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A Transdisciplinary Approach for Water Pollution Control: Case Studies on Application of Natural Systems

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ABSTRACT

Despite the enormous technical and economic efforts to improve environmental conditions, currently about 40% of the global population (or 2 billion people) are still lack access to safe water supply and adequate sanitation facilities. Pollution problems and transmission of water- related diseases will continue to proliferate. The rapid population growth and industrialization will lead to a reduction of arable land, thus exacerbating the food shortage problems and threatening environmental sustainability. Natural systems in this context are a transdisciplinary approach which employs the activities of microbes, soil and/or plants in waste stabilisation and resource recovery without the aid of mechanical or energy-intensive equipments. Examples of these natural systems are: waste stabilisation ponds, aquatic weed ponds, constructed wetlands and land treatment processes. Although they require relatively large land areas, the natural systems could achieve a high degree of waste stabilisation and at the same time, yield potentials for waste recycling through the production of algal protein, fish, crops, and plant biomass. Because of the complex interactions occurring in the natural systems, the existing design procedures are based mainly on empirical or field experience approaches. An integrated kinetic model encompassing the activities of both suspended and biofilm bacteria and some important engineering parameters has been developed which could predict the organic matter degradation in the natural systems satisfactorily.

Keywords: Constructed wetland, Integrated kinetic models, Natural systems, Water pollution, Waste stabilization ponds

1. Needs for Transdisciplinary Approach for Environmental Sustainability

A significant challenge confronting engineers and scientists in developing countries is the search for appropriate solutions to the collection, treatment, and disposal or reuse of domestic wastes.

Technologies of waste collection and treatment that have been taught to environmental engineering students and practiced by professional engineers for decades are, respectively, the waterborne sewerage and conventional waste treatment systems, such as activated sludge and trickling filter processes. However, the above systems do not appear to be applicable or effective in solving the sanitation and water pollution problems in developing countries. Supporting evidence for the above statement is the result of a United Nations (UN) survey on sanitation coverage for the decade 1981–1990 and their projection for the year 2000 [1]. As shown in Table 1, although the percentages of population served with adequate sanitation increased during the past decade, due to rapid population growth (estimated at 90 million more people per year), these percentages for the urban areas are expected to decrease in the 2000. The same trends are observed both for the Asia and Pacific region and globally.

Sanitation conditions in both urban and rural areas need to be much improved as large percentages of the population still and will lack these facilities (Table 1). There are approximately 25,000 people per day (or 9.1 million per year) who die from preventable water-related diseases alone, or in conjunction with malnutrition [2].

Polprasert and Edwards [3] cited several reasons for the failure to provide sewerage to the population of the cities of the developing countries. The construction of sewerage systems implies large civil engineering projects with high investment costs. These projects are ill-suited to incremental implementation in densely built-up cities and usually involve long planning periods, which can take up to a decade to implement. Meantime the problem has once more outstripped the solution.

Besides the sanitation problem, man's energy needs have also grown exponentially, corresponding with human population growth and technological advancements (Figs. 1 and 2).

Another concern for rapid population growth is the pressure exerted on our fixed arable land area on earth. Table 2 projects

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Table 1. Sanitation coverage [1].

Region	Percent covered in year		
	1980	1990	2000
Asia & Pacific			(Population = 3.5 billion)
Urban sanitation	65	65	58
Rural sanitation	42	54	65
Global totals			(Population = 6 billion)
Urban sanitation	69	72	67
Rural sanitation	37	49	58

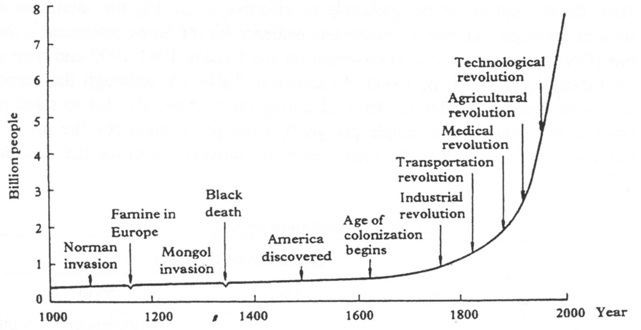

Fig. 1. World population increases with human advances in science and technology.

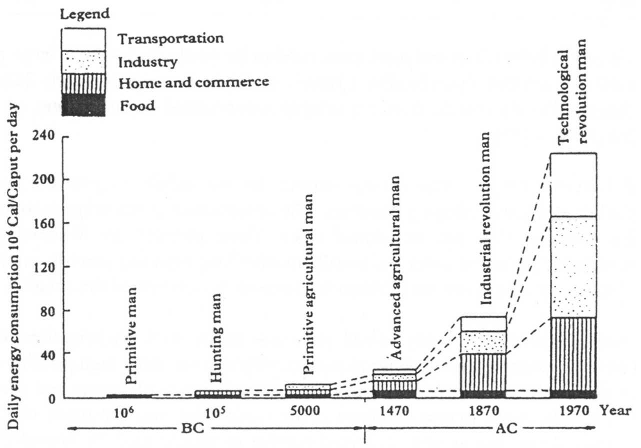

Fig. 2. Energy consumption increases and changes in use pattern with human advances in science and technology [4].

the ratio of arable land area over world population in the 2063 to be one third of that in the 2000. There is an obvious need to either control population growth or produce more resources for human needs.

Transdisciplinary approach in this context refers to the combined reactions of physical, chemical, and biological process utilizing the activities of plants, bacteria together with media (sand and gravel) in the system. It is therefore evident that a transdisciplinary approach which employs knowledge both within and beyond discipline boundaries should be adopted to deal with the above challenges. As the growth of microorganisms is temperature dependent, therefore organic degradation should be more favorable in hot climate area where most developing countries are located. Technologies of waste management which are simple, practical, and economical for use should be developed, and they should both safeguard public health and reduce environmental pollution. With the current energy crisis and since one of the greatest assets in tropical areas is the production of natural resources, the application of natural systems to treat and recycle wastewaters has received wide attention.

