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Anaerobic Waste Stabilization Ponds

A Low-Cost Contribution to a Sustainable Wastewater Reuse Cycle

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Abstract

Waste stabilization ponds (WSP) have been used extensively all over Europe over the last 50 yr for the treatment of municipal and industrial wastewaters. Models presented in manuals should be used only for guidance, and local experience from pilot and full-scale plants of a particular pond type is extremely valuable. Anaerobic WSP are single-stage, continuous-flow, anaerobic reactors operating at ambient temperatures and low volumetric organic loading as a pretreatment method. This article presents a literature review on the different available operational parameters of anaerobic ponds and examples from full-scale plant performance worldwide. On a wastewater management scheme, involving reuse for agriculture, the zero-energy demand of a waste stabilization pond series for the effective removal of organic and microbiological loading under existing legislation and guidelines will remain a valuable tool for sustainable development.

Index Entries: Waste stabilization ponds; anaerobic ponds; operational parameters; reuse.

Introduction

Sustainable wastewater treatment requires the purification of collected wastewater without expanding resources of any area in the world. In the developing countries, where 75% of the world's population live, resources are scarce and sustainable wastewater treatment is a vital condition for the health of present and future generations. It is estimated that only 5% of households in Latin America and Caribbean are connected to a wastewater treatment plant (wtp). Moreover, according to a 1997 World Bank report only 5% of wtp are operating satisfactorily *(1)*. The majority of the plants provide only primary treatment with no biological or nutrients removal. The level of urban wastewater treatment is much higher in developed countries. In the Netherlands 97% of wastewater is treated *(1)*. European Union (EU)

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member states had a high level of service in wastewater management when the 91/271 Directive was implemented in 1992. The population connected to a sewer is 82% with 86% of the collected flow being treated *(2)*. Analyzing data from the Directive's first year of implementation showed that 80% of operating plants could be considered as small (< 5000 population), with only 1.3% serving a population of more than 100,000 population *(3)*. Biological nutrient removal is mainly focused on nitrogen, with phosphorus being removed for only 13% of the sewered population *(2)*. Hungary is one of the countries that has applied for EU membership and at the closing of the environmental chapter in its EU negotiations a 2010 deadline was set for full wastewater treatment in all municipalities with a population larger than 10,000. The estimated cost is $10 billion US, and it will improve the existing level of wastewater services, since only 42% have access to sewer systems with only 18% being treated to any standard and 2% receiving tertiary treatment *(4)*. Poland's plans to join EU in 2005 needs an investment in the water sector of $30 billion US *(5)*.

Activated sludge methods produce large amounts of sludge, and sludge treatment usually involves thickening, anaerobic or aerobic digestion, chemical conditioning, and dewatering (e.g., filterbelt press, drying bed) before disposal. Recently, incinerators have become more common (110 plants in EU), as they reduce the volume of sludge that needs to be transported for disposal *(3)*. The disposal method most familiar to the public—before banning sea disposal, according to the 91/271 Directive—was in agriculture (42%), followed by sea disposal (30%), landfill (8%), and incineration (7%). Landfill will remain a viable option for sludge disposal, and it was estimated that about 17% will be disposed of in landfills when sea disposal stops *(6)*. Physicochemical stability is not expected to pose a problem when treated sludge has a 35% dry solids content.

Available EU project funding is possible mainly through either the Community Support Framework (CSF) for member states or the Instruments for Structural Policies for Pre-Accession countries (ISPA). Loans will remain a high preference option, but not a sustainable one, except for banks. Three billion Euros were lent to candidate countries in the year 2000, 26% for projects in the environmental sector projects. However, a more decentralized approach can lead to a low consumption of energy and water and a maximum reuse of treated wastewater and residues produced from the pollutants present in the wastewater such as fertilizers, soil conditioners and energy *(7)*.

Major operational problems at wastewater treatment plants in Europe are bulking and rising sludge, which are caused by microorganisms and uncontrolled denitrification, respectively, at all sizes of activated sludge plants in Europe *(8,9)*. Large seasonal fluctuations of wastewater flow (>3), mainly in the Mediterranean region, also present major design and operational problems. Work at the summer resort of Grand Canaria, Spain, has indicated that 50% of the mean daily flow occurs within a period of 7 h (from 11:00 to 18:00 h), creating severe operational problems at the plants *(8)*.

