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Stabilisation of dairy wastewater using limited-aeration treatments in batch reactors

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This research was conducted to study the treatment of dairy wastewater using limited-aeration treatments. The following process parameters were examined during the treatment process: (1) oxidation–reduction status; (2) organic matter degradation; (3) kinetics of bio-stabilisation; and (4) loss of ammonia. Results showed that during the first 3–4 days of limited-aeration treatments at 0.034 and 0.067 l [air] l^{-1}[manure] min^{-1}, dissolved oxygen (DO) remained close to the detection limit but, based on oxidation–reduction potential (ORP) levels (−30 to 100 mV), the wastewater oxidation–reduction status remained anoxic; the environment remained aerobic after this phase. The 70% maximum removal of both chemical oxygen demand (COD) and total volatile solids (TVS) observed by day 8 of treatment at either aeration rate indicated that the two-fold decrease in the aeration rate did not alter the ultimate reduction of the organic strength. Linear regressions performed on the COD against the TVS data obtained during this treatment indicate excellent linear relationships between the two parameters manifested in significantly high correlation coefficients ranging between 0.96 and 0.97. Either of the two parameters can thus be used to monitor the stabilisation of the wastewater and to determine the kinetics of bio-stabilisation. The kinetic studies established bio-stabilisation constants of 0.168 and 0.144 day^{-1} at the aeration rates of 0.067 and 0.034 l [air] l^{-1} [manure] min^{-1}, respectively. Accordingly, 50% bio-stabilisation (also referred to as half-life decay period) was achieved in approximately 4 and 5 days of treatment, respectively; meaning that reducing the aeration rate by 50% increased the half-life decay period by 25%, while reducing the decay rate by only approximately 14%. Effectively therefore, it is more economically prudent to aerate at the lower than at the higher airflow rate. In addition, a significantly higher ammonia loss was unaccounted for at the higher aeration rate (34% net loss) than at the lower aeration rate (23% net loss).

1. Introduction

Lagoons are widely used to store and treat livestock waste in most of the warmer regions in the US until land application (Chastain *et al.*, 2001; Shearin *et al.*, 2003; Chvosta & Norwood, 2003). In general, because of less odour nuisances, aerobic lagoons are more suitable for treatment and storage of these wastes than anaerobic lagoons. However, aerobic lagoons need to be shallow to allow aeration by natural wind currents and, therefore, usually have much larger surface areas (by as

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much as 25 times) than anaerobic lagoons (Westerman & Zhang, 1997). In contrast, anaerobic lagoons treating the same volume of waste have considerably larger depths and hence smaller surface areas than aerobic lagoons. Due to the tremendous area requirement for aerobic treatment lagoons, most lagoons are thus usually anaerobic. Anaerobic lagoons, however, have been the subject of much scrutiny in recent years for failing to provide the required treatment of the manure resulting in the generation of odours and other noxious gases (Classen *et al.*, 2000; Chastain *et al.*, 2001; Hawkins *et al.*, 2001; Cheng & Liu, 2002; Shearin *et al.*, 2003; Chvosta & Norwood, 2003; Miner *et al.*, 2003). These problems usually manifest in organically overloaded lagoons with degraded effectiveness of anaerobic treatment. To achieve adequate treatments, lagoon organic loading rates must be checked so that anaerobic treatment is not impeded (Hawkins *et al.*, 2001).

An effective and practical approach of reducing lagoon organic loadings is to decrease the mass loading of organic matter through pre-treatments. Aerobic treatment of animal slurries is one pre-treatment option whose efficacy in reducing organic strengths of numerous waste streams is proven (Burton *et al.*, 1998; Burton & Farrent, 1998). This technique has been widely used in treating industrial and municipal liquid wastes and substantial reduction of chemical oxygen demand (COD) and biochemical oxygen demand (BOD) have been achieved within reasonable treatments durations (Osada *et al.*, 1991; Bicudo & Svoboda, 1995). The biggest drawback to wider applications of this technology in the livestock industry has been the associated costs. Research efforts needed to make this technology more attractive in the management of wastes in the livestock industry need to focus on the reduction of the cost.

