the surplus oxygen by the heterotrophic bacteria responsible for major pollutant conversion processes. There are also mechanised variants, such as aerated lagoons and high-rate algal ponds. The appropriate design for a WSP system depends on wastewater characteristics, the treatment objectives, climate, and available land area. A recent innovation in the design of anaerobic ponds is the high-rate anaerobic pond (HRAnP) concept that includes a mixing pit, biogas collection, and settling compartment. This new concept combines the best of both, high-rate and low-rate anaerobic reactors.

There are many thousands of ponds in operation worldwide. They are particularly well suited for treating wastewater from small communities, although they can be used for large cities as well (e.g. a 350-acre WSP system provides treatment for about half of the wastewater from the city of Melbourne, Australia). Developing countries with large numbers of pond systems include Brazil, Mexico, Honduras, and Uganda. Industrialised countries with large numbers of pond systems include New Zealand, the United States, Australia, Germany and France. New pond systems are expected to play a significant role in achieving Sustainable Development Goal 6.3, which requires reducing the discharge of untreated wastewater by 50% around the world.

Although ponds are simple to design, build, and operate, the hydrodynamics as well as the physical, chemical, and biological treatment processes occurring in them are incredibly complex. Much of the research conducted by members of the Specialist Group focuses on advancing the understanding of these interdependent processes. Applied research is also being conducted to understand how to ensure successful operation and maintenance (such as sludge removal and conditioning) of pond systems.

Current state of knowledge and practice

Waste stabilisation ponds are simple to design, build and operate. Their dimensioning usually uses reasonably well-known recommended organic loading rates, hydraulic retention times and first-order rate constants. Their detailed design has traditionally concentrated mainly on the configuration and positioning of inlet and outlet structures and on protection and sealing of embankments and pond bottom. Their construction is simple, comprising mainly earth movement. Routine operation is indeed trouble free, and is more related to maintenance practices than to proper operational control measures with the exception of flow measurement and control. Un-mechanised ponds do not involve electromechanical equipment and do not consume electricity. If located down gradient from the service area such that the sewer system can operate solely with gravity flow, the entire collection and treatment system can operate with no electricity.

WSP systems are particularly well suited for production of recycled water for irrigation of agricultural crops or landscapes. Removal of pathogens is essential for water reuse, and well-designed and operated WSP systems are capable of high levels of removal of pathogens and indicator organisms. Effluents from facultative ponds are usually suitable for restricted irrigation (good helminth egg removal), and effluents from a series of maturation ponds may be fit for unrestricted irrigation (irrigation of crops that are eaten uncooked or unpeeled), as these ponds are able to remove coliforms to low counts and comply with the World Health Organization guidelines. This type of reuse has the benefit of recovering not only the water but also organic matter and nutrients contained in the water; the algae in the effluent may also beneficial for soil. Irrigation with pond effluents is successfully done in several countries around the world, especially those located in arid or semi-arid regions. However, it is felt that much more could be done to expand the use of WSP systems for water reuse. New institutional arrangements as well as good risk-management regulations may be required to link treated effluent producers (sanitation companies) and farmers.

Mechanised ponds involve the addition of paddle wheels to provide mixing in raceway high-rate algal pond (HRAP) configurations, or surface aerators to provide mixing and enhance aeration. HRAP and other mechanised ponds can be used to maximise algae production for subsequent recovery of energy in the form of biogas (via anaerobic digestion of the algal biomass) or hydrocarbons that can be further refined into solid or liquid fuels. Pond systems can also be integrated with some other unit processes such as up-flow anaerobic sludge blanket reactors (UASB), constructed wetlands, and additional disinfection such as ultraviolet light (UV).

Some limitations, which are context-specific to the application of WSP systems, include: the large land requirements, high-suspended solids in the effluent, and risk of bad odours in anaerobic ponds. Each of these issues is discussed below.

Reduction of land requirements

In warm-climate regions, facultative ponds usually require between 2 and 4 m^2 per inhabitant. In temperate climates, approximately double the area is required and in cold climates (where pond systems are also used), larger land requirements are observed. If a series of maturation ponds are included in the treatment line, the total area may double. This poses a practical limitation, because in some locations a suitably large area, with sufficient gradient and good soil is not available in the vicinity of the community.