EU Environmental Legislation

The existing legal framework is governed by a number of environmental directives adopted by all member states. The most important of them, with immediate implications for the economics of a wastewater management scheme, are briefly presented below:

- *75/440 Directive on surface waters quality intended for potable use (10)*: This Directive has classified all freshwater resources that can be used as potable water. Parameters that are related to the effluent quality of a wastewater treatment plant are BOD, TKN, ammonia, nitrate, phosphates, and FC effluent level.
- *76/160 Directive on bathing waters (11)*: It was among the first to be introduced, setting the desired physicochemical and microbiological parameters that a bathing area needed to comply with. Guide and imperative values for FC are 100 and 2000 per 100 μL, respectively.
- *86/278 Directive on sewage sludge use in agriculture (12)*: The term "treated sludge" is defined as a sludge that has undergone biological, chemical, or heat treatment, long-term storage, or any other appropriate process so as significantly to reduce its fermentability and the health hazards resulting from its use. Sludge application in agriculture depends on its actual concentration of nitrogen and phosphorus and on the maximum permissible heavy metal limits (mg/kg DS).
- *91/271 Directive on urban wastewater treatment (13)*: This Directive concerns the collection, treatment and discharge of urban wastewater, as well as the treatment and discharge of wastewater from certain industrial sectors, based on population. The minimum required removal rate for organic and nutrient loading in a wastewater treatment plant is related to the sensitivity of the receptor and the size of the population served. Generally, inland surface waters (rivers, lakes, closed bays, etc.) are susceptible to eutrophication and they are considered as sensitive, while open seas are not considered as sensitive. Treatment is defined as secondary (e.g., biological treatment with disinfection), tertiary (secondary with nutrient removal and disinfection), and appropriate. Removal of total nitrogen and phosphorus is required when discharge is to a sensitive receptor (one subject to eutrophication) and is related to population (> 10,000). Appropriate treatment involves any process and/or disposal system that after discharge allows the receiving waters to meet the relevant water quality objectives and provisions of this and other Directives. The Directive also introduced the reuse of treated wastewater and sludge whenever appropriate. It has also ensured the acceptance of waste stabilization ponds, which are required to produce only <25 mg *filtered* BOD per liter and <150 mg suspended solids per liter, recognizing the distinction between algal and sewage BOD.

Wastewater Reuse

EU legislation (91/271) encourages the reuse of treated wastewater. Treated effluent quality is determined by the preferred method of reuse and involves physicochemical and bacteriological parameters. Major types of reuse applications are for the irrigation of public parks, landscaped areas, golf courses (urban reuse), agricultural reuse, industrial reuse (evaporative cooling water, boiler feed water), and finally the creation of wetland habitats, aesthetic impoundment, and stream augmentation (recreational reuse).

Agricultural reuse for irrigation has been practiced for centuries and is socially accepted, especially in many developing countries and more than 80% of consumed water is allocated to it. Existing regulations and guidelines distinguish between the irrigation of food crops intended for human consumption (uncooked) and the irrigation of non-food crops (fodder, fiber, seed crops, etc.). The quality of the reclaimed water should comply with certain physicochemical and microbiological parameters. Physicochemical parameters are related directly to the quality of the drinking water and wastewater treatment has only a minor effect, while microbiological quality is directly related to it *(14)*.

Microbiological Quality

Pathogenic microorganisms in human excreta may be passed to another person via either the mouth or the skin. Infections are separated in five categories, according to the type of pathogen and their environmental transmission characteristics (such as infective dose, latency, multiplication abilities, and persistence) *(15)*. Four main protective measures can be taken to protect human health during agricultural reuse. These are wastewater treatment, crop restriction, method of wastewater application, and human exposure control.

The Engelberg Report *(16)* developed microbial quality guidelines and recommended that the number of intestinal nematode eggs should be less than 1 egg/L for all types of irrigation, and that fecal coliform numbers should not exceed 1000/100 mL for the irrigation of edible crops. Shuval et al. *(17)* assessed the epidemiological evidence of quantifiable human health effects associated with wastewater irrigation. The results of this report, together with the results of the Engelberg meeting, were adopted by WHO and the most recent standards on wastewater reuse were introduced. The desired level of microbiological quality for agricultural reuse was related to the type of crop to be irrigated, method of irrigation (drip, sprinkler, etc.), and the exposed population groups (workers, consumers, etc.). The expected removal of excreted microorganisms in various wastewater systems are presented in Table 1.