Some of the past research to advance aeration systems has centred on improving efficiency of aeration (Cumby, 1987; Yang & Wang, 1999), and reducing the duration as well as intensity of aeration (Phillips & Bulley, 1980; Sneath *et al.*, 1992; Zhang *et al.*, 1997; Luo *et al.*, 2001; Ndegwa *et al.* 2002; Zhu *et al.*, 2002). When the objective of an aeration treatment of livestock wastewater is the reduction of organic loading rates into secondary treatment systems such as lagoons as opposed to complete stabilisation of livestock wastewater, low-rate, low-intensity or limited-aeration has been recommended for the reduction of odour and other gaseous emissions (Zhang *et al.*, 2004; Ndegwa, 2004; Ndegwa *et al.*, 2002; Westerman & Zhang, 1997; Evans *et al.*, 1986). Most of the studies on limited-aeration for treatment of livestock wastewaters have been conducted on piggery wastewater but little research has been conducted on dairy wastewater. The objectives of this preliminary study were to determine the effect of limited-aeration treatment of dairy wastewater on: (1) oxidation–reduction status; (2) degradation of COD and total volatile solids (TVS); (3) kinetics of bio-stabilisation; and (4) loss of ammonia.

2. Methods and materials

2.1. *Reactor-systems and instrumentation*

This study was conducted in clear cylindrical Plexiglas reactors; 41 cm tall, 12.7 cm in diameter, with an operating volume of 4 l of liquid. To aerate the wastewater, a positive pressure air pump (Model DOA-P104-AA, Gast MFG Corporation, Cole-Parmer Instrument Company, Vernon.Hills, IL) was used to introduce air into the reactor-system through a fine-bubble air diffuser (Model 7” standard FlexAir Disc Diffuser, Environmental Dynamics Inc., Columbia, MO) located at the bottom of each reactor. Variable area flow meters (catalogue no. C-32460-40, Cole-Parmer Instrument Company, Vernon Hills, IL) were used to regulate and maintain the flow of aeration air in each unit. Based on previous research (Ndegwa, 2004; Ndegwa *et al.*, 2002; Lou *et al.*, 2001; Evans *et al.*, 1986), low-airflow rates of 0.067 and 0.034 l $[\text{air}]\,\text{l}^{-1}$ $[\text{manure}]\,\text{min}^{-1}$ (designated as R1 and R2, respectively, in this article) were selected and maintained throughout the study period in reactors 1 and 2, respectively, the latter being the lowest rate studied and documented so far.

The dissolved oxygen (DO) of the dairy wastewater was determined using DO probes (catalogue no. C-53202-00, Cole-Parmer Instrument Company, Vernon Hills, IL) and a DO meter/controller (catalogue no. C-01972-00, Cole-Parmer Instrument Company, Vernon Hills, IL). Both pH and ORP were measured using a combined pH-ORP meter (Orion Model 810, Orion Research Inc., Waltham, MA). Probes to monitor both pH (catalogue no.C-05993-70, Cole-Parmer Instrument Company, Vernon Hills, IL) and ORP (catalogue no. C-27001-62, Cole-Parmer Instrument Company, Vernon Hills, IL) were installed and retained in the reactors throughout the study period.

2.2. *Dairy wastewater, sampling and analyses*

Dairy wastewater was obtained from the equalisation tank in the Knotts Dairy Farm (Washington State University Dairy Research Facility). The manure collection system in this facility is primarily flushing using supernatant water drawn from a secondary lagoon. To avoid clogging the laboratory reactor systems during the experiments, the dairy wastewater was screened through a 2.5 mm sieve. Pertinent characteristics of the dairy wastewater used in this study are given in Table 1. Prior to filling the reactors, the wastewater was thoroughly mixed. Each reactor was then filled with 4 l of this well-mixed wastewater ready for the aeration treatment. Prior to commencing the aeration treatment, however, the wastewater in both reactors was again thoroughly stirred using a recirculation pump (Model 2E-38N, Little Giant Pump Co., Oklahoma City, OK) and a sample of approximately 100 ml was drawn from corresponding side-ports in each reactor for laboratory analyses. Similar sampling was done every day (at 11:00 am) from the same ports for the duration of the study.

