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OVERVIEW OF THE BIOLOGICAL PROCESSES AVAILABLE FOR THE TREATMENT OF SUGARCANE MILL WASTEWATER

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ABSTRACT

Cane sugar production generates a high volume of wastewaters (1-20 m^3/sugarcane tonne) heavily polluted by suspended solids (5-12 g/l) and organic matter (2-8 g COD/l). Consequently, these wastewaters cannot be discharged directly in the environment without causing a negative impact and must be submitted to a physico-chemical treatment for removing the suspended solids followed by a biological treatment for removing soluble organic matter. The COD/BOD$_5$ ratio of these wastewaters indicates that they are easily biodegradable and practically amenable to any kind of biological treatment. A brief description of the existing different types of treatment is given in the article focussing on the advantages and disadvantages of each one. A table comparing them on the basis of the treatment unit size (volume and area), energy consumption, sludge production, final wastewater quality and staff qualification is given for a mill with the capacity to process 4,000 sugarcane tonne/day. It appears from the discussion that the treatment scheme which seems to be economically the most convenient consists of an anaerobic pre-treatment followed by an aerobic polishing. In some instances, the water produced by the anaerobic treatment may be of good enough quality to be at least re-used in sugarcane washing or irrigation.

RESUME

La production de sucre à partir de canne génère un grand volume d'eau usée (1 à 20 m^3/tonne de canne) fortement chargé en matières en suspension (5 à 12 g/l) et matières organiques (2 à 8 g DCO/l). En conséquence, ces eaux ne peuvent pas être rejetées telles quelles dans l'environnement sans y entraîner un impact négatif et doivent au préalable être débarrassées de leurs matières en suspension par un traitement primaire physico-chimique et de leur contenu en matières organiques solubles par un traitement secondaire biologique. Le rapport DCO/DBO$_5$ de ces eaux usées indique qu'elles sont facilement biodégradables et que pratiquement tous les modes de traitement biologique peuvent leur être appliqués. Une description succincte de ces modes de traitement est donnée dans l'article en s'attachant plus particulièrement aux avantages et inconvénients de chacun. Un tableau comparant les différents procédés sur la base des dimensions des ouvrages nécessaires (volume et surface), consommation énergétique, production de boue, qualité finale de l'eau et qualification du personnel nécessaire à l'opération est également donné pour une sucrerie traitant 4000 tonnes de canne par jour. Il sort de la discussion que le schéma de traitement qui semble économiquement le plus intéressant consiste en un prétraitement par voie anaérobie suivi d'un traitement de finition aérobie encore qu'un simple traitement anaérobie puisse dans certains cas être suffisant, tout au moins pour produire une eau recyclable en lavage de canne ou utilisable pour son irrigation.

RESUMEN

La producción de azúcar de caña genera un gran volumen de aguas residuales (1 a 20 m^3/tonelada de caña) altamente cargadas en sólidos suspendidos (5 a 12 g/l) y materia orgánica (2 a 8 g DQO/l). Por lo tanto, estas aguas no pueden ser descargadas tal cual en el medio ambiente sin causar un impacto negativo y deben de ser sometidas a un tratamiento primario fisico-químico para eliminar los sólidos suspendidos seguido por un tratamiento biológico secundario para eliminar la materia orgánica soluble. La relación DQO/DBO$_5$ de estas aguas indica que son fácilmente biodegradables y prácticamente accesibles a todos los tipos de tratamientos biológicos. Una descripción conceptual de estos modos de tratamiento se presenta en el artículo enfocándose particularmente en las ventajas y desventajas de cada uno. Una comparación de los diferentes procesos sobre la base de las dimensiones de las unidades necesarias (volumen y superficie), del consumo energético, de la cantidad de lodo producido, de la calidad final del agua y de la calificación del personal necesario para la operación se presenta también bajo la forma de una tabla. Los cálculos están hechos para un ingenio que procesa 4000 toneladas de caña de azúcar al día. Resulta de la discusión que el esquema de tratamiento que parece ser económicamente el más interesante corresponde a un pre-tratamiento por vía anaerobia seguido de un pulimiento aerobio, aunque un simple tratamiento anaerobio pudiera en algunos casos ser suficiente para producir un agua de calidad adecuada para el lavado de la caña o su riego.