Table 2. Population growth and arable land.

Year	Estimated population (billion)	Arable land (ha/capita)
2000	6	1
2020	10	0.6
2063	22	0.3
2100	?	0.1–0.2

Earth total surface is 51 billion ha. Only 6 billion ha is arable land suitable for crop production (adapted from Oswald [6]).

However, the feasibility of natural treatment systems for environmental sustainability also depends on social, cultural, public health and institutional consideration. A large number of people in both developed and developing countries still lack of understanding and often neglect the benefits gained from natural treatment systems. Hence, the cost-effectiveness analysis including intangible benefits gained from the application of natural treatment systems should be taken into account. Besides, institutional support and cooperation with government agencies in promotion, training, operation and maintenance, social acceptance is also essential for success. The use of natural treatment systems for waste recycling through composting toilet and irrigation of septic effluents is more acceptable in Thailand, while several countries such as China, India, and Indonesia have been recycling human and animal wastes for centuries due to their socio-economic constraints. Thus, the social acceptability for waste reuse and recycling should be more positive than those in developed countries [5].

2. Natural Systems and Pollution Control

Natural systems in this context are those which employ activities of microbes, soil or plants in waste stabilisation without the aid of mechanical or energy-intensive equipment. The functioning of these natural systems is based on the interactions of physical, chemical and biological reactions with little environmental impacts. There are several types of natural systems that can be employed for waste stabilisation and pollution control. This section will describe three natural systems, namely, waste stabilisation ponds, aquatic weed ponds and constructed wetlands.

2.1. Waste Stabilisation Ponds

Waste stabilisation ponds (WSPs) refer to relatively shallow basin of water utilising the natural phenomena of waste degradation. The energy required to maintain the system is in renewable form and basically derived from the sun. The major biological components of the WSP system are algae and bacteria. Waste stabilisation in these systems is carried out by three major types of natural reactions namely physical, chemical and biological. WSP systems are basically classified into three major types according to the biological reactions occurring within the pond. Aerobic ponds posses a naturally aerated layer enriched with aerobic bacteria, whereas deeper oxygen deficient layers comprised of anaerobic bacteria are found in anaerobic ponds. Facultative ponds, characterised with aerobic layer at the surface, a middle facultative zone and an anaerobic bottom, are the most effective in waste decomposition.

The relationship occurring in facultative ponds is called the 'Algae-Bacteria Symbiotic Reactions'. The top, aerobic layer of the ponds contains algal cells which, in the present of sunlight, perform photosynthesis and producing oxygen (O_2) gas, according to Eq. (1).

$$NH_3 + 7.62CO_2 + 2.53H_2O \xrightarrow[\text{ALGAE}]{\text{Sunlight}} \underset{\text{(New algal cells)}}{C_{7.62}H_{8.06}O_{2.53}N} + 7.62O_2 \quad (1)$$

The O_2 gas produced in Eq. (1) is then used by suspended bacteria to oxidise the incoming organic waste, as shown in Eq. (2).

$$\underset{\text{(Organic Waste)}}{C_5H_7O_2N} + 5O_2 \xrightarrow{\text{bacteria}} 5CO_2 + NH_3 + 2H_2O + \text{energy} \quad (2)$$

As long as the algae can provide an excess of O_2 above that required by the bacteria, an aerobic environment is maintained. Thus it can be seen that there is interdependence between algae and bacteria, with the algae supplying oxygen required by the bacteria, and the bacteria making available the CO_2 and inorganic nutrients required by the algae. Effluent of facultative ponds normally contains low dissolved organic matter, but high content of algal and bacterial cells which can be removed further in maturation or polishing ponds connected in series to the facultative ponds.

2.2. Aquatic Weeds

Aquatic weeds are prolific plants growing in water bodies which can create a number of problems due to their extensive growth and with high productivity. Since they exhibit spontaneous growth, they usually infest polluted waterways or water bodies, reducing the potential uses of these water courses. However, turning these aquatic weeds into productive uses, such as in wastewater treatment, in making compost fertiliser, and as human food or animal feed, some of the problems created by aquatic weeds may be minimised. Table 3 describes functions of the plant parts in wastewater treatment mechanisms.

The floating aquatic weeds that have been employed for wastewater treatment are water hyacinth—*Eichhomia crassipesy*, duckweeds (*Woifia arrhiga*) and water lettuce (*Pistia stratiotes*). Waste stabilisation in an aquatic weed pond is accomplished through the reactions listed in Eqs. (1) and (2), except O_2 gas in Eq. (1) is produced by the photosynthetic activity of the aquatic weeds and the produced O_2 is transferred to the roots and stems for the biofilm bacteria to biodegrade the organic matter (Eq. (2)). Reported values of O_2 release rates from the roots of emergent plants are 5–45 g O_2/m^2/day, with a mean value of 20 g O_2/m^2/day.

Table 3. Functions of aquatic weeds in aquatic treatment systems [8].

Plant part	Function
Root and/or stems in the water column	Surfaces on which bacteria grow. Media for filtration and adsorption of solids.
Stems and/or leaves at or above the water surface	Attenuate sunlight and thus can prevent the growth of suspended algae Reduce the effects of wind on the water. Reduce the transfer of gases between the atmosphere and water. Transfer of oxygen from leaves to the root surfaces

Because there will be less algae growing in aquatic weed ponds, the aquatic weed pond effluent should contain less suspended solids and low organic matter content, suitable for discharging into water bodies or further reuse.

