3.

Wastewater treatment in WSP

3.1 TYPES OF WSP AND THEIR FUNCTION

WSP systems comprise a single series of anaerobic, facultative and maturation ponds, or several such series in parallel. In essence, anaerobic and facultative ponds are designed for BOD removal and maturation ponds for pathogen removal, although some BOD removal occurs in maturation ponds and some pathogen removal in anaerobic and facultative ponds. In many instances only anaerobic and facultative ponds will be required: for example, prior to restricted crop irrigation (Section 10.1) and fishpond fertilization (Section 10.4), and also when a relatively weak wastewater (up to 150 mg/l) is to be treated prior to surface water discharge. In general maturation ponds will be required only when the treated wastewater is to be used for unrestricted irrigation and has to comply therefore with the WHO guideline of > 1000 faecal coliforms per 100 ml, and when stronger wastewaters (BOD >150 mg/l) are to be treated prior to surface water discharge. (Restricted irrigation refers to the irrigation of industrial crops, such as cotton and sunflower, and food crops not for direct human consumption, such as wheat. Unrestricted irrigation covers vegetable crops, including those eaten uncooked, such as salad crops.) However, if WSP effluents can be assessed on the basis of filtered BOD (see Section 4.1), anaerobic and facultative ponds will be sufficient without the need for maturation ponds for the treatment of wastewaters with a BOD up to 300 mg/l.

Designers should not be afraid of including anaerobic ponds. Their principal perceived disadvantage – odour release – can be eliminated at the design stage (Section 4.3), and they are so efficient at removing BOD that their inclusion substantially reduces the land area required (see Design Example No. 1 in Annex I).

3.1.1 Anaerobic ponds

Anaerobic ponds are commonly 2-5 m deep (see Section 5.5) and receive such a high organic loading (usually >100 g BOD/m^3 d, equivalent to >3000 kg/ha d for a depth of 3 m) that they contain no dissolved oxygen and no algae, although occasionally a thin film of mainly C*hlamydomonas* can be seen at the surface. They function much like open septic tanks, and their primary function is BOD removal (see Section 3.2). Anaerobic ponds work extremely well in warm climates: a properly designed and not significantly underloaded anaerobic pond will achieve around 60 percent BOD removal at 20°C and over 70 per cent at 25°C. Retention times are short: for wastewater with a BOD of up to 300 mg/l, 1 day is sufficient at temperatures >20°C (see Section 4.3).

Designers have in the past been too afraid to incorporate anaerobic ponds in case they cause odour. Hydrogen sulphide, formed mainly by the anaerobic reduction of sulphate by sulphate-reducing bacteria such as *Desulfovibrio*, is the principal potential source of odour. However in aqueous solution hydrogen sulphide is present as either dissolved hydrogen sulphide gas (H_2S) or the bisulphide ion (HS^-), with the sulphide ion (S^{2-}) only really being formed in significant quantities at high pH. Figure 3.1 shows how the distribution of H_2S, HS^- and S^{2-} changes with pH. At the pH values normally found in well designed anaerobic ponds (around 7.5), most of the sulphide is present as the odourless bisulphide ion. Odour is only caused by escaping hydrogen sulphide molecules as they seek to achieve a partial pressure in the air above the pond which is in equilibrium with their concentration in it (Henry's law). Thus, for any given total sulphide concentration, the greater the proportion of sulphide present as HS^-, the lower the release of H_2S. Odour is *not* a problem if the recommended design loadings (Table 4.1) are not exceeded and if the sulphate concentration in the raw wastewater is less than 300 mg SO_4/l (Gloyna and Espino, 1969). A small amount of sulphide is beneficial as it reacts with heavy metals to form insoluble metal sulphides which precipitate out, but con-

