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8430 DISCUSSION

The development of design equations for facultative waste stabilization ponds in semi-arid areas

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The BOD_5 removal rates achieved in four primary facultative lagoons in Malaysia and Brazil are shown in Table 11. The critical loading rate, defined as that above which a facultative lagoon becomes completely anaerobic, can be calculated for the Mairipora lagoon at an ambient temperature of 24°C to be 689 kg/ha per day on the basis of equation (1). The critical rate according to McGarry and Pescod[1] would be 578 kg/ha per day. The Mairipora lagoon operates satisfactorily as a facultative lagoon at a loading rate of 661 kg/ha per day; hence it would appear that the Author's equation for predicting critical loading rates at high ambient temperatures is valid in this case.

35. The data in Table 12 compare the actual BOD_5 removal rates recorded in the four lagoon systems with those predicted using the empirical relationships derived by the Author and by Mara and Silva[3] and McGarry and Pescod.[1] In general the predicted removal rates exceed those recorded; the largest discrepancy occurs with equations (11) and (12). The empirical equation (4), which according to the Author is less accurate than the equations incorporating a BOD_5 removal rate constant, is in closer agreement with the actual BOD_5 removal rates.

36. Table 12 shows that the removal rates recorded in the Malaysian and Brazilian lagoons are closer to the empirical prediction equations developed in those countries, despite the fact that the equations are based on operating data from lagoons excluding those in Table 12. For example, the Mara and Silva[3] equation derived from work carried out in Brazil predicts the removal rates in the RCG and Mairipora lagoons to within 5%. The McGarry and Pescod[1] equation, derived for design purposes in tropical Asia, predicts the removal rates in the Kota Kinabalu and Kuala Lumpur lagoons to within 10%—a closer relationship than that predicted from any of the other equations.

37. The recommendation by the Author that a primary facultative lagoon should be designed on the basis of the optimum BOD_5 removal rate—which in the case of the Author's experience in Nigeria represents 86% of the critical rate—results in a very small safety margin. Although an occasional overloading of a facultative lagoon may be acceptable there are many instances where odour problems have resulted from prolonged overloading.

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Table 11. Facultative lagoon operating data

System	Ambient temperature, °C	Hydraulic retention, d	Feed BOD_5		BOD_5 removal	
			mg/l	kg/ha per day	kg/ha per day	%
Kota Kinabalu, Sabah, Malaysia	28	6	124	304	222	77
Kuala Lumpur, Malaysia[16]	29	6·5	157	307	212	69
RCG Brasilia, Brazil[15]	24	10	163	84	72	86
Mairipora, Brazil[15]	24	12	517	661	522	79

Table 12. Comparison of actual and predicted BOD_5 removals in facultative lagoons

System	BOD_5 removal, kg/ha per day					Reliability,* %
	Actual	Equation (4)	Equations (11) and (12)	McGarry and Pescod[1]	Mara and Silva[3]	
Kota Kinabalu, Sabah, Malaysia	222	247	265	231	242	+4 to +20
Kuala Lumpur, Malaysia	212	249	272	233	245	+21 to +28
RCG Brasilia, Brazil	72	86	74	72	68	−6 to +20
Mairipora, Brazil	522	508	585	490	524	−6 to +12

* Reliability expressed as 100(predicted − actual)/actual.

38. In developing countries it is not always possible to define to an acceptable degree of accuracy for such factors as future sewage flows and characteristics, particularly where the successful implementation of a sewerage scheme depends on connecting premises which are already served by other means, e.g. septic tanks. Even if a reliable estimate of the connection rate can be made, there is no guarantee that traditional plumbing practices, such as discharging sullage wastes to storm drains, will also change. Because of these and other uncertainties the waste treatment system must be capable of operating over a wide range of feed characteristics.

39. The Author makes a valid point that stabilization lagoons are ideal treatment systems in developing countries where climatic conditions are favourable and land is available. His empirical design relationships developed for conditions in Nigeria are similar to those developed by other workers in other countries, although it is apparent that in general terms empirical relationships are more reliable for lagoon systems existing in the region in which the operating data used for the derivation of the equations were collected.