2.3. Constructed Wetlands

Wetland is an area which is inundated or saturated by surface or ground water at a frequency or duration sufficient to maintain saturated conditions and growth of related vegetation. Emerged aquatic weeds, such as cattails (*Typha*), bulrushes (*Scirpusy*) and reeds (*Phragmites*) are the major and typical component of the wetland systems. Wetland is a natural system where complex physical, chemical and biological reactions essential for wastewater treatment, exist. Constructed wetlands can range from creation of a marshland to intensive construction involving earth moving, grading, impermeable barriers or erection of tanks or trenches [7].

Two types of constructed wetlands have been developed for wastewater treatment, namely, free water surface (FWS) and subsurface flow (SF). An FWS system consists of parallel basins or channels with relatively impermeable bottom and soil and rock layers to support the emergent vegetation, and the water depth is maintained at 0.1–0.6 m above the soil surface. An SF system, also called 'root zone', 'rock-bed filter' or 'reed beds', consists of channels or trenches with impermeable bottom and soil and rock layers to support the emergent vegetation, but the water depth is maintained at or below the soil surface. To reduce short-circuiting, the length to width ratios of constructed wetland units should be more than 2/1. Although it might appear that SF constructed wetlands could be subjected to frequent clogging problems, performance data reported so far have shown them to function satisfactorily with high degree of removal efficiencies [9]. A typical layout of a SF constructed wetland is given in Fig. 3.

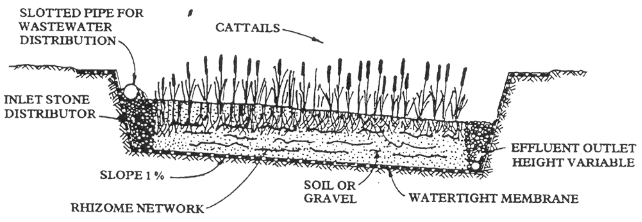

Fig. 3. Typical cross-section of subsurface flow constructed wetlands [7].

The reactions responsible for organic matter degradation are similar to those of the aquatic weed ponds, but the wetland bed media will assist in the filtration and adsorption of solids and other pollutant compounds. Hence, constructed wetland can accommodate wide range of organic-rich wastewater and effluent of a well operated constructed wetland is normally of high quality suitable for discharge or reuse. Further, modification of constructed wetland system by changing media content or integrating earthworms into constructed wetland can be applicable for phosphorous removal and reduce biomass production [10-12].

3. Natural Systems and Waste Recycling

Besides their effectiveness in pollution control, the natural systems described in the previous section have potential for waste recycling in which the nutrients present in the wastewater can be converted to become protein biomass in the form of algal cells, fish and compost fertiliser. Some of the waste recycling potentials are described below.

3.1. Algal Protein Production

As algal cells contain approximately 50% protein, Eq. (1) suggests that it is possible to culture algal biomass from wastewater. The data in Table 4 show that the potential of algal mass production of 70 tons/ha/yr, equivalent to algal protein production of 35 tons/ha/yr, the productivity which is much greater than those to be obtained from growing wheat, rice or potato. When considering the need to produce more protein for the ever increasing population growth, algal production is an aspect that cannot be ignored.

Fig. 4 shows a schematic diagram of high-rated algal ponds (HRAP) normally constructed to cultivate algal cells from wastewaters. The HRAP depth is 20–40 cm so that sunlight can penetrate the whole liquid depth, thus maximising algal production. In addition, organic matter will be stabilised in the HRAP according to Eq. (2).

The main problem associated with the production of algal protein is the small size of algal cells (approximately 1–20 μm) which causes difficulty in the harvesting of algal cells from the HRAP effluent and concentrating them in, to paste or pellet forms suitable for use as animal or human feeds. The available harvesting technologies, such as micro-straining, belt filtration and centrifugation are still not cost-effective and more research in this area is needed. Most algal species, except *Spirulina*, have rigid cell walls not easily digestible by non-ruminants and the high nucleic acid content may cause some health effects if ingested in large quantity.

Table 4. Comparative productivity.

	Mass production (tons/ha/yr)	Protein production (tons/ha/yr)
Algae	70	35
Wheat	3	0.36
Rice	5	0.6
Potato	40	0.8

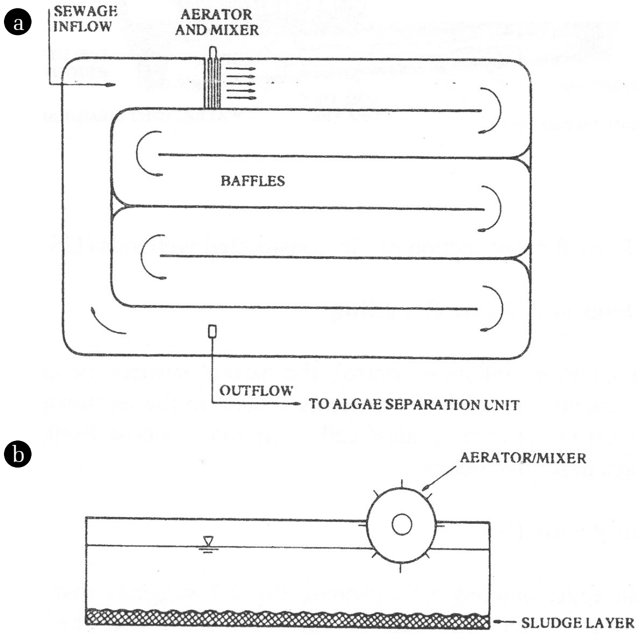

Fig. 4. High-rate algal pond: (a) schematic plan, (b) schematic cross-section.