EU standards for treated effluent reuse have not yet been established. France has set its own health regulation standards since 1991,

Table 1
Removals of Excreted Pathogens
Achieved by WSP and Conventional Treatment Processes *(18)*

Excreted pathogens	Removal in WSP	Removal in conventional treatment processes
Bacteria	Up to 6 $\log_{10}$ units[a]	1–2 $\log_{10}$ units
Viruses	Up to 4 $\log_{10}$ units	1–2 $\log_{10}$ units
Protozoan cysts	100%	90–99%
Helminth eggs	100%	90–99%

[a]1 log unit = 90% removal; 2 = 99%; 3 = 99.9%.

for the reuse of treated wastewater for the irrigation of crops, parks, and public gardens *(19)*. According to these regulations, irrigation water for products that can be eaten raw and for public parks and gardens must not contain more than one human intestinal helminth egg or more than 10^4 thermotolerant coliforms per liter. For other crops and for parks or gardens not open to public, quality relates only to parasitic contamination. There is no constraint for crops irrigated by subsurface or drip irrigation.

Anaerobic Digestion

Anaerobic digestion treatment technologies have been used for hundreds of years and offer many advantages compared with aerobic methods. The three main operational parameters are temperature, pH, and retention time. Unheated systems operate at ambient temperatures maintaining submesophilic and psychrophilic bacterial populations. In the psychrophilic temperature region, digestion becomes slower when temperatures decrease below 15°C, but never stops. Methanogenesis has been observed during the low-temperature digestion of manure, in pond sediments polluted by the paper industry, and in tundra soils *(20)*. The pH of an anaerobic digester should generally be in the neutral region. Depending on the substrate to be digested, the microbial flora require different pH values for optimal performance. Retention time is dictated by the type of substrate, the operating temperature, and type of reactor.

Their main advantages over aerobic systems are:

- The ability to operate under higher volumetric loading rates (>10 kg COD/m^3 d), resulting in smaller reactors with high BOD and COD removal rates;
- By-products (biogas and microbiologically safe digested sludge) can be used beneficially; and
- The production of smaller quantities of sludge to be disposed of, as only 10% of the inlet substrate is converted to microbial cell mass as compared to about 50% for aerobic reactors *(21)*.

Table 2
WSP Design Areas in Various European Countries

Country	Area (m^2/pe)	Reference
Norway and Sweden	4.5–10	*28*
France	7–10	*29*
Germany	5–15	*30*

Waste Stabilization Ponds

Waste stabilization ponds are shallow basins in which wastewater is treated by bacteria (anaerobic/aerobic) and algae. They have been used world-wide during the last 50 yr for populations ranging from a few hundred to more than a million (Al Samra in Jordan; Melbourne in Australia) and in diverse climates—for example, in Manitoba, Canada where the temperature can be as low as –45°C *(22)*. Their use as a treatment system for mosques at Damascus in Syria also shows their sociocultural acceptance *(23)*. This method of treatment is classified as a *natural* treatment system among reed bed and land treatment systems. In the Mediterranean region they are widely adopted with 2500 systems in France, serving populations of up to 50,000 *(24)*.

The advantages of ponds are many and the most important is their low capital, operational, and maintenance costs. Their long retention time and good dilution enable ponds to withstand organic and hydraulic shock loadings. Experience of full-scale plants has shown that a microbiologically safe effluent can be provided with a removal of 6 $\log_{10}$ units for FC (< 100 FC/ 100 mL), and 3–4 $\log_{10}$ units for viruses and complete removal of protozoa and helminths *(24)*.

Performance of a WSP system depends on many factors, and it is very difficult to derive a model to take into account all the parameters involved for the performance prediction of the three different pond types. Therefore, models should be used only for guidance, and local experience is extremely valuable. Modifications to the physical design of WSP (dimensions, depth, split of ponds), as well as other operational practices (recirculation, removal of effluent algae, etc.), can improve pond effluent quality *(25–27)*. The guidelines shown in Table 2, which are based on in-country experience, can be used at the preliminary design stage for an estimation of the required area. It should be noted that these values do not include an anaerobic pond, but only treatment in primary facultative and maturation ponds.