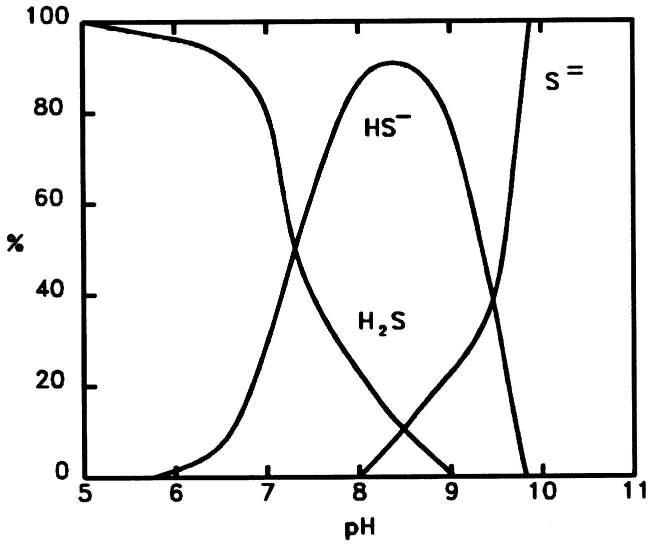

Figure 3.1
Effect of pH on hydrogen sulphide – bisulphide – sulphide equilibrium (Sawyer *et al.*, 1994).

centrations of 50-150 mg/l can inhibit methanogenesis (Pfeffer, 1970). A further important advantage of small concentrations (10-12 mg/l) of sulphide in anaerobic ponds is that they are rapidly lethal to *Vibrio cholerae*, the causative agent of cholera (Oragui *et al.*, 1993).

3.1.2 Facultative ponds

Facultative ponds (1-2 m deep) are of two types: primary facultative ponds which receive raw wastewater, and secondary facultative ponds which receive settled wastewater (usually the effluent from anaerobic ponds). They are designed for BOD removal on the basis of a relatively low surface loading (100 -400 kg BOD/ha d) to permit the development of a healthy algal population as the oxygen for BOD removal by the pond bacteria is mostly generated by algal photosynthesis (see Sections 3.2 and 4.4). Due to the algae facultative ponds are coloured dark green, although they may occasionally appear red or pink (especially when slightly overloaded) due to the presence of anaerobic purple sulphide-oxidising photosynthetic bacteria. The algae that tend to predominate in the turbid waters of facultative ponds (see Table 3.1) are the motile genera (such as *Chlamydomonas, Pyrobotrys* and *Euglena*) as these can optimise their vertical

Table 3.1 Examples of algal genera present in waste stabilisation ponds

Algae	Facultative Ponds	Maturation Ponds
Euglenophyta		
Euglena	+	+
Phacus	+	+
Chlorophyta		
Chlamydomonas	+	+
Chlorogonium	+	+
Eudorina	+	+
Pandorina	+	+
Pyrobotrys	+	+
Ankistrodesmus	⊗	+
Chlorella	+	+
Micractinium	⊗	+
Scenedesmus	⊗	+
Selenastrum	⊗	+
Carteria	+	+
Coelastrum	⊗	+
Dictyosphaerium	⊗	+
Oocystis	⊗	+
Rhodomonas	⊗	+
Volvox	+	⊗
Chrysophyta		
Navicula	+	+
Cyclotella	⊗	+
Cyanophyta		
Ocsillatoria	+	+
Anabaena	+	+

+ = present; ⊗ = absent

position in the pond water column in relation to incident light intensity and temperature more easily than non-motile forms (such as *Chlorella*, although this is also fairly common in facultative ponds). The concentration of algae in a healthy facultative pond depends on loading and temperature, but is usually in the range 500-2000 μg chlorophyll *a* per litre.

As a result of the photosynthetic activities of the pond algae, there is a diurnal variation in the concentration of dissolved oxygen. After sunrise, the dissolved oxygen level gradually rises to a maximum in the mid-afternoon, after which it falls to a minimum during the night. The position of the oxypause (the depth at which the dissolved oxygen concentration reaches zero) similarly changes, as does the pH since at peak algal activity carbonate and bicarbonate ions react to provide more carbon dioxide for the algae, so leaving an excess of hydroxyl ions with the result that the pH can rise to above 9 which kills faecal bacteria (see Section 3.3.1).