Table 1 – Pertinent characteristics of the raw dairy wastewater used in this study

Total solids (TS), $\text{g}\,\text{l}^{-1}$	11.02 ± 4.70
Total volatile solids (TVS), $\text{g}\,\text{l}^{-1}$	6.97 ± 3.93
pH	7.78 ± 0.00
Chemical oxygen demand (COD), $\text{g}\,\text{l}^{-1}$	13.75 ± 5.91
Total Kjeldahl nitrogen (TKN), $\text{mg}\,\text{l}^{-1}$	1027 ± 21
Total ammoniacal nitrogen (TAN), $\text{mg}\,\text{l}^{-1}$	651 ± 6

Laboratory analyses were performed immediately after the sampling whenever possible and if not, the samples were frozen for future analyses. Before conducting the analyses, frozen samples were allowed to thaw and equilibrate with the room temperature. The COD was measured using the standard ampule method (Adams, 1990). The analyses of TVS, total solids (TS), total Kjeldahl nitrogen (TKN), and total ammoniacal nitrogen (TAN) were performed according to standard methods (APHA, 1998). The pH, oxidation–reduction potential (ORP), and DO of the reactor contents in both reactors were recorded more frequently during the first day of treatment and once a day (at 11:00 am) for the remainder of the study period.

3. Results and discussion

3.1. *Oxidation–reduction status during treatment*

The oxidation–reduction status as indicated by both ORP and DO levels during the limited-aeration treatment at the two aeration rates (R1 and R2) is presented in Fig. 1. During the first 3–4 days of aeration, the DO remained close to the detection limit while according to the schedule proposed by Charpentier *et al.* (1987) for describing oxidation–reduction status based on ORP levels, the oxidation-reduction status remained in the anoxic regime (−30 to 100 mV). This ORP range is much higher than the level of −50 mV ORP suggested by Evans *et al.* (1986) for minimal aerobic activity. In essence, it appears that whatever limited oxygen reaches the wastewater via the limited-aeration air is consumed as quickly as it is delivered.

The gradual decline in ORP and the somewhat stagnant DO levels represent the more active microbial degradation phase of wastewater or the consumption of the easily degradable organic matter in the wastewater. This is sometimes referred to as the fast-rate degradation stage in the organic matter degradation kinetics. The end of the fast-rate oxidation stage is indicated by a rapid rise in the ORP of the wastewater, which is also marked by a parallel step-rise in the DO. The end of fast-rate is the beginning of the slow-rate oxidation/degradation and marks the slowing down of microbial activity most probably because only the more recalcitrant organic matter is remaining. For practical purposes, this then defines the critical wastewater stabilisation point that can be used to control the end of the limited-aeration pre-treatment of dairy wastewater suggested in this study. Beyond this point, both DO and ORP increase rapidly and environment in this wastewater remains completely aerobic.

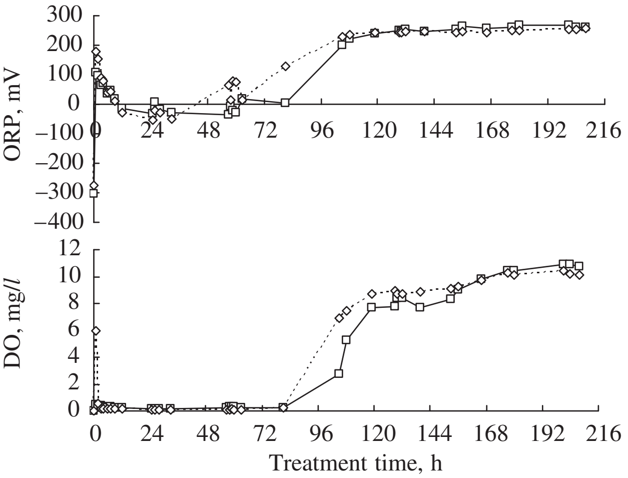

Fig. 1 – Changes in oxidation–reduction potential (ORP) and dissolved oxygen (DO) with time during aeration treatment: ····◊···, R1; ——□——, R2.