Anaerobic WSP

Anaerobic WSP are single-stage, continuous-flow, anaerobic reactors operating at ambient temperatures and low volumetric organic loadings.

They are used as a pretreatment stage for BOD, COD, and SS removal, for both domestic and industrial wastewaters. Anaerobic ponds are normally placed ahead of a treatment line involving secondary facultative and maturation ponds. They have also been used successfully with infiltration basins *(31)*, aerated lagoons *(32)*, and trickling filters *(33)*. Treatment mechanisms involve the removal of SS, through sedimentation, and therefore associated particulate BOD is also removed; the settled solids are digested anaerobically with biogas production. Typical domestic wastewater particulate BOD is in the range of 40–60%.

Analysis of a large number of performance results (n = 680) was obtained from 48 mo monitoring of the full-scale anaerobic ponds in the Al Samra WSP system *(34)*. Ponds were operating at temperatures between 12 and 28°C and an average retention time of 5.1 d. Raw wastewater characteristics, and especially the percentage of settleable (particulate) BOD, and SS proved to be very important. The small increase in the BOD removal efficiency (5.4%) due to temperature increase was attributed to the long retention time. Work by Mara and Pearson *(35)* has indicated that a 40% increase was possible with the increase of operating temperatures from 10 to 20°C.

Process Design

Their design is based on maximum and minimum BOD volumetric loading. This is also the proposed design method by different manuals. Mara *(36)* suggested that for high temperatures (>20°C) and a hydraulic retention time of 2.5 d, BOD removal would be 60%. Doubling the retention time would only achieve a 17% increase, with a removal rate of 70%. A removal of 50% was suggested for a retention time of only 1 d. Arthur *(37)* proposes a normal range of loadings between 100 and 400 g, BOD/m^3 d, with the higher loading applicable only within the temperature range of 27–30°C. The higher applied loading is also related to odors released at high inlet sulfate levels. According to the wsp design manual for Mediterranean Europe *(38)*, design load should not be higher than 300 g BOD/m^3 d for summer conditions, unless local experience for higher loads exists. For the region of East Africa, proposed loadings are in the range of 100–300 g BOD/m^3 d. Minimum and maximum removal rates range from 40% to 60% according to temperature and applied loading *(39)*. Anaerobic ponds can be satisfactorily designed, without the risk of odor nuisance, on the basis of volumetric BOD loading (load volume, kg BOD/m^3 d). Proposed design loadings in anaerobic ponds operating at the Mediterranean climate range, as well as predicted BOD removal rates, are given in Table 3.

From operating experience of anaerobic ponds in the Federal Republic of Germany and Israel, the winter design loading should be kept to 100 g BOD/m^3 d, if temperatures are below 10°C. To avoid odor problems, volumetric loading should be less than 400 g BOD/m^3 d, if the inlet sulfate concentration is less than 500 mg SO_4/L. A smaller value of inlet sulfate concentration was considered as critical, which was only 100 mg SO_4/L *(40)*.

Table 3
Design Values of Permissible Volumetric BOD Loadings on and Percentage BOD Removal in Anaerobic Ponds at Various Temperatures

Temperature (T, °C)	Volumetric loading (g/m^3 d)	BOD removal (%)
<10	100	40
10–20	20T – 100	2T + 20
20–25	10T + 100	2T + 20
>25	350	70

Source *(24)*.

Physical Design

A recommended length-to-breadth ratio of 2:1 or 3:1 is normally used. Inlet should discharge below the liquid level so as to minimize short circuiting, and effluent take-off levels should be 300 cm below the surface *(38)*. Deep ponds with a bottom inlet and surface overflows were installed in South Africa after 1991. For South African conditions 6–10 mo is needed for an anaerobic pond to reach optimum biological breakdown efficiency. A bottom sludge draw-off is proposed for sludge removal (without the need for the pond to be emptied) every 2–3 yr *(33)*.

Operational Measures

Main operational measures that are required are the withdrawal of sludge and the control of possible odors through recirculation of pond effluent from final ponds. To determine the volume of sludge that needs to be disposed every 2–3 yr local experience is required. Values presented in the literature were in the range of 0.03–0.05 m^3/person/yr *(40)*. However, the waste stabilization pond system at Auckland (512 ha), one of the biggest in the world, has never been desludged even after 34 yr of operation *(41)*. Usually one-third of the pond volume should be used for sludge accumulation. Local experience is valuable because anaerobic digestion of settled sludge is temperature dependent, thus volume reduction due to anaerobic mass balance transformations is variable.