KEYWORDS

Anaerobic digestion, wastewater, lagoon, pollution, environmental protection, sugar mill wastewater, sugarcane

ABBREVIATIONS

AS	Activated sludge, which can be operated at low, medium or high rate.
BD	Biodisks
BOD_5	Biochemical oxygen demand at 5 days
BVF	Bulk volume fermenter (low rate upflow anaerobic sludge bed reactor)
COD	Chemical oxygen demand
EGSB	Expanded granular sludge bed
SF	Submerged filter
SS	Suspended solids
TF	Trickling filter
VSS	Volatile suspended solids
UASB	Upflow anaerobic sludge bed

INTRODUCTION

Sources and characteristics of the wastewaters.

Cane sugar and beet sugar processing requires large volumes of water for its operation. In the case of cane and in the absence of any closed loop, this requirement can be about 20 m^3 per tonne of milled cane (or 200 m^3/tonne of produced sugar), which also corresponds in first estimation to the volume of wastewater potentially released to the environment (Anonymous, 1998). When good water management is implemented using recycling systems, water consumption and thereby wastewater discharge can be lowered to 0.9 – 2 m^3/tonne of cane (Baguant and Ramjeawon, 1996; Ramjeawon, 2000). The discharge cannot be reduced further easily because it includes the water originally present in the cane (0.7 tonne or m^3 of water/tonne of cane) and which is not lost with bagasse (around 0.275 tonne of bagasse with 50% moisture/tonne of cane). Most of the resulting wastewater volume (approximately 75%) comes from the cane washing when it is applied (Figure 1; Chang *et al.*, 1990). Other wastewater sources correspond to some of the cooling waters, the boiler blowdown and the overflow of the scrubbers used to remove the fly ash generated during the combustion of bagasse, but also water used for washing floors in different workshops, mills and other equipments. Sometimes, the wastewater even includes the condensed waters but since they are poorly contaminated they are most often mixed with the cooling waters of the condenser and recycled (Noël and Vellaud, 1977). For a detailed analysis of water management in cane sugar mills, readers are referred to two excellent reviews on the subject (Baguant and Ramjeawon, 1996; Ramjeawon, 2000).

The physico-chemical properties of the wastewater generated by the sugar factories obviously vary from one plant to another because of differences in the outputs of the various processes used, the mode of cane crop, the type of soil on which it was cultivated, the varieties employed, and the water quality and quantity used in the mill (Yang *et al.*, 1991). Effluents of all the factories however are characterized by a high concentration of organic matter (expressed as Chemical Oxygen Demand or COD) and suspended solids (SS), which can rise to 8 and 12 g/l (Table 1), respectively. The nitrogen concentrations are also normally significantly high (Anonymous, 1998) whereas other salts (P, K, SO_4^{2-}) are in low concentration (Chang *et al.*, 1990). The organic matter present in the effluents corresponds primarily to sugars coming from losses in various points of the manufacturing process and to organic acids (such as acetic, propionic, butyric acids) resulting from their fermentation in the effluent evacuation trenches and storage areas. The suspended matter corresponds to soil particles recovered during the cane washing and bagasse residues (Yang *et al.*, 1991).