3.2. *Wastewater organic strength profile*

The percentage reductions in TVS and COD during the limited-aeration treatment of the dairy wastewater are presented in Fig. 2. Within the range of experimental errors, the respective reductions at both the lower and the higher aeration rates were essentially the same. Evidently, the two-fold difference in the aeration rates did not significantly alter the degradation rates of both the TVS and the COD. Between days 6 and 8 of treatment, the period when maximum removal seemed to have been achieved, approximately 70% reduction of both COD and TVS were observed at both aeration rates. The reduction in COD is comparable to the 76% reduction obtained in a similar study in 9 days with swine wastewater (Ndegwa, 2004). Within the control study, only approximately 20% reduction in both COD and TVS was achieved during the same time.

Linear regression equations between the COD and the TVS of the dairy wastewater during the limited-aeration treatment shown in Fig. 3 indicate excellent linear relationships between COD and TVS, at the individual aeration rates and also for the pooled data. These linear regressions are highly

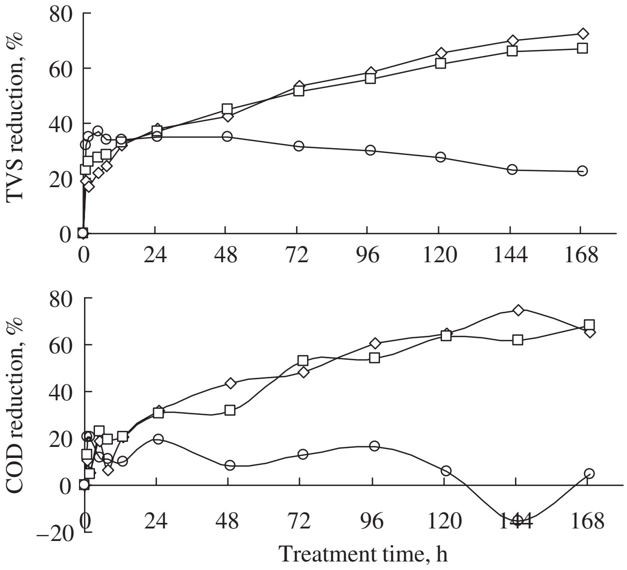

Fig. 2 – Reduction of total volatile solids (TVS) and chemical oxygen demand (COD) during the treatment: —◊—, R1; ——□——, R2; ——○——, R3 (control).

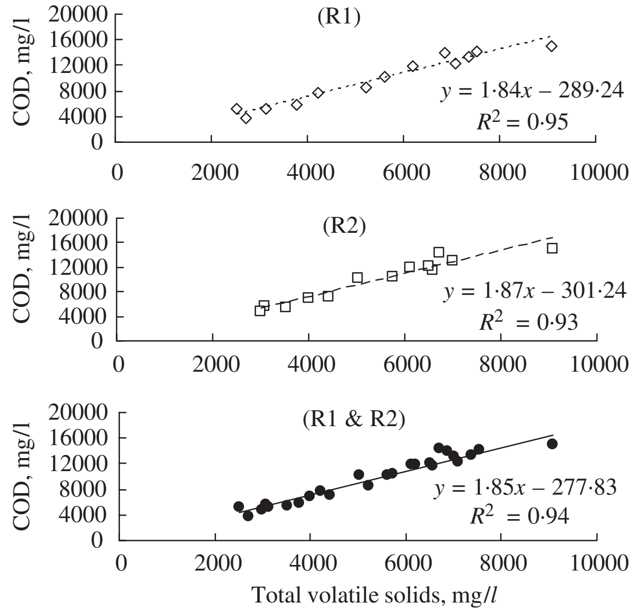

Fig. 3 – Linear regressions between chemical oxygen demand (COD) and total volatile solids (TVS) during limited-aeration treatment: ◇, R1; □, R2, ●, R and R combined; · · · · ·, linear regression for R1 data; –·–·–, linear regression for R2 data; ——, linear regression for combined R1 and R2 data; R^2, coefficient of determination.