3.2. Fish Production

The difficulty of algal harvesting mentioned in the previous section could be overcome using fish to graze on the algal cells or feeding the algal laden wastewater from HRAP into fish ponds. Herbivorous fish, such as Tilapia, grass carp and silver carp which feed mainly on plankton (algal cells) and other aquatic weeds are the desirable species. Table 5 compares the relative growth and feed utilisation of farm animals and fish, showing that fish have a better food conversion ratio (FCR) than farm animals. This is because fish are cold-blooded animals and, unlike other farm animals such as cattle or poultry, do not have to spend a lot of energy for movement.

The cultivation of waste-grown fish can be done by 1) rearing fish directly in waste stabilisation ponds (such as in maturation ponds) or 2) feeding effluent of facultative ponds or HRAP into fish ponds. Reported fish yields from various locations worldwide range from 1,000–10,000 kg/ha/yr depending on the operation modes, fish species and stocking density and climatic conditions.

Because fish can be harvested by nets, a much easier harvesting technique than those required for algal harvesting, the harvested

Table 5. Efficiency of feed utilization of various animal species per 1,000 g of feed intake.

Species	Live weight gain (g)	Food conversion ratio	Energy gain (kcal)	Protein gain (g)
Chicks	356	2.8	782	101
Pigs	292	3.4	1,492	30
Sheep	185	5.4	832	22
Steers	163	6.1	748	26
Channel catfish	715	1.4	935	118
Brown trout	576	1.7	608	75

Adapted from Hastings and Dickie [13].

Table 6. Tentative microbiology quality criteria for the aquacultural use of wastewater and excreta [14]

Reuse process	Viable trematode eggs[a] (arithmetic mean number per L or kg)	Fecal coliform (geometric mean number per 100 mL or per 100 g)
Fish culture	0	$<10^4$
Aquatic microphyte culture	0	$<10^4$

[a] *Clonorchis, Fasciolopsis, and Schistosoma.* Consideration should be given to this guideline only in endemic area.

[b] This guideline assumes that there is a one log10 unit reduction in fecal coliform occurring in the pond, so that in pond concentration are <1,000 per 100 mL. If consideration of pond temperature and retention time indicates that a higher reduction can be achieved, the guideline may be relaxed accordingly.

fish can be readily used as animal or human foods. To avoid public health problems, these waste-grown fish may be put in clean water for 1–2 weeks to enable a natural process called depuration to remove some microorganisms from the fish body. Wastewater effluent to be fed to fish ponds must be treated so that its microbiological quality meets the World Health Organisation (WHO) standards for aquaculture reuse stated in Table 6. However, it is essential to investigate the accumulation of potentially toxic elements (PTEs) in the production system, which may contribute a food safety risk as some toxic elements have a great potential to accumulate in both edible and non-edible parts of aquatic plants [15].

3.3. Biomass Production

The aquatic weeds such as water hyacinth or duckweeds grown in ponds and emergent plants (such as cattails or reeds) grown in constructed wetlands need to be regularly harvested, especially those under tropical conditions, In theory, the frequency of plant harvesting should be based on area doubling time, which is the time taken for the plants to double themselves. Under favourable conditions, the area doubling time of most aquatic weeds ranges between 2–4 weeks, depending on weather.

A water hyacinth pond (WHP) normally has plant density about 20 kg/m^2 (wet weight). For a pond with a surface area of 1 ha, if 50% of the water hyacinth plants are harvested once in 2 weeks, the amount of water hyacinth biomass available is 200 tons/mon or the biomass productivity of water hyacinth is 200 tons/ha/mon. Because aquatic weeds contain about 95% of water content, the dry biomass productivity of water hyacinth is approximately 120 tons/ha/yr (or annual protein production of 20 tons/ha/yr).

Because of the high moisture content, the harvested aquatic weeds should be dewatered prior to being reused. Table 7 shows the composition of some aquatic weeds. They can be used as feed for herbivorous fish, livestock fodder or raw materials to make compost fertilisers.

4. An Integrated Kinetic Model for the Design of Natural Systems

Despite its simplicity in operation, the design of waste stabilization ponds (WSPs) is perhaps the least well-defined of all the biological treatment process designs. This is still equally true, not only in the case of WSP, but in other natural treatment systems, such as constructed wetlands, land treatment, and WHPs. Most of the design criteria of these systems are either based on the empirical methods or organic or nutrient loading rates simulated from the actual performance obtained during previous studies. There are two basic reasons associated with the least development of en-

Table 7. Approx. composition (% dry weight) of some aquatic plants and alfalfa hay [16]

Species	Ash	Crude protein[a]	Fat[b]	Cellulose[c]
Eichhornia crassipes[d]	18.0	17.1	3.6	28.2
Pistia stratiotes[d]	21.1	13.1	3.7	26.1
Nelumbo lutea[e]	10.4	13.7	5.2	23.6
Nuphar advena[e]	6.5	20.6	6.2	23.9
Nymphoides aquatica[f]	7.6	9.3	3.3	37.4
Potamogeton diversifolius[f]	22.7	17.3	2.8	30.9
Nigas guadalupensis[f]	18.7	22.8	3.8	35.6
Ceratophyllum demersum[f]	20.6	21.7	6.0	27.9
Hydrilla verticillata[f]	27.1	18.0	3.5	32.1
Egeria densa[f]	22.1	20.5	3.3	29.2
Typha latifolia[g]	6.9	10.3	3.9	33.3
Justicia americana[g]	17.4	22.9	3.4	25.9
Sagittaria latifolia[g]	10.3	17.1	6.7	27.6
Alternanthera philoxeroides[g]	13.9	15.6	2.7	21.3
Orontium aquaticum[g]	14.1	19.8	7.8	23.9
Alfalfa hay	8.6	18.6	2.6	23.7

Each value is the average of 3-15 samples. All samples represent plants which were in lush, green stage of growth.