To increase ponds applicability, a reduction of land requirements is obviously welcome. The inclusion of anaerobic ponds ahead of the facultative ponds may reduce the area to around two-thirds of that needed for facultative ponds only. In some warm-climate countries, upflow anaerobic sludge blanket (UASB) reactors are replacing the anaerobic and facultative ponds, and the overall system of UASB reactors plus maturation ponds becomes smaller (but still land intensive). In this sense, the development of the HRAnP mentioned earlier has the same effect of the UASB reactor and reduces the footprint of the WSP systems down waters somewhere between 25% and 30% depending on the average water temperature.

Reduction of suspended solids in the effluent

Well operating facultative and maturation ponds rely on a good production of microalgae, which are responsible for photosynthesis. However, a large amount of these algae leave with the final effluent, and are responsible for the increase of suspended solids and particulate BOD in the wastewater discharged to water bodies. If the effluent from a pond needs to have its quality improved in terms of organic matter and suspended solids, then algae removal is a good choice.

Some of the possibilities are (1) intermittent sand filters, (2) rock filters, (3) micro-sieves, (4) ponds with floating macrophytes, (5) land application, (6) wetlands, (7) coagulation and clarification processes, (8) flotation, (9) aerated biofilters and (10) trickling filters.

Sand filtration produces an effluent with excellent quality, but tend to clog very quickly. Coarse rock filtration is not so efficient, but gives a good contribution and is much less prone to clogging (they can run for years without cleaning). Recent experiments with aerated rock filters have shown good removal of other constituents, such as coliforms. Floating macrophytes, such as duckweed, are used in several ponds in order to reduce sunlight penetration and thus decrease algal growth. These ponds give the possibility of using the high-protein content duckweed for fish ponds, but require a good strategy for their removal from the pond surface.

The inclusion of any of these processes, especially the mechanised ones, should naturally find a justification from the point of view of the needs of the receiving water body (and not only as a safeguard in terms of compliance to discharge standards), since they imply an elevation of the treatment costs and operational complexity. Wastewater treatment by ponds must remain simple, and the challenge here is to improve their effluent quality without deviating from the primary characteristic of conceptual simplicity.

Reduction of risks of malodours from anaerobic ponds

Anaerobic ponds are open anaerobic reactors, and thus may be subject to the release of malodorous gases, especially hydrogen sulphide. Substantial experience exists on how to reduce these risks, based on the implementation of ponds far away from houses, adoption of suitable organic loading rates, a good knowledge of the influent characteristics (amount of sulphate in the wastewater) and the utilisation of inlet pipes close to the pond bottom, to allow good contact between organic matter and biomass. However, because a natural treatment process is being used, there is always the risk that during a certain period something will not go on as planned, and obnoxious odours may be emanated.

Some anaerobic ponds are being covered to capture the gas and thus control their release into the atmosphere. This also creates the opportunity of biogas utilisation and carbon credits compensation. However, in many cases the anaerobic ponds are very large, and the challenge is to reliably cover a large surface area without allowing gases to escape, and still keeping simplicity as a key element. The HRAnP has a mixing chamber such that biogas collection occurs in the first quarter to third of the length, so this makes it easier to cover a smaller area and help to control bad odours.

Recent advances and hot topics

Pathogen removal mechanisms and design equations

Ponds are very important natural treatment systems for the removal of pathogenic organisms. Design equations are available to estimate the removal of helminth eggs, protozoan cysts, and faecal indicator bacteria. Current research is being conducted to develop an empirical design equation for the removal of viruses by WSP, based on performance data from many pond systems.

The main mechanism of removal for helminth eggs is sedimentation. Protozoan cysts may also be removed by sedimentation; although their settling rates are quite slow so long hydraulic retention times are required. Individual bacteria and viruses cannot be removed by sedimentation, but if they are attached to larger particles they can be removed by this mechanism. A recent review paper identified that virus attachment to solids and removal by settling is a significant knowledge gap, with conflicting reports in the literature. Current research aims at filling this knowledge gap by quantifying the fraction of different viruses associated with particles in different size ranges. It should be noted that pathogens that are removed by settling are concentrated in the sludge layer. It has been documented previously that pathogens, especially *Ascaris* eggs, can persist in pond sludge for many years. Thus, sludge that is removed from ponds (a critical maintenance activity in primary ponds) must be treated to reduce the concentration of viable pathogens.

Bacteria and viruses are mainly removed by inactivation mechanisms, especially in maturation ponds. Potential mechanisms include sunlight inactivation, predation, degradation by enzymes, and stress due to unfavourable environmental conditions. Of these three, sunlight inactivation is the best understood, and has the greatest potential to be exploited to achieve high removals in maturation ponds. Recent research provided evidence that echovirus was degraded by proteases in WSP water whereas MS2 coliphage was not. The significance of this mechanism in actual WSP systems is not yet known, but this is an exciting area for future research.