significant in the range of 0.96 and 0.97. This observation is not totally unexpected because COD, which is usually an alternate to BOD, is essentially a measure of degradable organic matter; just like the volatile solids. It is evident from these observations, therefore, that any of these parameters can be used to monitor the stabilisation of the dairy wastewater as well as to describe its kinetics of bio-stabilisation. The latter is discussed in detail in the next section of this article.

3.3. *Kinetics of bio-stabilisation*

Bio-stabilisation refers to the degradation of organic materials during biological treatment processes and is usually defined by a bio-stabilisation constant, which essentially indicates the rate at which the organic material is degraded (Metcalf & Eddy Inc., 1991; Adani *et al.*, 2002). Assuming first-order kinetics model to describe organic matter degradation, Eq. (1) can be used to estimate decay of the TVS, the BOD or the COD:

$$S_t = S_0 e^{-kt}, \tag{1}$$

where S_t is the mass concentration of substrate at time t in $\mathrm{g\,l^{-1}}$, S_0 is the initial mass concentration of substrate in $\mathrm{g\,l^{-1}}$, k is the bio-stabilisation constant in $\mathrm{h^{-1}}$ or $\mathrm{day^{-1}}$, and t is the time in h or day. In this study, TVS and COD were considered as the substrates for the determination of the stabilisation constants and the results were compared.

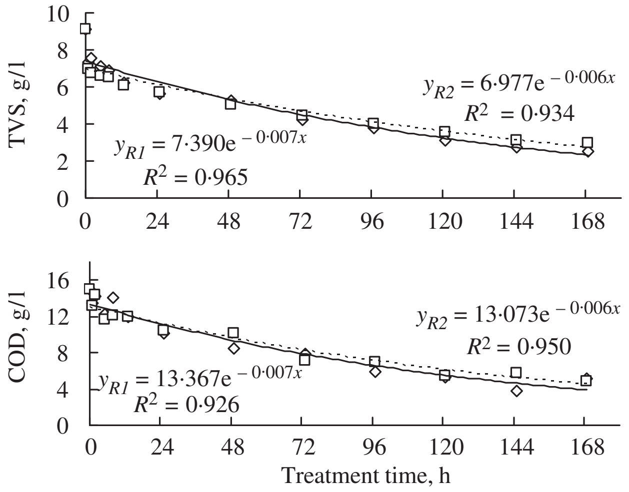

Fig. 4 – Kinetics of bio-stabilisation during the limited-aeration treatments of dairy wastewater: ◇, R1; □, R2; ——, first-order regression for R1 (higher aeration rate data); · · · · ·, first order regression for R2 (lower aeration rate) data; R^2, coefficient of determination.