[a] Nitrogen×6.25, [b] ether-extractable material, [c] cellulose values are slightly lower than values for crude fibre, [d] floating species, [e] floating–leaved species, [f] submerged species, [g] emergent species.

gineering designs of the natural treatment systems: firstly, there is not a long history of recognition of the potential of the natural system in pollution control and environmental protection and, secondly, the kinetics and mechanisms of these systems are complex compared to the conventional pollution control systems. Further, the components of these systems comprise of all the three sources, i.e., physical, chemical and biological and the processes governing the operation of the systems are naturally controlled depending on climatic conditions.

4.1. The Need for an Integrated Kinetic Model

Although the biochemical reactions undergoing in the natural systems as outlined in the previous section are mainly governed by two types of suspended and biofilm bacteria, the design equations formulated in the past emphasized the role of the suspended bacteria only. An early study by Reynolds et al. [17] recognized the potential of biofilm bacteria growing on the surface of baffles submersed in the pond water in organic stabilization. Some previous researches on self-purification in shallow streams and rivers have shown biofilm bacteria growing in open-channel beds to be effective in biodegrading organic carbon compounds [18-22]. Recent studies on attach-growth WSPs found the biofilm bacteria growing on attached-growth media installed in the pond water to be effective in waste stabilisation [23-25]. From their laboratory experiments, Kilani and Ogunrombi [26] reported that WSP installed with baffles yielded better treatment performance than those without baffles; although they attributed the improved efficiencies to a reduction in dispersion number in the baffled ponds, the biofilm biomass, presumably growing on the baffle surfaces, could, together with the suspended biomass, contribute partly to the organic matter degradation. Because WSP normally have low flow velocities, but are subjected to higher organic loading rates than streams and rivers, biofilm biomass can be expected to grow at the bottom and side walls of the ponds. Hence, it can be concluded that the role of biofilm bacteria is important in the organic matter decomposition process and should be duly considered in the design equations.

There are numerous literatures indicating improved biochemical oxygen demand (BOD) or chemical oxygen demand (COD) removal efficiencies in WSPs implanted with aquatic plants. Orth and Sapkota [27] found the COD and SS removal efficiencies to increase more than 50% in a facultative pond implanted with water hyacinth when compared with a control facultative pond without water hyacinth plants. Reports from Brazil [28] and the United States [29] found BOD removal efficiencies in ponds stocked with water hyacinth to be about 20% better than those without the plants. It is therefore reasonable to hypothesize from these results that the improved organic removal efficiency in these WHP units was due to the activity of biofilm bacteria attached on the roots of the plants.

The media of the constructed wetlands provides comparatively higher number of sites for the biofilm bacteria than what is there in WSP or WHP. Further, the activity of suspended bacteria is obviously lower in constructed wetlands as the water depth is either less or absent. In wetlands, the path of the water is through the pores or microchannels of the soil/gravel-root matrix. Hence, the activity of biofilm bacteria plays a major role in the biochemical transformations occurring in the wetlands.

Realizing these facts, an integrated kinetic model that could incorporate the activities of both the suspended and biofilm bacteria, hydraulic regime in the system, and the effects of environmental factors in these natural treatment units was developed.

4.2. Current Design Models

The traditional approach towards design and performance evaluation of the WSP, WHP, constructed wetlands has been to assume the occurrence of either complete mixing or plug flow conditions. The formulas for the completely-mixed and plug-flow conditions, assuming first-order kinetics, steady state conditions, and no effluent losses due to evaporation and seepage, are shown in Eqs. (3) and (4), respectively.

$$\frac{C_e}{C_0} = \frac{1}{1+kt} \tag{3}$$

$$\frac{C_e}{C_0} = e^{-kt} \tag{4}$$

in which k is the first-order reaction rate which varies as temperature, C_e, and C_0, are the effluent and influent substrate concentration, and t is the hydraulic retention time.

The natural treatment systems are complex encompassing the existence of several reactions and hydraulic phenomena. The realization that none of the two extreme flow patterns really exists in practice, led to the development of models that could account for partial fluid mixing in these systems. The model defining the partial mixing of the fluid is termed as dispersed flow model and characterized by a parameter called the dispersion number. The dispersion number of flow, d, can be expressed as

$$d = \frac{D}{\mu L} \tag{5}$$

in which D is the longitudinal or axial dispersion coefficient characterizing the degree of back mixing during flow, u is the flow velocity, and L is the length of fluid travel path from the inlet to outlet section. The dispersion coefficient is analogous to the molecular diffusion coefficient in Fick's law and describes the concentration change due to back-mixing [30].

Wehner and Wilhelm [31] derived the following equation for chemical reactors which exhibit first-order kinetics and non-ideal mixing or partially mixed flow conditions under any kind of entrance or exit conditions:

$$\frac{C_e}{C_0} = \frac{4a_1 e^{\frac{1}{2d}}}{(1+a_1)^2 e^{\frac{a_1}{2d}} - (1-a_1)^2 e^{\frac{a_1}{2d}}} \tag{6}$$

in which

$$a_1 = \sqrt{1+4ktd} \tag{7}$$

4.3. Concept of the Integrated Kinetic Model

A conceptual illustration of organic matter (substrate) biodegradation in a treatment unit due to suspended and biofilm bacteria is shown in Fig. 5, in which x is distance from inlet along the pond length, y is the substrate travel distance in the biofilm, L_s is liquid sublayer thickness, L_f is thickness of biofilm, C_w is substrate concentration in bulk water, C_s is substrate concentration at the liquid sublayer and biofilm interface, and C_f is the substrate concentration in biofilm.