The wind has an important effect on the behaviour of facultative ponds, as it induces vertical mixing of the pond liquid. Good mixing ensures a more uniform distribution of BOD, dissolved oxygen, bacteria and algae and hence a better degree of waste stabilisation. In the absence of wind-induced mixing, the algal population tends to stratify in a narrow band, some 20 cm thick, during daylight hours. This concentrated band of algae moves up and down through the top 50 cm of the pond in response to changes in incident light intensity, and causes large fluctuations in effluent quality (especially BOD and suspended solids) if the effluent take-off point is within this zone (see Section 5).

3.1.3 Maturation ponds

A series of maturation ponds (1-1.5m deep) receives the effluent from a facultative pond, and the size and number of maturation ponds is governed mainly by the required bacteriological quality of the final effluent (see Sections 4.1 and 4.5). Maturation ponds usually show less vertical biological and physicochemical stratification and are well oxygenated throughout the day. Their algal population is thus much more diverse than that of facultative ponds (Table 3.1) with non-motile genera tending to be more common; algal diversity increases from pond to pond along the series.

The primary function of maturation ponds is the removal of excreted pathogens, and this is extremely efficient in a properly designed series of ponds (Table 3.2). Maturation ponds achieve only a small removal of BOD, but their contribution to nutrient (nitrogen and phosphorus) removal can be significant (see Sections 3.4 and 4.5.4).

3.2 BOD REMOVAL

In anaerobic ponds BOD removal is achieved (as in septic tanks) by sedimentation of settleable solids and subsequent anaerobic

Table 3.2 Geometric mean bacterial and viral numbers[a] and percentage removals in raw wastewater (RW) and the effluents of five waste stabilisation ponds in series (P1-P5[b]) at a mean mid-depth pond temperature of 26°C.

Organism	RW	P1	P2	P3	P4	P5	Percentage removal
Faecal coliforms	2×10^7	4×10^6	8×10^5	2×10^5	3×10^4	7×10^3	99.97
Faecal streptococci	3×10^6	9×10^5	1×10^5	1×10^4	2×10^3	300	99.99
Clostridium perfringens	5×10^4	2×10^4	6×10^3	2×10^3	1×10^3	300	99.40
Campylobacters	70	20	0.2	0	0	0	100.00
Salmonellae	20	8	0.1	0.02	0.01	0	100.00
Enteroviruses	1×10^4	6×10^3	1×10^3	400	50	9	99.91
Rotaviruses	800	200	70	30	10	3	99.63
BOD (mg/l)	215	36	41	21	21	18	92

[a] Bacterial numbers per 100 ml, viral numbers per 10 litres.
[b] Pl was an anaerobic pond with a mean hydraulic retention time of 1 day; P2 and P3-P5 were secondary facultative and maturation ponds respectively, each with a retention time of 5 days.
Source: Oragui *et al*. (1987).

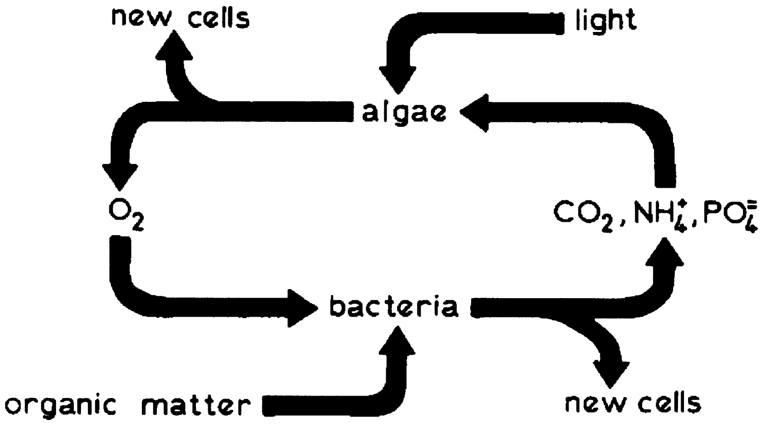

Figure 3.2 Mutualistic relationship between pond algae and pond bacteria.

digestion in the resulting sludge layer : this is particularly intense at temperatures above 15°C when the pond surface literally bubbles with the release of biogas (around 70 percent methane and 30 percent carbon dioxide); methane production increases sevenfold for every 5°C rise in temperature (Marais, 1970).