The kinetics of both the TVS and the COD of the dairy wastewater during the low-intensity aeration are shown in Fig. 4. The first-order model assumption of the dairy wastewater degradation during this treatment is confirmed by the first-order regression equations, which are highly significant as shown by the high correlation coefficients ranging between 0.96 and 0.98. Based on these first-order regression equations for degradations of TVS and COD, the two parameters were similar in describing the dairy wastewater bio-stabilisation. At the higher aeration rates (0.067 l [air] $\mathrm{l^{-1}}$ [manure] $\mathrm{min^{-1}}$), both TVS and COD indicate a value of 0.168 $\mathrm{day^{-1}}$ for the bio-stabilisation constant k, while at the lower aeration rates (0.034 l [air] $\mathrm{l^{-1}}$ [manure] $\mathrm{min^{-1}}$) the bio-stabilisation constant was 0.144 $\mathrm{day^{-1}}$ for both the TVS and COD. The bio-stabilisation rate of dairy wastewater k_{dairy} of 0.168 $\mathrm{day^{-1}}$ is close to the bio-stabilisation rate observed in an earlier study for pig manure ($k_{pig} = 0.164$ $\mathrm{day^{-1}}$) subjected to similar aeration treatments (Ndegwa, 2004). Using the respective models obtained in this study, it was estimated that 50% bio-stabilisation (also known as half-life decay period) was achievable in approximately 4 and 5 days of limited-aeration treatment at the higher and lower aeration rates, respectively. In other words, by reducing the aeration rate by 50%, the half-life decay period is increased by 25%, while the decay rate is reduced by only approximately 14%. It is therefore more economically prudent to aerate at the lower airflow rate.

Past studies have recommended COD removal of approximately 50% via aerobic treatment for odour control from manure (Westerman & Zhang, 1997; Barker *et al.*, 1980; Humenik *et al.*, 1975). In this regard, 4 and 5 days of limited-aeration treatment are thus sufficient to control odour from the effluents in subsequent lagoon treatments. The results from the present study are similar to those of past studies on aerobic treatment of swine wastewaters at various aeration regimes, which indicated a mean residence time of between 1 and 6 days for adequate stabilisation (Ndegwa, 2004; Burton *et al.*, 1998). In addition, since the highest reduction of COD and TVS observed was only 70% during the entire 9 days of treatment it will thus cost approximately double to remove the next 20% assuming a constant daily operational cost for this system. The degradation rate is higher initially when the more degradable dissolved substrate that is usually responsible for wastewater instability and odour problems is consumed. Since the goal of the proposed treatment is to reduce as much of the organic load into the anaerobic treatment lagoons for further treatment without causing or raising air pollution concerns from the further treatment facilities, prolonged low-rate aeration treatments beyond the 50% reduction of COD or TVS is not economically justifiable. As previously pointed out, it may cost as much to remove the next 20% as it costs to remove the initial 50% of the COD or TVS.

3.4. *Effect on ammonia in the wastewater*

The single most important environmental concern associated with any aeration treatment is stripping of odour and other gaseous pollutants from the wastewater being treated. Livestock wastewaters usually contain large amounts of nitrogen and ammonia, and stripping is therefore, particularly important in aeration treatments of livestock wastewaters. The changes in the concentrations of TKN, TAN, and organic nitrogen (organic-N) are presented in Fig. 5. The control experiment indicates insignificant change in both TKN and TAN concentrations with treatment time. In contrast, at the aeration rates of 0.034 and 0.067 l [air] l^{-1} [manure] min^{-1}, reductions of TKN were 28% and 42% while that of TAN were 23% and 34%, respectively (Table 2). This is not surprising because higher ammonia stripping would be expected from higher airflow rates. However, during the first 4 days of treatment during which approximately 50% of both the COD and TVS were degraded, the TAN reductions were basically the same at both aeration rates at approximately 15%. It can, therefore, be inferred that if a 50% reduction in organic loading is targeted for removal prior to loading the dairy wastewater in to anaerobic lagoon, then either flow can be used without exacerbating ammonia loss during the pretreatment process.

In all cases, organic-N decreased significantly to approximately 61%, 56%, and 26% at the higher, the lower, and in the control experiment, respectively. In tandem with reduction of COD, it is evident that substantial organic-N was also mineralised to ammoniacal-N. This is believed to be probably the main explanation of the differences observed in the TKN and TAN percentage reductions during the aeration treatment, i.e., much more ammonia was lost than explained by the reduction in TAN because there was some form of replenishment of TAN from the mineralised TKN.