At pH values found normally in well-operating anaerobic ponds (7.5) most of the sulfide is present as the odorless bisulfide ion. However, for the control of odor from an anaerobic pond, recirculation has been practiced *(33)*. In the Dan Region, Israel, recirculation for odor control is optimized at a rate between 1.5 and 2.5 of inlet flow, according to climate and organic loading rates *(42)*.

Local experience can provide an empirical basis for estimating performance in any particular location *(42)*. Results from full-scale plants operating under different environmental conditions and operational parameters are presented below, proving their abilities under adverse operational conditions (hydraulically and organically overloaded).

- Southeast Spain. Data of two wsp systems in Murcia are given by Soler et al. *(43)*. Ponds were designed for a population of 27,500 pe, but fruit processing industry wastewaters increase this to 95,000. Organic load and sulfate concentration are both high, 3,500–5,600 kg BOD/d (design load was 1,650) and 400–1,100 mg/L SO_4, respectively. In addition, BOD removal is 75% in winter and 84% in summer. The volumetric loading on the 3 m deep anaerobic pond ranged from 180 to 200 g BOD/m^3 d and the calculated BOD and COD removals were 46% and 49%. *Salmonella* removal was 57% in the anaerobic ponds. Results obtained from nine wsp systems in Almeria (800–10,000 pe) show an unfiltered COD effluent of less than 200 mg/L *(24)*.
- Egypt. Field studies at a village anaerobic ponds were undertaken *(44)*; the average load was 146 g BOD/m^3 d at a hydraulic retention time of 4.3 d. Inlet BOD had a soluble fraction of 34.5%; and removal rates, for total and filtered BOD, were 68% and 58.7%, respectively.
- Kenya *(27)*. Higher than predicted BOD removal rates (82%) were reported from an anaerobic pond at the Dandora, Nairobi WSP system, operated at 17°C with a loading of 240 g BOD/m^3 d. The overloaded (industrial wastes) WSP system at Nakuru, was monitored for periods of 1 wk at three different times in 1988–1989 *(45)*. The two anaerobic ponds had a depth of 4 m and were designed for a 1.2 d retention time and a loading of 380 g BOD/m^3 d. During these periods the volumetric loading was 1.1–4.8 times higher; the hydraulic retention time was too small, ranging only between 0.38 and 0.6 d. The influent had a high proportion of industrial wastes (tanneries) and a sulfide level of 350 mg/L. The performance of the anaerobic ponds, in terms of total COD removal, fluctuated between 15% and 46%. For a loading of 182 g BOD/m^3 d and a retention time of 0.6 d, the removal of total COD was 46%. However in terms of soluble COD, removal was negligible at all three periods (2.6%), indicating the need to monitor ponds for both total and soluble COD removal.
- Sana'a, Yemen Republic. Anaerobic ponds (2.0 m deep) have been operated under a medium organic loading (340 g BOD/m^3 d), at low hydraulic retention time (1.2 d) and with air temperatures of 13.5–23.5°C. The inlet wastewater was strong with average BOD and COD of 800 and 1600 mg/L, respectively. Ammonia concentrations of 150–200 mg N-NH_3/L were reported and the sulfate concentration was 30–40 mg/L. Total and filtered BOD removal rates were high: 80% and 75%, respectively *(46)*.
- Melbourne, Australia *(32)*. The anaerobic ponds, some of the largest in the world have been reported to achieve a BOD removal of 62%, with temperature differences throughout the year of 10°C. The anaerobic ponds are covered with HDPE membranes, producing 20,000 m^3 of biogas per day, with a methane content of 80%.