The mechanisms of sunlight inactivation are now fairly well understood because of recent research. Endogenous damage occurs when chromophores in microorganisms absorb sunlight photons leading to damage. Direct damage may occur to the chromophores (this is particularly important in viruses). Indirect damage may also occur, if the excited chromophores produce highly reactive transient species, which subsequently cause damage. Exogenous damage may occur if chromophores in the water (i.e., sensitisers) absorb light and produce reactive species that subsequently cause damage to microorganisms. Organic matter and algae are believed to be the main sources of sensitisers. Thus, organic matter has two competing effects on pathogen inactivation: it decreases inactivation by the endogenous mechanism by absorbing light, and simultaneously increases inactivation by the exogenous mechanism. Because different organisms have different susceptibility to endogenous vs. exogenous mechanisms, their relative rates of inactivation can vary depending on the water quality and specific conditions. In particular for bacteria, these mechanisms are influenced by environmental conditions in the ponds, such as dissolved oxygen, pH, and temperature. Current research is aimed at quantifying the individual and combined effects of these factors. Priorities for future research include continuing to understand the targets of damage, the susceptibility of pathogens of concern, and the influence of environmental conditions.

Models to estimate the inactivation of viruses and bacteria by sunlight in WSP have been developed, taking into account the individual mechanisms. A priority for future research is to further validate these models in full-scale ponds, with different designs and conditions. The prediction of pathogen removal efficiency involves not only the kinetic aspects of inactivation, but also the hydraulic behaviour of the ponds, which are influenced by the presence of baffles, the length-to-width ratio and the placement of inlet and outlet structures. Advancements in this field have been achieved, as discussed further below.

Understanding the mechanisms of nutrient removal

Removal of nutrients (nitrogen and phosphorus) by WSPs is highly dependent on the system design. Although simple pond systems (one to three un-mechanised ponds in series) do not typically provide much removal, specific configurations, such as maturation ponds and high-rate algal ponds are able to achieve high nitrogen removals. In the literature, classical mechanisms for N removal are reported to be: assimilation of ammonia and nitrate by algal biomass, conventional nitrification-denitrification, sedimentation of dead biomass, accumulation and decomposition on sludge layer after partial hydrolysis, as well as some degree of ammonia volatilisation. Amongst those, ammonia volatilisation due to high pH induced by photosynthesis has been frequently referred to as the main mechanism. However, recent researches are pointing out that this may not be the case. Tracer experiments with ^{15}N-stable isotopes and field measurements of actual ammonia lost by volatilisation have shown that the fraction of N removed by this mechanism may be small and have only a minor influence on the overall removal. Nitrification has been observed in some ponds and not in others – a possibility is that the presence of ammonia in the form of free ammonia (NH_3) due to high pH values may inhibit the growth of nitrifying organisms. Organisms responsible for anaerobic ammonia oxidation (Anammox) are also being investigated, using molecular biology techniques and proteomics mechanisms, in order to see if they play an important role in nitrogen removal. Anyway, nitrogen removal in shallow ponds seems to be greater than in deeper ponds.

Regarding phosphorus, a major removal mechanism could be the precipitation of the phosphates in the form of hydroxyapatite or struvite under high pH conditions. In the case of phosphorus removal, the dependence of high pH values is larger than with nitrogen: the pH should be at least 9 so that there is a significant phosphorus precipitation. Such high pH values are not consistently maintained, night and day, in most ponds, and this could be the reason why phosphorus removal efficiencies are not large in most ponds. Recent research has identified the possibility that algae can also develop a mechanism of luxury P uptake, like phosphate accumulating bacteria do in activated sludge. If this in indeed the case, and one is able to control the environmental conditions that favour this mechanism, an important possibility for phosphorus removal in ponds may be obtained.

The road is still open for more fundamental research that can deepen the understanding of mechanisms, thus allowing ponds to be more effective in nutrient removal, enhancing their applicability in situations in which the effluent needs to be discharged to sensitive water bodies or reused for an application that does not benefit from the presence of phosphorus.