The substrate is utilized by the suspended bacteria in the bulk liquid flow and by the biofilm bacteria, with substrate transport through the liquid sublayer acting as a link between the two. With the assumptions mentioned elsewhere [32], a substrate mass balance in a control volume (bulk liquid and biofilm) under steady state condition and without lateral flow can be written as:

$$d\frac{d^2C_w}{dz^2}=\frac{dC_w}{dz}+tr+ta_sJ \tag{8}$$

in which, z is fractional distance along the pond length is equal to x/L, x is distance from the inlet along the pond length (m), J is substrate flux into the biofilm (g/m^2/day), r is substrate utilisation rate by suspended microbes (g/m^3/day), as is specific surface area of the biofilm per unit volume of the treatment unit (m^2/m^3), and other terms are defined previously.

Considering first-order kinetics for the suspended and biofilm bacteria and assuming a linear variation of the substrate concentration across the liquid sublayer, Eq. (8) was modified to describe the substrate concentration as a function of fractional distance downstream of the ponds lengths as:

$$d\frac{d^2C_w}{dz^2}=\frac{dC_w}{d}+t\left(k_{fs}+a_s\frac{\alpha\beta}{\alpha+\beta}\right)C_w \tag{9}$$

in which,

$$\alpha=\frac{D_w}{L_s};\beta=\frac{\tanh(\phi)k_{fa}L_f}{\phi};\phi=\sqrt{k_{fa}L_f^2/D_f};$$

ϕ is characteristic biofilm parameter, D_w is diffusion coefficient in liquid sublayer (m^2/day), D_f is diffusion coefficient in biofilm (m^2/day), k_{fs} is first-order rate constant of suspended bacteria (1/day), and k_{fa} is first-order rate constant of biofilm (1/day).

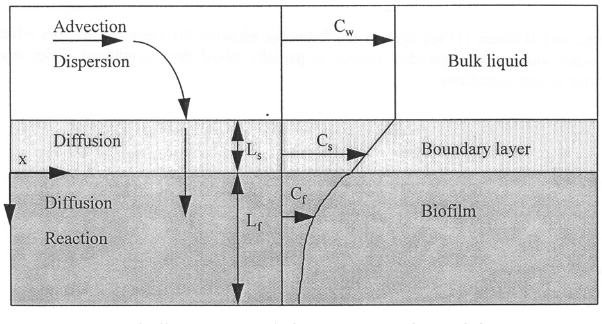

Fig. 5. Conceptual illustration of the integrated model.

Applying the boundary conditions,
$C_w=C_0$ at z=0 and $dC_w/dz=0$ at z=1.

Eq. (9) was integrated to obtain

$$\frac{C_e}{C_0}=\frac{2a_1e^{\frac{1}{2d}}}{(1+a_1)e^{\frac{a_1}{2d}}-(1-a_1)e^{-\frac{a_1}{2d}}} \tag{10}$$

in which, C_e and C_0 are the effluent and influent substrate concentrations respectively, and

$$a_1=\sqrt{1+4ktd} \tag{11}$$

$$k=k_{fs}+a_s\frac{\alpha\beta}{\alpha+\beta} \tag{12}$$

where, k = over-all first order rate constant (1/day).

If kfb represents the term $\alpha\beta/(\alpha+\beta)$, Eq. (12) becomes

$$k=k_{fs}+a_sk_{fb} \tag{13}$$

The relative importance of the biofilm bacteria compared to suspended bacteria in the organic removal for a natural system can be estimated by comparing the biofilm reaction rate to the sum of the both reaction rates [21]. Thus the percentage of total removal rate due to biofilm bacteria (p), determined from Eq. (14), is:

$$p=\frac{a_sk_{fb}C_w*100}{k_{fs}C_w+a_sk_{fb}C_w} \tag{14}$$

or

$$p=\frac{100}{1+\frac{k_{fs}}{k_{fb}a_s}} \tag{15}$$

Eq. 10 is the model equation for the substrate degradation in natural treatment systems treating wastewaters. The substrate removal efficiency by suspended biomass only can be determined from Eq. (10) by making as in Eq. (12) equal to zero. Similarly, if the substrate removal efficiency by biofilm biomass only can be obtained from the same equation by making kfs equal to zero in Eq. (12). To determine C, from Eq. (10), several model parameters need to be determined either from the experiments or from the literature.

4.4. Application to WSP and Attached-growth WSP

Polprasert and Agrawalla [32] applied the integrated model (Eq. (10)) to two full-scale facultative ponds located in central Thailand by comparing the computed effluent BOD_5 concentrations with the observed BOD_5 concentrations. The model was able to predict the effluent BOD_5 concentrations of these two ponds reasonably well, indicating the significance of these biofilm bacteria in organic matter degradation in facultative ponds (Fig. 6).

A design chart based on the proposed model for aiding in pond design or estimating additional attached growth area (baffles or other types of attached-growth media) to be installed in the pond water to improve efficiency of the pond performance was also developed (Fig. 7).

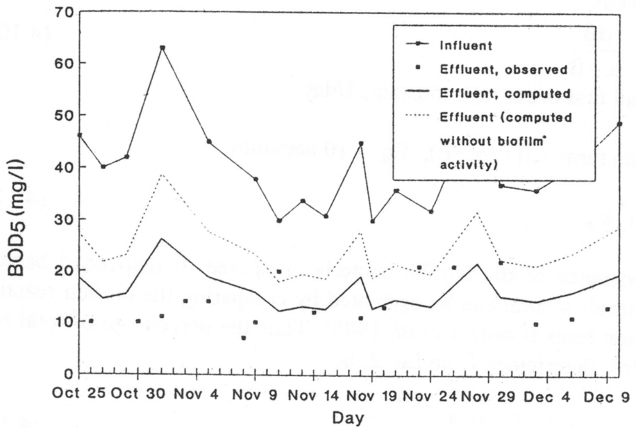

Fig. 6. Computed and observed effluent biochemical oxygen demand (BOD5) concentration of Asian Institute of Technology ponds [33].