Conclusions

A large number of operating plants need to be constructed or updated according to existing legal EU framework (91/271, etc.) up to the end of 2005, calling for large investments in this sector. Nutrient removal at populations below 10,000 is not required for effluent discharges in nonsensitive receptors (open sea). For a wastewater management scheme, involving reuse for agriculture, the zero-energy demand of a waste stabilization pond series for the effective removal of organic and microbiological loading under existing legislation and guidelines will remain a valuable tool for sustainable development. A wsp treatment line can achieve the imperative FC effluent values required by the Bathing Directive, providing secondary treatment level effluent. Amount of sludge produced is minimum compared with aerobic methods (e.g., activated sludge) due to the anaerobic digestion of settled material at the anaerobic pond, and microbiologically safe due to the long-term storage required by the 86/278 Directive. Provision for the monitoring method of a wsp treatment line effluent is made at the 91/271, securing their future.

The main parameters affecting organic loading removal efficiency in an anaerobic pond are temperature, retention time and volumetric loading. Also, of major importance seems to be the type of substrate, with its physical properties. There appears to be sufficient sets of available performance results from worldwide full-scale plants, operating satisfactorily under adverse operational conditions at minimum cost. However, performance should always be monitored and local experience, derived from pilot-scale studies, will help to promote ponds.

In Europe, where the majority of the plants can be characterized as small (<5,000 population), WSP incorporating an anaerobic pond can become a widely adopted treatment method as they can sustain hydraulic and organic overloading at low capital and operational cost with a zero-energy input. The main disadvantage of WSP is their large demand for land, but for a small-plant, the same area would probably be needed for a sludge management scheme incorporating agricultural disposal. As Europe is focusing on the agricultural land "set aside" policy, the demand for large areas can be easily satisfied. Little research has been conducted in terms of permissible optimal volumetric COD loadings, and further work is needed in this field.

References

1. Idelovitch, E. and Ringskog, K. (1997), *Wastewater Treatment in Latin America: Old and New Solutions*. Washington, DC: The World Bank.
2. Henze, M. (1996), *Water Quality Intl.* July–August, 32–36.
3. Hall, J. E. (1995), *J. Water Environ. Mngt.* **9(4),** 335–343.
4. Denies, T. (2001), *Water Wastewater Intl.* **16(4),** 19–20.
5. Koslacz, R. (2000), *Water Wastewater Intl.* **16(4),** 31–32.
6. Davis, R. D. (1996), *J. Water Environ. Mngt.* **10(1),** 65–69.