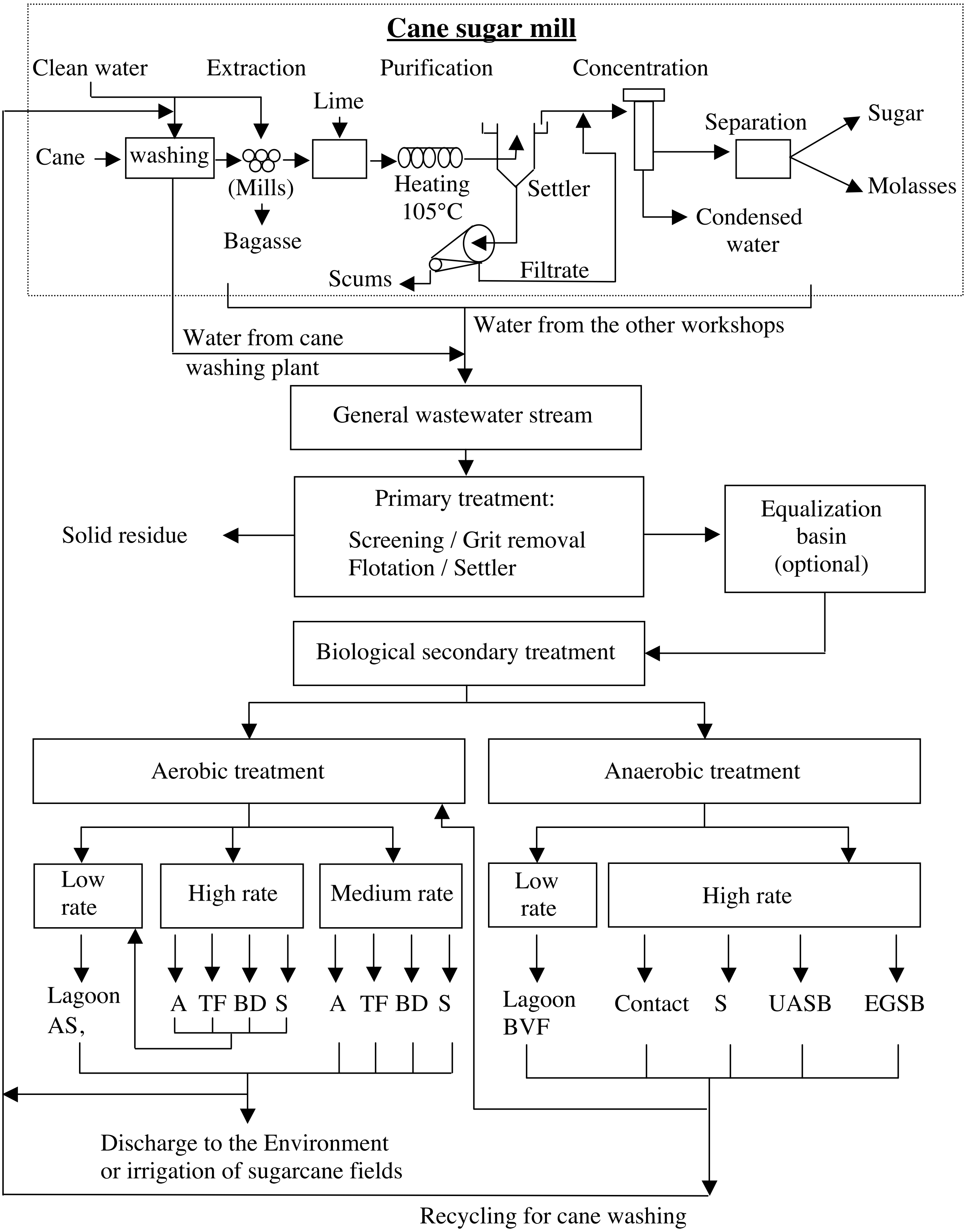


Figure 1. Diagram showing the basic operations in a cane sugar mill, the sources of wastewater and the different options, which can be applied for their treatment (for the abbreviations see the first page of the paper; the part about the sugar mill was adapted from Noël and Vellaud, 1977).

Environmental impact

Although this may still happen in many cane sugar producing countries, those effluents that pollute the enviroment cannot be released as the adverse effects on its ecological balance will be apparent. It is clear, for example, that by SS sedimentation, a rapid siltation and filling of the receiving body would occur, especially in small rivers with low flow. The SS would also generate turbidity having a negative impact on the photosynthesis of the aquatic flora. Further, soluble organic matter, by stimulating the microbial activity, markedly reduce the dissolved oxygen concentration levels to less than 1 mg/l, which are inadequate for many forms of aquatic life. This has been observed in Australia, Cameroon and Mauritius in the natural water bodies receiving the discharge from sugar mills (Pearson and Penridge, 1987; Takougang et al., 1993; Ramjeawon and Baguant, 1995). In few cases, however, paradoxically, this led to the elimination of certain parasitic disease vectors and had a positive effect on human health (Takougang *et al*., 1993; Cot *et al*., 1995). The fall of dissolved oxygen concentration would also be accompanied by the production of bad smells, intolerable for the neighbourhood in the case of sugar factories built near strongly urbanized zones. Pollution of groundwater due to sugarcane mill effluents has also been reported in India (Pawar *et al*., 1998). This is particularly of concern when the populations use the same groundwater as a source of drinking water.