Development of reliable hydraulic and kinetic mathematical models

Hydrodynamics in waste stabilisation ponds is highly dependent on the physical design (e.g. dimensions, location and type of inlet and outlets) and the climatic conditions (e.g. wind, solar radiation and temperature). Although they are often designed assuming either ideal complete-mix or plug-flow reactors hydraulics, dispersed-flow models can also be used, which better approximate the actual flow conditions. Experimental determination of the dispersion number using tracers has been done at several sites, leading to empirical equations for their simple estimation, based on physical characteristics of the pond.

Current research often employs computational fluid dynamics (CFD) models to capture the effects of short-circuiting and stratification in 2D or 3D geometries. Most recently, heat transfer models are in development., These more sophisticated approaches can be used to study the best arrangement for inlet and outlet structures and for the placement of baffles or mechanical mixing devices, aiming at increasing pollutant removal efficiencies. This better representation of the specific hydraulic behaviour of each pond is of course associated with a higher degree of complexity, but the increase in the availability and use of CFD software may result in its more systematic use by consulting companies in the design of ponds.

Traditional kinetic models for the prediction of effluent concentrations from stabilisation ponds have used first-order reactions, but recent approaches focus on the representation of biomass growth rates and the resulting uptake or release of constituents. Structures similar to the IWA Activated Sludge Model (ASM) are being developed for ponds, with the added degree of difficulty that not only bacterial growth and decay need to be modelled, but also algal biomass. At a higher level are recent models that jointly incorporate CFD and ASM models, being thus hopefully able to provide a better representation of the hydrodynamics and reaction kinetics at stabilisation ponds.

With the development of more advanced and reliable mathematical models, designers will hopefully have better tools to tailor each pond to the particular influent and site characteristics, as well as effluent quality requirements. This research is also an exciting opportunity to advance the understanding of microbial ecology in different types of wastewater systems.

Resource recovery in WSP

Significant advances are being made in recovering resources from WSP systems. Several examples have already been provided: using effluent for irrigation, the localised generation and collection of biogas in anaerobic ponds, and phosphorus recovery in algal biomass. Several groups are working on fully integrated resource recovery systems that maximise the production of algae, with subsequent recovery of energy from the algae via anaerobic digestion or production of bio-fuels. It is believed that integrated pond systems can be capable of net energy production. Several new designs are being explored for increasing algal growth rates in raceway configurations through improved mixing, recycling of algae, and feeding of CO_2. There is some evidence that feeding CO_2 into ponds can increase algal production under some conditions, whereas if the BOD is sufficient in the influent, the CO_2 produced by the heterotrophic bacteria is enough to maximise algal growth. A challenge with anaerobic digestion of algae is that the cell walls are not easy to break down. Extracting lipids from algae was found to require more energy than the gain in biogas production. Priorities for future research include optimising the overall integrated designs to recover resources with maximum efficiency. In this sense, the integration with other natural systems such as constructed wetlands and soil treatment may decrease the carbon foot-print of conventional WSP systems, but at the same time improve the energy balance of the overall system. This is a new exciting research area that may feed upon previous knowledge on agro-ecosystems for biofuels production.

Concluding remarks

The inherent simplicity of a natural wastewater treatment process is one of the first concepts that come to mind when one thinks on stabilisation ponds. For some practitioners, there may be an impression that everything that is needed is already known in this relatively old treatment process.

However, as was seen in this text, this does not mean that everything that relates to ponds is really simple: in the field of wastewater treatment, it is one of the most complex systems to understand, describe and model. From the biological point of view, the simultaneous interaction of different groups of bacteria with different algae species leads to a very complex ecological system, with mutualistic relationships between heterotrophs and autotrophs. The understanding, quantification and mathematical representation of the several different resulting biochemical processes and reactions and the growth rates of the various organisms involved are a challenge for pond's researchers. In addition, because ponds are large open reactors, their hydraulic behaviour is very much influenced by temperature, solar radiation rates, wind and placement and type of inlet and outlet structures. A reasonable representation of pond's hydrodynamics in conformity with its complex nature represents another monumental challenge.

Fortunately, with the advancement of field and laboratorial detection techniques and mathematical modelling tools, scientists are now coming somewhat closer in the understanding and representation of the mechanisms involved in ponds behaviour. The expectation is that this will assist in a better prediction of the removal efficiency of key pollutants under different environmental conditions, leading to better designs, tailored to each situation.

In closing, the future looks bright for the continued application of WSP systems to treat wastewater from small communities or any biodegradable wastewater with very favourable environmental footprints and lower capital and operation and maintenance costs compared with mechanical wastewater treatment. The future is also bright for fundamental and applied research to continue to advance our understanding of the complex processes occurring in these engineered aquatic ecosystems.