The bacterial groups involved are the same as those in any anaerobic reactor – the anaerobic acidogens and the methanogens, and those in anaerobic ponds are equally sensitive to the same toxicants, one of which is low pH (< 6.2). Acidic wastewaters thus require neutralising prior to treatment in anaerobic ponds.

In secondary facultative ponds that receive settled wastewater (usually anaerobic pond effluent), the remaining non-settleable BOD is oxidised by the normal heterotrophic bacteria of wastewater treatment (*Pseudomonas, Flavobacterium, Archromobacter* and *Alcaligenes* spp.), but with one important difference : these bacteria obtain the oxygen they need not from mechanical aeration (as they do in aerated lagoons, oxidation ditches and activated sludge tanks), but from the photosynthetic activities of the micro-algae which grow naturally and profusely in facultative ponds, giving them their characteristic dark green colour. The algae, in turn, depend largely on the bacteria for the carbon dioxide which they photosynthetically convert into sugars:

$$6CO_2 + 12H_2\mathbf{O} \rightarrow C_6H_{12}O_6 + 6H_2O + 6\mathbf{O}_2$$

So there exists a *mutualistic* relationship between the pond algae and the pond bacteria: the algae provide the bacteria with oxygen and the bacteria provide the algae with carbon dioxide (Figure 3.2). Of course some oxygen and carbon dioxide comes

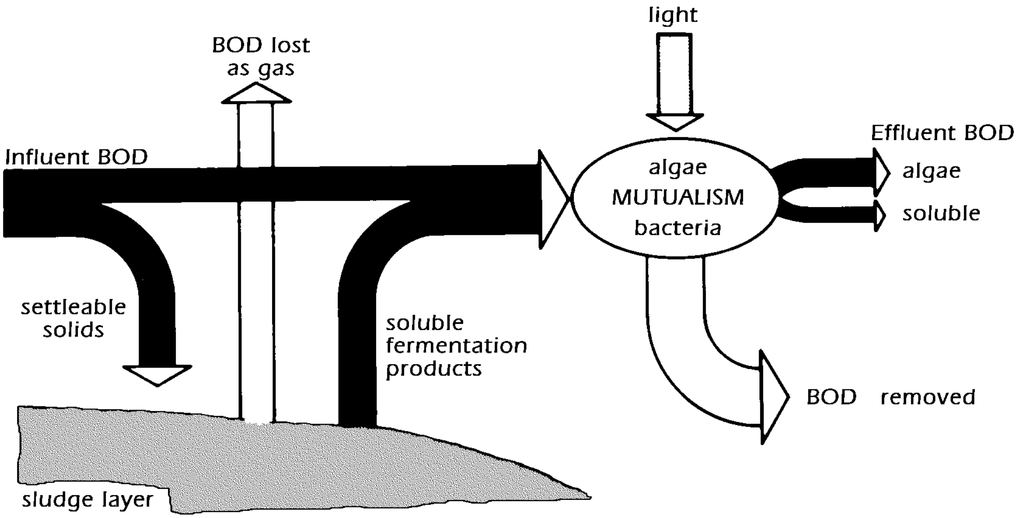

Figure 3.3 Pathways of BOD removal in primary facultative ponds (after Marais, 1970).

from the atmosphere by mass transfer, but the bulk is supplied by algal-bacterial mutualism.

In primary facultative ponds (those that receive raw wastewater) the above functions of anaerobic and secondary facultative ponds are combined, as shown in Figure 3.3. Around 30 percent of the influent BOD leaves a primary facultative pond in the form of methane (Marais, 1970).