Table 1. Composition of sugarcane mill wastewater and discharge guidelines of the World Bank (after Chang *et al*., 1990; Sastry *et al.,* 1990; Baguant and Ramjeawon, 1996; Anonymous, 1998; Ramjeawon, 2000).

Parameter	Raw wastewater	World Bank discharge guidelines
COD (mg/l)	2300 - 8000	250
BOD_5 (mg/l)	1700 - 6600	50
COD/BOD_5	1.4 - 2.5	NA*
SS (mg/l)	630 - 12000	50
Total nitrogen (TKN-N) (mg/l)	4 - 70	NA
(NH_4-N) (mg/l)	NA	10
Total phosphorus (mg/l)	0.9 – 10.5	2
COD/N/P	< 100/0.55/0.08	NA
Oil & Grease (mg/l)	2.4 - 45	10
Temperature (°C)	32 - 40	increase ≤ 3°C
pH	4.4 - 7.6	6 - 9

* NA: not available or not applicable.

VARIOUS STEPS AND VARIOUS MODES OF TREATMENT

The previous considerations show that water effluents from cane sugar mills must be treated before discharge. The importance of the treatment to be applied will depend on the local environmental regulations, which must be based on the self-purification capacity of the receiving body (Ramjeawon and Baguant, 1995) or, in the case of a recycling, in production or use in irrigation, on the water quality necessary for each of these activities. At least, and in agreement with the World Bank directives (Table 1), COD and SS concentrations in the water released into the environment should not exceed 250 and 50 mg/l, respectively. Precise discharge limits for thirteen countries can be found in two papers (Purchase et al., 1995; Ramjeawon and Baguant, 1995). The achievement of these values requires the installation of a primary treatment for the elimination of the suspended matter followed by a secondary treatment for lowering the soluble COD.

Primary treatment

Frequently in cane sugar factories, this stage is carried out in large open sedimentation basins with hydraulic retention times up to several days (Chang et al., 1990; Calero et al., 2000). Very often, these installations generate bad smells due to the rapid development of anoxic conditions and so can become a problem for the neighbourhood. An alternative could be to implement more compact units consisting of a more or less fine screening system according to the size of the particles to remove, followed by a desanding unit to eliminate the mineral particles of high density. According to the characteristics of the remaining SS (floating or easily settling) and the required elimination level, these two units could be complemented by a primary settler or a dissolved air flotation system. This last system would also have the advantage of eliminating the oils and greases coming from the machinery (Figure 1). The design of these units is very important because the efficiency of the secondary treatment will greatly depend on the SS reduction achieved at this level. An additional basin with a reduced residence time (from 12 to 24 h) could remain necessary according to the type of secondary treatment in order to protect it from significant fluctuations of organic loads, pH, etc (Figure 1).

Secondary treatment

As the COD/BOD_5 ratio of the sugar factory effluents is below 2.5 (Table 1), this indicates that their organic matter is very easily biodegradable which is logical since it corresponds primarily to sugars and volatile fatty acids. The pH and the temperature of these effluents are also compatible with a biological treatment (Table 1). The pH may however require adjustment if it is too acidic ($<$ 6-6.5). This indicates that in theory it should be possible to use all the existing biological treatments. As a consequence, the choice of a process will first be dictated by economic considerations which are strongly influenced by the local conditions such as the available surfaces, the land cost, the installation complexity, the workers' qualification and the inoculum availability. In a synthetic way, biological treatments are divided in two categories, the aerobic and the anaerobic ones (Figure 1).

Aerobic treatment. Aerobic treatments use bacteria, which need oxygen to develop, and which mineralize the organic matter into CO_2 and H_2O (equation 1).