7. Lens, P., Zeeman, G., and Lettinga, G. (2001), *Decentralised Sanitation and Reuse*. London, England: IWA Publishing.
8. CEDEX Proyecto DEREA (DEmonstracion en REutilizacion de Aguas) (1996), *Informe No 1: Resultados de los Travajos de Investigacion y Desarrollo Realizados en el ano 1995*, p. 138 (In Spanish).
9. Chambers, B. (1993), *Water Sci. Technol.* **28(10),** 251–258.
10. Council of the European Communities (1975), *Official J. European Commun.* L194/ p. 26 (25 July).
11. Council of the European Communities (1976), *Official J. European Commun.* L31/1–7 (5 February).
12. Council of the European Communities (1986), *Official J. European Commun.* L191/ 0023 (15 July).
13. Council of the European Communities (1991), *Official J. European Commun.* L135/40–52 (30 May).
14. Ayers, R. S. and Westcot, D. W. (1985), *Water Quality for Agriculture*. Irrigation and Drainage Paper No. 29, Rev. 1. Rome: Food and Agriculture Organisation of the United Nations.
15. World Health Organisation (1989), *Health Guidelines for the Use of Wastewater in Agriculture and Aquaculture*. Geneva: WHO.
16. Engelberg Report (1985), *IRCWD News* **23,** 11–19.
17. Shuval, H. I., Adin, A., Fattal, B., Rawitz, E., and Yekutiel, P. (1986), *Wastewater Irrigation in Developing Countries: Health Effects and Technical Solutions*. World Bank Technical Paper No 51, The World Bank, Washington, D. C.
18. Feachem, R. G., Bradley, D. J., Garelick, H., and Mara, D. D. (1983), *Sanitation and Disease: Health Aspects of Excreta and Wastewater Management*. Chichester, England. John Wiley.
19. Bunel, F., Carre, J., Legeas, M., and Etienne, M. (1995), *Water Sci. Technol.* **31(12),** 409–416.
20. Norhevnikova, A. N. and Kotsyurbenko, O. R. (1994), Anaerobic digestion under psychrophilic conditions. *Proceedings of the 7th International Symposium on Anaerobic Digestion*. Cape Town. 23–27 January, pp. 90–98.
21. Hobson, P. N. and Wheathey, A. D. (1993), *Anaerobic Digestion: Modern Theory and Practice*. Elsevier Science Publishers, p. 269.
22. Oleszkiewicz, J. A. and Sparling, A. B. (1987), *Water Sci. Technol.* **19(12),** 47–53.
23. Simpson, H. (1997), E-mail contribution. lcsewerage@mailbase.ac.uk.
24. Mara, D. D. and Pearson, H. W. (1998), *Design Manual for Waste Stabilization Ponds in Mediterranean Countries*. European Investment Bank, Lagoon Technology International Ltd.
25. Wrigley, T. J., Toerien, D. F., Moller, A., and Pieterse, A. J. H. (1988), *Water Res.* **22(10),** 1287–1292.
26. Ceballos, B. S. O., Konig, A., Lomans, B., Athayde, A. B., and Pearson, H. W. (1995), *Water Sci. Technol.* **31(12),** 267–273.
27. Pearson, H. W., Avery, S. T., Mills, S. W., Njaggah, P., and Diambo, P. O. (1996), *Water Sci. Technol.* **33(7),** 91–98.
28. Odegaard, H., Balmer, P., and Hanaeus, J. (1987), *Water Sci. Technol.* **19(12),** 71–78.
29. Racault, Y. (1993), *Water Sci. Technol.* **28(10),** 183–192.
30. Bucksteeg, K. (1987), *Water Sci. Technol.* **19(12),** 17–23.
31. Guessab, M., Bize, J., Schwartzbrod, J., Maul, A., Morlot, M., Nivault, N., and Schwartzbrod, L. (1993), *Water Sci. Technol.* **27(9),** 91–95.
32. Hodgson, B. and Paspaliaris, P. (1996), *Water Sci. Technol.* **33(7),** 157–164.
33. Meiring, P. G. J. and Hoffman, J. R. (1994), Anaerobic Pond Reactors in Line with Biological Removal of Algae. *Proceedings of the 7th International Symposium on Anaerobic Digestion*. Cape Town. 23–27 January, pp. 385–395.
34. Saqqar, M. M. and Pescod, M. B. (1996), *Water Sci. Technol.* **33(7),** 141–145.
35. Mara, D. D. and Pearson, H. W. (1986), *Artificial Freshwater Environment: Waste Stabilization Ponds Technology*, Vol. 8, Chapter 4, (Rehm, H. J. and Reed, G., eds.), Weinheim: VCH Verlagsgesellschaft, pp. 177–206.

36. Mara, D. D. (1976), *Sewage Treatment in Hot Climates*. John Wiley, Chichester.
37. Arthur, J. P. (1983), *Notes on the Design and the Operation of Waste Stabilisation Ponds in Warm Climates in Developing Countries*. Urban Development, Technical Paper No 6, The World Bank, Washington D. C. USA, April.
38. Mara, D. D. and Pearson, H. W. (1987), *Waste Stabilization Ponds Design Manual for Mediterranean Europe*. World Health Organisation Regional Office for Europe, Copenhagen.
39. Mara, D. D., Alabaster, G. P., Pearson, H. W., and Mills S. W. (1992), *Waste Stabilisation Ponds: A Design Manual for Eastern Africa*. Lagoon Technology International Ltd.
40. Gloyna, E. F. (1971), *Waste Stabilization Ponds*, Monograph no 60. Geneva, Switzerland: World Health Organization.
41. Lawty, R., Ashworth, J., and Mara, D. D. (1996), *Water Sci. Technol.* **33(7),** 107–115.
42. Soler, A., Torrella, F., Saez, J., Martinez, I., Nicolas, J., Liorens, J., and Torres, J. (1995), *Water Sci. Technol.* **31(12),** 81–90.
43. El-Gohary, F., Wahaab, R. A., El-Hawary, S., Shehata, S., Badr, S., and Shalaby, S. (1993), *Water Sci. Technol.* **27(9),** 115–123.
44. Alabaster, G. P., Mills, S. W., Osebe, S. A., et al. (1991), *Water Sci. Technol.* **24(1),** 1991.
45. Veestra, S., Al-Nozaily, F. A., and Alaerts, G. J. (1995), *Water Sci. Technol.* **31(12),** 141–149.