As a result of these algal-bacterial activities, a high proportion of the BOD that does not leave the pond as methane ends up as algal cells. Thus in secondary facultative ponds (and in the upper layers of primary facultative ponds) "sewage BOD" is converted into "algal BOD" and this has important implications for effluent quality requirements (see Section 4.1).

In maturation ponds only a small amount of BOD removal occurs, principally as a result of lower algal concentrations (and hence lower "algal BOD") which, in turn, result from a decreased supply of nutrients and predation by protozoa and micro-invertebrates such as *Daphnia* or by fish such as carp if these are present. Around 70-90 percent of the BOD of a maturation pond effluent is due to the algae it contains.

3.3 PATHOGEN REMOVAL

3.3.1 Bacteria

Faecal bacteria are mainly removed in facultative and especially maturation ponds whose size and number determine the numbers of faecal bacteria (usually modelled in terms of faecal coliforms) in the final effluent (Section 4.2.4.), although there is some removal in anaerobic ponds principally by sedimentation of solids-associated bacteria.

The principal mechanisms for faecal bacterial removal in facultative and maturation ponds are now known to be:

(a) time and temperature,
(b) high pH (> 9), and
(c) high light intensity together with high dissolved oxygen concentration.

Time and temperature are the two principal parameters used in maturation pond design (Section 4.2.4.): faecal bacterial die-off in ponds increases with both time and temperature (Feachem *et al.,* 1983). High pH values above 9 occur in ponds due to rapid photosynthesis by the pond algae which consumes CO_2 faster than it can be replaced by bacterial respiration; as a result carbonate and bicarbonate ions dissociate:

$$2HCO^{-}_{3} \rightarrow CO^{2}_{3} + H_2O + CO_2$$

$$CO^{2-}_{3} + H_2O\ 2 \rightarrow 2OH^{-} + CO_2$$

The resulting CO_2 is fixed by the algae and the hydroxyl ions accumulate so raising the pH, often to above 10. Faecal bacteria (with the notable exception of *Vibrio cholerae*) die very quickly (within minutes) at pH > 9 (Pearson *et al.,* 1987*c*).

The role of high light intensity and high dissolved oxygen concentration has recently been elucidated (Curtis *et al.,* 1992). Light of wavelengths 425 – 700 nm can damage faecal bacteria by being absorbed by the humic substances ubiquitous in wastewater: these then enter an excited state for long enough to damage the cell. Light-mediated die-off is completely dependent on the presence of oxygen, and it is considerably enhanced at high pH. The sun thus plays a threefold role in promoting faecal bacterial removal in WSP (Figure 3.4): directly, by increasing the pond temperature ; and more indirectly, by providing the energy for rapid algal photosynthesis which not only raises the pond pH above 9 but also results in high dissolved oxygen concentrations

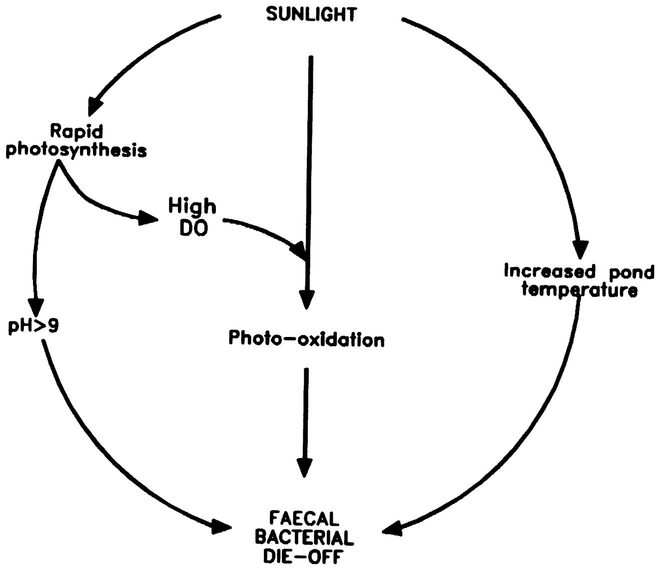

Figure 3.4 Conceptual mechanisms for faecal coliform die-off in ponds.

which are necessary for its third role, that in promoting photo-oxidatative damage.