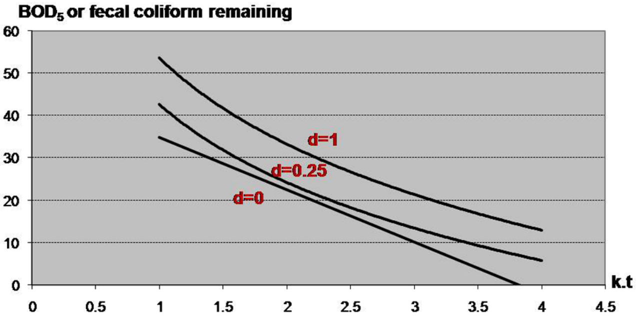

Fig. 7. Design chart for biochemical oxygen demand (BOD5) and fecal coliform removal for partially mixed reactors at various dispersion number [36].

4.5. Application to Water Hyacinth Ponds

Polprasert and Khatiwada [33] applied the integrated model (Eq. (10)) to WHPs treating a low-strength anaerobic pond effluent with an account of the biofilm surface area contributed by the water hyacinth roots. The model was validated by comparing the predicted effluent BODs concentrations values with the observed effluent BOD5 concentrations of a facultative pond implanted with water hyacinth plants located in central Thailand. The predicted effluent BOD_5 values were found in close agreement with the observed effluent values (Fig. 8). Based on the model, Polprasert and Khatiwada [34] found the contribution of the biofilm bacteria attached to the roots of the water hyacinth plants in the WHPs directly related to the improvement on the effluent quality when compared to a similarly operated WSP as is demonstrated in Fig. 9. A design chart in Fig. 7 based on Eq. (10) can be used for WHPs, whereas other design considerations are summarized in Table 8 [4].

4.6. Application to Duckweed Ponds

Apart from water hyacinth, duckweed is also an efficient aquatic plant used for treating domestic wastewater. The integrated kinetic model for organic and nutrient removal in terms of COD, BOD_5, NH_3-N, and TN can be applied in the duckweed ponds, while

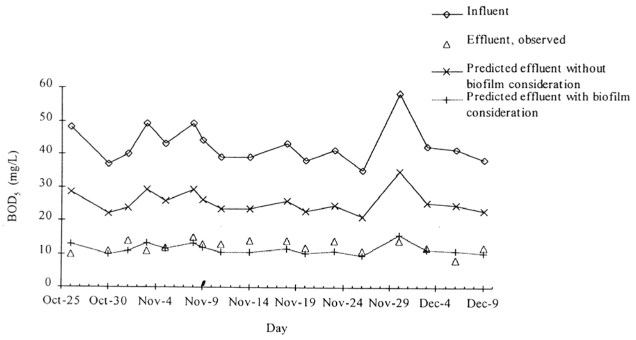

Fig. 8. Predicted and observed effluent biochemical oxygen demand (BOD_5) concentration of the water hyacinth pond [33].

Table 8. Summary of water hyacinth ponds design considerations [4]

Location	Types of pre-treatment	Surface area (ha)	Depth (m)	Hydraulic loading rate (m^3/ha/day)	Hydraulic residence time (day)	Organic loading rate (kg/ha/day)	Hyacinth cover (%)
National Space Technology Lab	None	2.00	1.22	240	54	26	100
Lucedale, MS, USA	None	3.60	1.73	260a	Approx. 67[a]	44	100
Orange Grove, MS, USA	Facultative lagoons	0.28	1.83	3,570	6.8	179	100
Ceder Lake, MS, USA (Duckweed)	One aerated and one facultative lagoon	0.07	1.50	700	22	31	100
Williamson Creek, TX, USA Phase I	Plant A: aeration basin, clarifier, three lagoons in series	0.06	1.00	1,860	5.3	43	100
Austin-Hornsby Bend, TX, USA	Excess activated sludge lagoons overflow to hyacinth ponds	1.40	1.23	430	Approx. 3	-	100
University of Florida, Gainseville, FL, USA	Trickling filter and activated sludge with polishing pond	0.76	1.40	1,220	0.63	5.2	100

[a] Based on effluent flow rate.

Table 9. Summary of wetland design considerations [36].

Design consideration	Constructed wetland	
	Free water surface	Subsurface flow
Maximum water depth (cm)	10–60	Water level below ground surface
Bed depth[a] (cm)	Not applicable	30–90
Minimum aspect ratio[b]	2:1	2:1
Bed slope[c] (%)	1–5	1–5
Minimum hydraulic retention time (day)	5–10	5–10
Maximum hydraulic loading rate (cm/day)	2.5–5	6–8
Minimum pretreatment	Screening and sedimentation	Screening and sedimentation
Configuration	Multiple units in parallel and series	Multiple units in parallel and series
Maximum loading (kg/ha/day)		
BOD_5	100–110	80–120
TN	60	60
Additional considerations	Mosquito control with mosquito fish; vegetation harvesting regularly	Vegetation harvesting regularly

BOD: biochemical oxygen demand, TN: total nitrogen.

[a] Bed depth is to support plant growth. [b] Aspect ratio is length/width (L/W) in this case for horizontal-flow CW. [c] Bed slope is for horizontal-flow mode.