Organic matter (100% COD) + O_2 ---------> CO_2 + H_2O + biomass (50% COD) (equation 1)

This makes these processes extremely energy consuming. Actually due to its low water solubility, oxygen must be brought to the water by a forced mechanical aeration in a quantity equivalent to that of the COD to degrade and, according to the type of aerators, 0.5 to 1.6 kWh are necessary to transfer 1 kg O_2 (García Encina et al., 1986; Fonade et al., 2001). The energetics aspect may not be of so much importance in cane sugar mills where the energy requirements are met by combustion of bagasse (Clarke, 1997). Part of this cheap energy source could be used to generate the electricity necessary for the operation of an aerobic treatment plant in case it is located not too far from the mill. The aerobic processes are also high sludge producers because the micro-organisms that are involved reproduce rapidly. Indeed, they can transfer approximately 50% of the carbon initially present in the organic pollution into carbon of new cells (equation 1). These sludges, because of their biological nature, must be stabilized before being discharged to the environment. Since the micro-organisms need nitrogen, phosphorus and sulphur to synthesize their proteins, nucleic acids (genetic material) and ATP (adenosine triphosphate, chemical form of energy reserve), this implies also that a COD/N/P/S ratio of about 100/4.5/1.13/0.375 must be maintained in the water. Consequently the wastewater must be dosed with these compounds if they are not present naturally in adequate proportions, which is the case of sugar mill effluents (Table 1). Besides their high growth rate, the aerobic micro-organisms are able to decrease the BOD_5 and COD concentrations to very low levels producing usually a water of sufficient quality to be rejected directly into the environment.

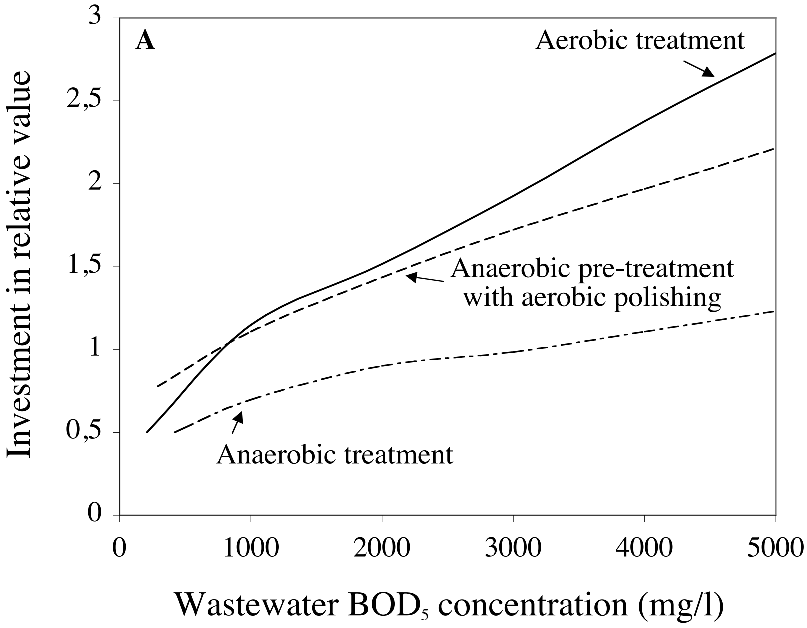
Anaerobic treatment. Contrary to the previous mode of treatment, the anaerobic processes utilize a trophic chain of micro-organisms which do not use oxygen for their metabolism and which transform, in its absence, the organic matter into CH_4 and CO_2 (equation 2).

Organic matter (100% COD) --> ---> ---> CH_4 + CO_2 + biomass (10% COD) (equation 2)

The energy consumption of these processes are then limited to that of pumping operations and so they are economical in this aspect. They can even be energy producers if the CH_4 formed at a rate of 0.35 m^3 (0°C, 1 atm) per kg of degraded COD, and the combustion of which generates roughly 12 MJ (Lescure *et al.*, 1986), is valorised to operate a boiler or produce electricity. For the reason mentioned above, this source of energy is obviously of little importance for the sugar mills. It is, however, still possible to consider the use of the produced CH_4 as a domestic fuel for the populations established around the factories if a distribution network (which can be very simple) is set up. As an example of the viability of this concept, such a network has been successfully implemented in Guatemala for the centralized anaerobic treatment of urban wastewater (Conil *et al.*, 1996).