3.3.2 Viruses

Little is definitely known about the mechanisms of viral removal in WSP, but it is generally recognised that it occurs by adsorption on to settleable solids (including the pond algae) and consequent sedimentation.

3.3.3 Parasites

Protozoan cysts and helminth eggs are removed by sedimentation. Their settling velocities are quite high (for example, 3.4×10^{-4} m/s in the case of *Ascaris lumbricoides)*, and consequently most removal takes place in the anaerobic and facultative ponds. It has recently become possible to design WSP for helminth egg removal (Ayres *et al.,* 1992*a*; see Section 4.5.2. and Design Example No. 2 in Annex I); this is necessary if the effluent is to be used for restricted crop irrigation (Section 10.1).

3.4 NUTRIENT REMOVAL

3.4.1 Nitrogen

In WSP systems the nitrogen cycle is at work, with the probable exception of nitrification and denitrification. In anaerobic ponds organic nitrogen is hydrolysed to ammonia, so ammonia concentrations in anaerobic pond effluents are generally higher than in the raw wastewater (unless the time of travel in the sewer is so long that all the urea has been converted before reaching the WSP). In facultative and maturation ponds, ammonia is incorporated into new algal biomass. Eventually the algae become moribund and settle to the bottom of the pond; around 20 percent of the algal cell mass is non-biodegradable and the nitrogen associated with this fraction remains immobilised in the pond sediment. That associated with the biodegradable fraction eventually diffuses back into the pond liquid and is recycled back into algal cells to start the process again. At high pH, some of the ammonia will leave the pond by volatilization.

There is little evidence for nitrification (and hence denitrification, unless the wastewater is high in nitrates). The populations of nitrifying bacteria are very low in WSP due primarily to the absence of physical attachment sites in the aerobic zone, although inhibition by the pond algae may also occur.

Total nitrogen removal in WSP systems can reach 80 percent or more, and ammonia removal can be as high as 95 percent. Equations for estimating total and ammoniacal nitrogen removals are given in Section 4.5.4.

3.4.2 Phosphorus

The efficiency of total phosphorus removal in WSP depends on how much leaves the pond water column and enters the pond sediments – this occurs due to sedimentation as organic P in the algal biomass and precipitation as inorganic P (principally as hydroxyapatite at pH levels above 9.5) – compared to the quantity that returns through mineralization and resolubilization. As with nitrogen, the phosphorus associated with the non-biodegradable fraction of the algal cells remains in the sediments. Thus the best way of increasing phosphorus removal in WSP is to increase the number of maturation ponds, so that progressively more and more phosphorus becomes immobilized in the sediments. A first order plug flow model for phosphorus removal has been developed, (Huang and Gloyna, 1984), but it is not in a form useful for design. The model shows that, if the BOD removal is 90 percent, then phosphorus removal is around 45 percent.

3.5 ENVIRONMENTAL IMPACT OF WSP SYSTEMS

Adverse environmental impacts resulting from the installation of a waste stabilisation pond system should normally be minimal, and the positive impacts, such as alleviation of water pollution, should greatly outweigh any potential negative impacts such as odour nuisance or mosquito breeding (but these do *not* occur in well-designed and well-maintained WSP). However, environmental impact assessments (EIA) are now recognised as an essential component in any development project and as an important decision-making tool, and the appropriate procedures should be followed. Annex III outlines the guidelines recommended by UNEP (1990) for the preparation of an EIA document for a sewage treatment plant for cities with populations of 10,000 – 100,000 and 100,000 – 1,000,000. The reader is also referred to the *Environmental Assessment Sourcebook* published by the World Bank (1991).