40. In the absence of reliable long-term operating data in a particular region I feel that it is preferable to design a facultative lagoon system on the basis of empirical relationships in similar areas, and to try to ensure that the critical loading rate will not be reached until later, by which time operating data on sewage characteristics and lagoon efficiency will have become available. In practice the designer must decide on a factor with which to reduce the critical loading rate so as to arrive at a design rate. In my opinion the reduction of 14% does not allow an adequate safety margin to prevent a facultative lagoon from being completely anaerobic, possibly for long periods. A reduction of 35–50% should be adequate for the design of a first phase scheme and, although the lagoon may prove larger than required as a result, the risk of nuisance will be minimal and the acceptability of the system by the local community will be achieved. The rapid rate of population growth in urban areas in most developing countries will ensure that the additional capacity in the lagoon will be used eventually and can be taken into account in the construction of subsequent phases.

Mr J. Lumbers, Imperial College of Science and Technology

The pond systems investigated by the Author were very small. What scale-up problems are envisaged, and to what extent are the conditions in an oil drum stirred with a paddle a simulation of those found in a full-scale pond with adequate wind-induced mixing?

42. The design equations developed along the lines of the McGarry and Pescod's research[1] perpetuate a statistical error in approach commonly encountered in waste water treatment process evaluation. A regression analysis of areal BOD removed versus the influent load has been put forward and a correlation coefficient of 0·97 quoted. Unfortunately the apparent excellence of this coefficient is largely due to the influent load appearing on both sides of the regression equation, i.e. the regression is $(\mathrm{BOD_{in}} - \mathrm{BOD_{out}})$ versus $\mathrm{BOD_{in}}$.

43. Were more terms considered in perhaps a multiple non-linear regression analysis? One could envisage a model of

$$\text{mass } \mathrm{BOD_{out}} = £(\text{mass BOD load, pond area, pond depth, ambient temperature, sludge layer depth, effective solar radiation, degree of wind mixing or perhaps wind speed, and so on})$$

44. Were the BOD tests suppressed against including nitrification?

45. With respect to §13(*d*), was the degree of mixing sufficient to make a comparison of this kind?

46. Regarding Fig. 10 and the derivation of an optimal BOD loading I should like to ask the following questions.

(*a*) Are the points plotted single points for loading rate or averages of groups of data?

(*b*) What are the K and BOD loading error bands on these points?

(*c*) Over what period were the data collected and had a significant and active sludge layer accumulated or been imposed artificially?

47. To what extent would the Author agree that to start the design of waste stabilization ponds by considering BOD removal is using the wrong emphasis? Invariably it is the removal of pathogens (as measured by some indicator organism) which is the most important consideration.

Dr Arthur

The data presented by Dr Bradley show the BOD_5 removals predicted using equations (11) and (12) to be consistently considerably greater than those observed from the pond systems investigated in Malaysia and Brazil (Table 12). These discrepancies may largely be due to the fact that equations (11) and (12) were developed using filtered effluent samples. This was done in an attempt to eliminate the effect of widely fluctuating algal concentrations on the BOD_5 test. This allowed the mechanics of dissolved BOD_5 removal to be considered more closely.

49. Table 12 shows a BOD_5 removal of 86 kg/ha per day predicted for the Brazilian ponds by equation (4) when Table 11 shows the BOD_5 loading rate to be only 84 kg/ha per day. Clearly equation (4) is not valid at such low BOD_5 loading rates, and both equations (4) and (5) can only really be considered valid at loading rates greater than about 150 kg BOD_5/ha per day. At a loading rate of 92·5 kg BOD_5/ha per day, equation (4) predicts complete BOD_5 removal. It should be noted from Figs 3 and 4 and Table 2 that most of the data used in the derivation of equations (4) and (5) were for BOD_5 loading rates considerably in excess of 150 kg BOD_5/ha per day.