In addition to their low energy consumption, the anaerobic processes are also characterized by the fact that they produce approximately five times less biomass than the aerobic ones because the fermentation (as opposed to respiration) converts only 10% of the carbon initially present in the organic pollution in the form of new cells (equation 2). Correspondingly, the requirements for nitrogen, phosphorus and sulphur are reduced in the same proportion and as a consequence, a COD/N/P/S ratio of only 100/1/0.225/0.075 has to be maintained. Another important characteristic of these processes is their flexibility towards discontinuous feeding. Indeed, the degradation ability of their biomass decreases very slowly over time under starving conditions, which means that these systems can be restarted in a matter of days after several months of inactivity. This is particularly adapted to cane sugar mills for which the production campaign covers only 140 to 250 days of the year (Anonymous, 1998). The principal disadvantage of these processes is that micro-organisms cannot reduce the BOD_5 and COD concentrations to levels comparable to those achieved by an aerobic treatment. Consequently, if a direct discharge to the environment is planned, they should be complemented by a post-treatment step which will probably be aerobic. Nevertheless, it is possible that for other uses (recycling in the washing of cane, irrigation of the fields), the quality of the water obtained by a simple anaerobic treatment will be more than sufficient. Another disadvantage of the anaerobic processes lies in the fact that they should be preferentially inoculated in order to reduce their start-up time and that an inoculum with adequate characteristics or in sufficient quantity will not necessarily be available in the vicinity implying its purchase and/or transport from remote zones.

Economic aspects. The low energy consumption, low requirement of nutrients (N, P, S) and weak sludge production of the anaerobic systems suggest intuitively that they correspond to a treatment option economically more attractive than those using aerobic processes. In their comparative study, Eckenfelder et al. (1988) have shown that if this economic advantage was not so clear for the treatment of diluted effluent (low concentration of organic matter), it was well the case for the effluents containing more than 1000 mg BOD_5/l, which include those from cane sugar mills. The graphs established by these authors (Figure 2) show that above this concentration, the investments and operational costs of an anaerobic treatment are always lower than those of an aerobic treatment and that the difference increases markedly with the BOD_5 concentration. It is important to see also that this remains true even when an aerobic post-treatment is taken into account in order to reach the same final water quality. These curves were established for specific aerobic and anaerobic treatment processes but the tendencies remain true independently of the process in consideration.



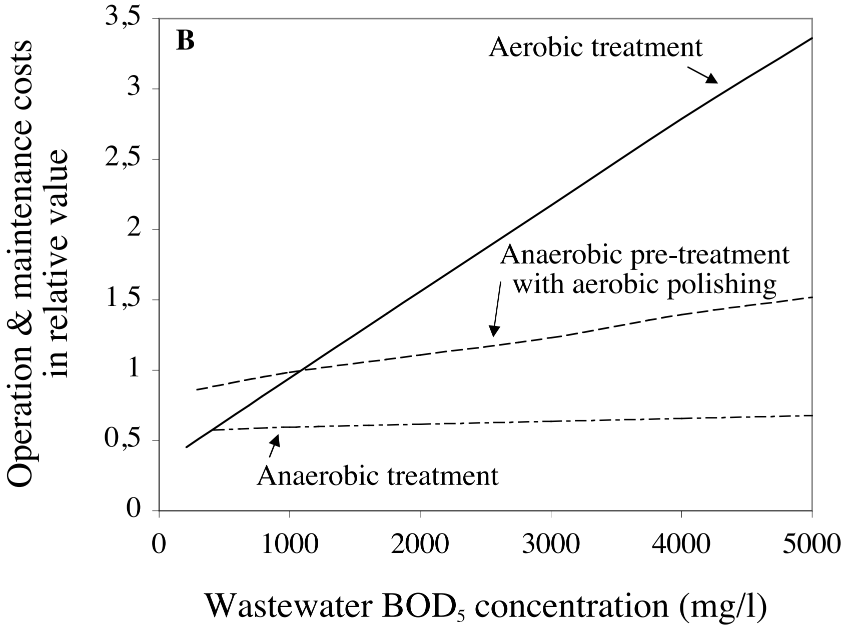


Figure 2. Comparison of the investments (A) and of the operation costs (B) between (i) an aerobic treatment by activated sludge, (ii) an anaerobic treatment with a UASB reactor and (iii) an anaerobic treatment with a UASB reactor followed by aerobic polishing with activated sludge (according to the graphs developed by Eckenfelder et al., 1988, reproduced with permission from the copyright holders, IWA).