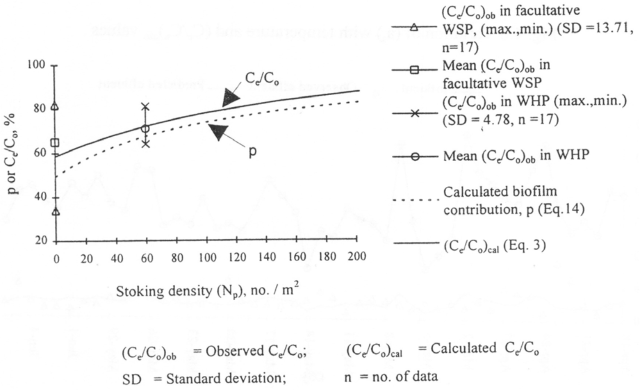

Fig. 9. Biofilm contribution as a function of number of plants per unit pond areal surface area [33, 34]. WSP: waste stabilisation pond, WHP: water hyacinth pond.

hydraulic retention time, organic loading rate, and stocking density are varied during operation period. The observed values from pilot-scale experiment at the Wageningen University, Netherland and the Birzeit University, Palestine and the integrated kinetic model finding developed from experiment at the Asian Institute of Technology, Bangkok illustrate high correlation [35].

4.7. Application to Constructed Wetlands

In an attempt to apply the integrated kinetic model to predict organic matter removal in FWS constructed wetlands, the value of effective surface areas (where the biofilm bacteria grow) in a wetland bed needs to be determined. Because these effective surface areas include those on the roots and stems of the vegetation, the media soil matrix and litter, direct measurement of the area is impractical. Based on the data of some laboratory-scale FWS constructed wetlands having f 85–110 no./m^2, 10 cm water depth and 60 cm media depth data and with the aid of the integrated kinetic model, the effective specific surface area, as, was found to be approximately 4.40 m^2/m^3 (Fig. 10). Fig. 11 shows that the integrated kinetic model could predict organic matter (COD) removal in a FWS constructed wetland satisfactorily. A design chart in Fig. 7 based on Eq. (10) can be used for constructed wetlands, whereas other design considerations are summarized in Table 9 [36].

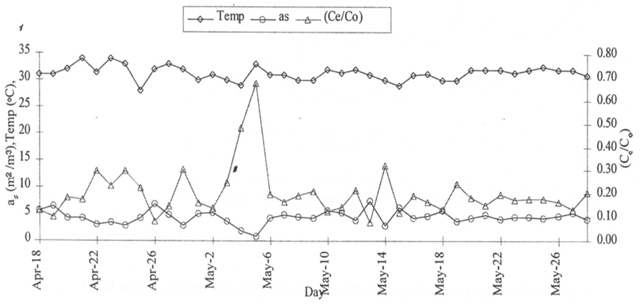

Fig. 10. Variation of (as) with temperature and (Ce/C0)obs values [32].

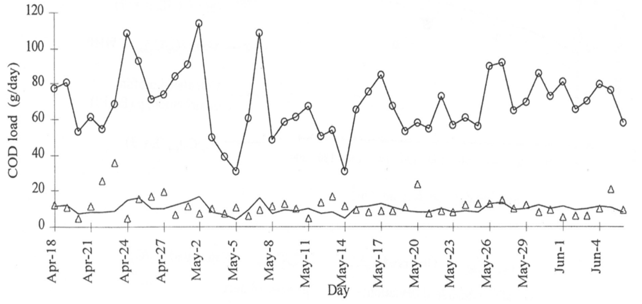

Fig. 11. Predicted and observed effluent chemical oxygen demand (COD) load of the pilot scale [32].

5. Summary

Natural systems are potential alternatives for effective pollution control and waste recycling. If land is available at reasonably low cost, the natural systems, such as waste stabilisation ponds, aquatic weed ponds and constructed wetlands, as described in this paper, should be chosen which will result in satisfactory treatment performance and saving in the construction, operation and maintenance costs. Besides these systems offer possibilities for the production of algal protein and fish biomass.

The application of natural systems is a transdisciplinary approach which involves complex physical, chemical and biological reactions and climatic factors. An integrated kinetic model encompassing the activities of both suspended and biofilm bacteria, flow hydraulics and hydraulic retention time has been developed. The model was able to predict organic matter removal in some waste stabilisation ponds, WHPs and constructed wetlands satisfactorily. A design chart for WSPs, WHPs and FWS constructed wetlands based on the integrated kinetic model was included.

Nomenclatures

BOD = biochemical oxygen demand
COD = chemical oxygen demand
FCR = food conversion ratio
FWS = free water surface
HRT = hydraulic retention time
HRAP = high-rate algal ponds
SF = subsurface flow
WHP = water hyacinth pond
WSP = waste stabilisation pond
a_s = effective specific surface area of biofilm per unit control volume (m^2/m^3)
C_o = influent substrate concentration (mg/L)
C_e = effluent substrate concentration (mg/L)
C_w = substrate concentration in bulk water (mg/L)
d = dispersion number
D = longitudinal dispersion coefficient (m^2/day)
D_f = diffusion coefficient in biofilm (m^2/day)
D_w = diffusion coefficient in liquid sublayer (m^2/day)
h = depth of flow, m
J = flux of substrate into biofilm (kg/m^3/day)
k_{fa} = first-order rate constant of biofilm bacteria (1/day)
k_{fs} = first-order rate constant of suspended bacteria (1/day)
k_{fb} = $ab/(a + b)$
L = length of the system (m)
L_f = biofilm thickness (m)
L_o = organic loading rate (kg/ha/day)
L_s = liquid sublayer thickness (m)
r = substrate utilisation rate by suspended bacteria (kg/m^3/day)
t = hydraulic retention time (day)
u = flow velocity (m/day)
W = system width (m)
a = D_w/L_s
b = $\tanh(\phi)k_{fa}L_f/\phi$
ϕ = characteristic biofilm parameter

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