50. For a primary facultative waste stabilization pond to be operated at maximum efficiency, the BOD_5 loading rate should be equal to 86% of the critical BOD_5 loading rate. This ensures optimum BOD_5 removal as this was where the maximum BOD_5 removal rate was found to occur. A pond system should surely be designed to be as efficient as possible, and it is the accuracy with which the contributing flow and organic loadings are predicted which will dictate whether or not the system is over or under designed. In my experience pond systems in developing countries are more likely to be over designed than under designed. This means unnecessary expense to the contributing population both in terms of land used and construction cost. Designers should aim at providing the most efficient and cost-effective pond system possible.

51. Dr Bradley's suggestion that primary facultative ponds should be designed on the basis of a reduction of 35–50% from the critical loading rate at a particular ambient temperature, raises two problems. First, there is a corresponding increase in the size of the primary pond and hence also in the land requirement and the capital cost of the system. There is also a decrease in the efficiency of BOD_5

removal. In the case of a 50% reduction, using the data shown in Fig. 10, this results in a reduction in the value of the first order BOD_5 removal rate constant from about 0·9 day^{-1} at optimum removal rate to about 0·67 day^{-1} at 50% of the critical BOD_5 loading rate.

52. Although in some cases it may be possible and/or desirable to allow a facultative pond to operate at a loading rate equal to half that which could be allowed, this is not always the case. Where land is relatively expensive but waste stabilization ponds remain the only feasible solution to sewage treatment problems, it may be necessary to construct a small and efficient pond system to serve immediate needs, and to plan for an additional parallel system in the longer term. This prevents the initial community being presented with the burden of paying for a large waste treatment system which it does not need, which is what often happens with systems where a future increase in contributing population is required to make the system more efficient and affordable.

53. In reply to the points made by Mr Lumbers, although the pond systems investigated were very small, good agreement was observed between the pilot scale ponds and the primary drums with similar detention times. However, as can be seen from Figs 6 and 7, the larger ponds tended to show marginally higher BOD_5 removal rate constants than the primary drums with corresponding detention times. This would appear to suggest that a small improvement in performance could be expected with the scaling up of the pond system. One of the major limitations in the use of the oil drums is the vertical sides which, combined with the small surface area, cause considerably different boundary considerations from those experienced in a full-size pond. Although this reduced the amount of sunlight reaching the subsurface layers of the drums, the results show that in fact this effect did not vastly reduce the treatment efficiency of the drums, nor did it affect the algal concentration significantly. A major advantage of using the drums was that they enabled a large number of different arrangements and detention times to be used in field conditions. Such a set-up is superior in terms of reproducing actual pond conditions to anything that could be set up in a laboratory.

54. No attempt was made to reproduce exactly the effects of either wind or thermal mixing by using a paddle to stir the upper layers of drum liquid. The mixing experiments were done because it was felt that wind mixing in the drums would be minimal due to the small surface area. By comparing the performance of the unmixed drums with that of drums under identical loading conditions but with forced mixing carried out twice a day, it was hoped to determine whether any treatment advantage resulted from the mixing. It was intended that these comparisons would allow verification or rejection of the claim by Marais[14] that mixing is one of the most important factors in determining pond performance. The research work included investigation of pond stratification, and in general the mixed drums remained unstratified for about 2 hours after mixing. However, thermal stratification was found to become progressively re-established over the ensuing 2 hours. Dissolved oxygen and pH stratification were also re-established over a similar time period, but these parameters did not stratify at the same level as temperature.

55. The appearance of the influent BOD_5 term on both sides of equations (4) and (7) does contribute to the very high regression coefficients. However, the data presented by Dr Bradley suggest that equations of this form are useful in predicting BOD_5 removal rates, at least in the regions in which they were developed.

56. A multiple non-linear regression of the form suggested by Mr Lumbers was not attempted in the data analysis. However, as shown in Table 5, linear regression

of BOD_5 removal rates for particular units with fixed detention times against various climatic factors showed only average ambient temperature to be highly significant. Application of such analysis was limited by an inability to vary the physical dimensions of the pilot units, many of which were of the same area and depth. Furthermore, the relatively short period of operation meant only small amounts of sludge build-up, which varied little between primary units regardless of organic loading and detention time.