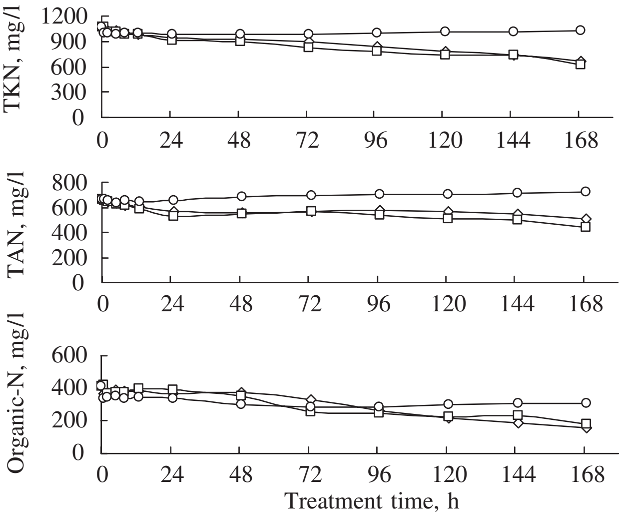

Fig. 5 – Effect of limited-aeration treatment on ammonia emission from the dairy wastewater: —◇—, R1; —□—, R2; —○—, R3 (control).

4. Conclusions

Experiments were conducted to study bio-stabilisation of dairy wastewater using limited-aeration treatment. The following process parameters were examined during the treatment process: (1) oxidation–reduction status; (2) degradation of chemical oxygen demand (COD) and total volatile solids (TVS); (3) kinetics of bio-stabilisation; and (4) loss of ammonia. The conclusions of these studies are as follows:

(1) During the first 3–4 days of limited-aeration treatments at the rates of 0.034 and 0.067 l [air] l^{-1} [manure] min^{-1}, the dissolved oxygen (DO) remained close to the detection limit but based on oxidation-reduction potential (ORP) levels the oxidation–reduction status were considered to be anoxic (−30 to 100 mV). Beyond the fourth day, the environment in the wastewater then remained aerobic.

(2) The maximum removal of both COD and TVS occurred by approximately day 8 of the limited-aeration treatments. Within this period approximately 70% reduction of both COD and TVS were observed at both the higher and the

Table 2 – Percentage changes in the wastewater total ammoniacal nitrogen (TAN), total Kjeldahl nitrogen (TKN), and organic nitrogen (organic-N) during treatment

Species	Initial concentration, mg l^{-1}	Final concentration, mg l^{-1}			Maximum change, %		
		R1	R2	R3	R1	R2	R3
TKN	1075	623	623	1028	−38	−42	−4
TAN	663	508	723	440	−23	−34	9
Organic-N	412	161	305	183	−61	−56	−26

lower aeration rates. Evidently, the two-fold difference in the aeration rates did not significantly alter the ultimate reduction of the organic matter content in the wastewater.

(3) Linear regression equations between the COD and the TVS of the dairy wastewater during the limited-aeration treatment indicated excellent linear relationships between COD and TVS manifested in significantly high correlation coefficients ranging between 0.96 and 0.97. Either of the two parameters can, therefore, be used to monitor the stabilisation of the wastewater as well as to describe and/or to determine the kinetics of bio-stabilisation.

(4) Bio-stabilisation constants of 0.168 and 0.144 day^{-1} were observed at limited-aeration rates of 0.067 and 0.034 $\text{l [air] l}^{-1}\text{ [manure] min}^{-1}$, respectively. Based on these constants, 50% bio-stabilisation (also known as half-life decay period) was achievable in approximately 4 and 5 days at the higher and the lower treatments, respectively. By reducing the aeration rate by 50%, the half-life decay period is increased by 25%, while the decay rate is reduced only by approximately 14%. It can therefore be inferred that it is more economically prudent to aerate at the lower than at the higher airflow rate to achieve intended organic strength reduction.

(5) A significantly higher loss in ammonia was unaccounted for at the higher aeration rate (34% net loss) than at the lower aeration rate (23% net loss). It is, therefore, plausible to conclude that more air ammonia stripping occurred at the higher airflow rate than at the lower airflow rate. This observation further supports the preceding conclusion.

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