57. The BOD_5 tests were not specifically suppressed against including nitrification because of problems with the supply of the necessary reagent. The azide modification of the Winkler method was used for the determination of dissolved oxygen levels in the BOD_5 tests.

58. In spite of the relatively rapid re-establishment of stratification in the mixed drums after mixing, results averaged over the year showed that the mixed

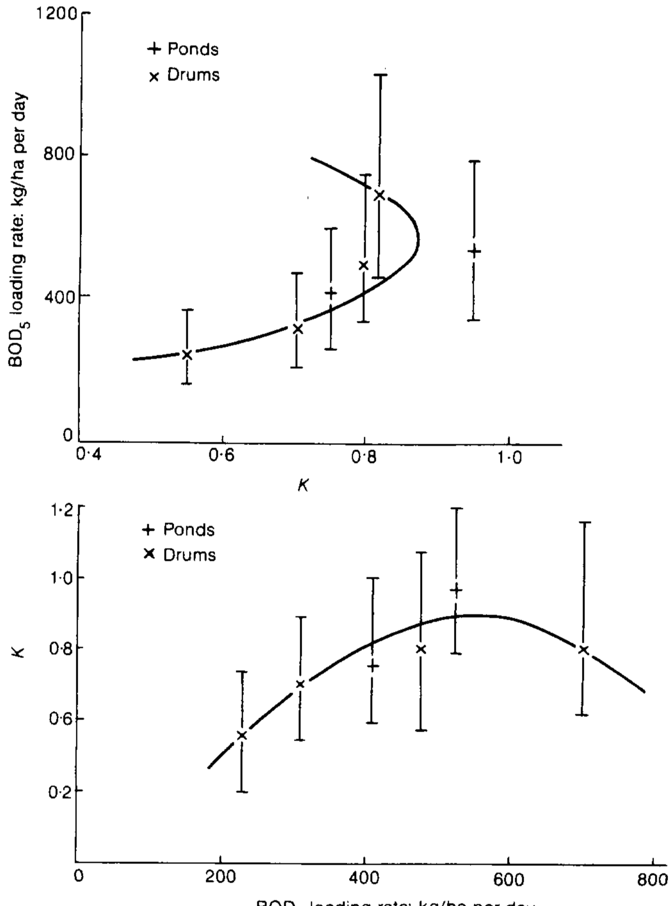

Fig. 14. 95% confidence limits for values of *K* and BOD_5 loading

drums achieved better treatment efficiency than the unmixed drums. This is shown in Fig. 5 for BOD_5 and in Fig. 11 for both faecal coliform and faecal streptococci removals. Thus better organic and bacterial removals were achieved in the drums where the stratification was temporarily destroyed twice daily, in spite of the short period of mixing and crude mixing method used.

59. Figure 10 shows the loading rates and first order BOD_5 removal rate constants of all the primary units operating at detention times of 6, 7, 9·8, 10, 14 and 20 days, averaged over the first six months of operation. The error bars showing 95% confidence limits for the BOD_5 loading rates and first order BOD_5 removal rate constants K are shown in Fig. 14. The first six months of operation followed a one month settling down period, and all the primary units were seeded with sludge from a neighbouring package treatment plant. All the primary ponds and drums showed evidence of an active sludge layer during the first six months of operation by the release of methane from the pond surface.

60. With regard to the design of waste stabilization ponds on the basis of faecal bacterial removal, I agree with Mr Lumbers that the primary consideration in sewage treatment for developing countries should be the elimination of pathogens. However, the major function of the primary pond in a system is to remove as much of the organic load as possible with maximum economy and without causing nuisance. The primary anaerobic or facultative pond should then be designed to remove the organic load as efficiently as possible, thus minimizing the land requirement and construction cost. Secondary and tertiary units may then be geared towards achieving maximum pathogenic bacterial removal with the greatest possible efficiency, which may mean, for example, a series of several shallow ponds with short detention times. This might be in contrast to primary anaerobic or facultative ponds which would be deep, and in the case of facultative ponds with a longer detention time to satisfy critical loading conditions.

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