In view of the previous elements and in first analysis, it seems that for cane sugar mill water effluents, the economically most viable treatment option corresponds to an anaerobic stage followed by aerobic polishing if the objective is a direct discharge to the environment. Several options of treatment processes can, however, be considered for each stage of the treatment.

DIFFERENT AEROBIC AND ANAEROBIC TREATMENT PROCESSES.

Without entering into a detailed description that the reader will find without difficulty in the specialized literature (for instance: van den Berg, 1984; Lescure et al, 1986; Young and Yang, 1989; Hickey et al, 1991; Metcalf and Eddy, 1991; Nähle, 1991; Defour et al, 1994; Kleerebezem and Macarie, 2003), the different systems of treatment, independently of their aerobic or anaerobic character, can be classified into low and high rate. In the case of aerobic processes an additional class of medium rate can be defined (Figure 1). As their name indicates, the low rate processes allow the treatment of a small quantity of COD and thus, in the same way, of a low volume of effluent per unit of reactor volume, while the medium and high rate processes allow the opposite. The first are generally implemented in the form of lagoons without devices for the retention of biomass whereas the others are equipped with such devices. These equipments allow the independence of the cellular retention time from the hydraulic retention time and thus increase the concentration of biomass in the reactors and consequently the load which can be applied.

The biomass retention devices can be external or internal to the reactors.

The external devices correspond usually to secondary settlers where the biomass is recovered by sedimentation and then reintroduced in the reactor. This scheme gave rise to the classic activated sludge aerobic process and its equivalent in anaerobiosis called "anaerobic contact". More recently, the secondary settler was replaced by ultrafiltration units giving rise to membrane reactors allowing the rejection of an effluent without SS. Their utilisation still remains limited however. In some cases, the decanter has been also replaced by a flotation unit.

The internal devices can be of two types, (i) supports of various kinds (Raschig rings, disks, tubes, sand, etc) fixed or mobile, or (ii) a secondary settling tank built-in to the body of the reactor. Processes utilizing a support in aerobiosis are (i) the trickling filters, (ii) the submerged filters, (iii) the biodisks and (iiii) the fluidized bed reactors. Once again, the equivalents of these processes are found in anaerobiosis. The reactors with built-in decanters are only found among the anaerobic processes. They allow the self-aggregation of the micro-organisms in the form of granules, which can reach up to several millimetres in diameter giving them good sedimentation properties. According to the upflow velocities at which they operate, these reactors are divided into sludge bed (UASB, IRIS) and expanded granular sludge bed (EGSB) reactors.

Practically all the former processes have been applied in sugar mills, at least in those processing beet sugar (Huss, 1979; Schiweck et al., 1985; Verrier et al., 1985; Lescure et al., 1986; Naehle, 1990; von der Emde and Kroiss, 1991; Fonade et al., 2000; Brookes, 2001), which have been in advance for the protection of the environment because they were under pressure due to the early adoption of restrictive environmental legislations in the sugar beet producing northern countries. The UASB and IRIS reactors were even originally developed specifically for the wastewater of the beet sugar industry (Lescure and Bourlet, 1979; Lettinga et al., 1980; Lescure et al., 1986; Kuzminski et al., 1991). Much less information is available in the literature about wastewater treatment in cane sugar mills and this information is most often restricted to aerobic systems (Bevan, 1971; Bruijn, 1977; Aitken et al., 1980; Calero et al., 2000). The downflow and upflow submerged filters and the UASB reactor seem to be the only anaerobic processes for which detailed studies on real effluents of cane sugar factories have been published (Sastry et al., 1990; Yang et al., 1991; Sánchez Hernández and Travieso Cordoba, 1994; Baguant and Ramjeawon, 1996; Ramjeawon et al., 1997). These works correspond however to laboratory and pilot scale and as far as we know no information is available about their application on an industrial scale.

A preliminary comparison of some of the previous processes, based on the dimensions of the installations (volume of the reactors and surfaces used including those of the secondary settlers),

Table 2. Comparison of some of the different treatment options available for a mill processing 4000 sugarcane tonne/day and discharging 200 m^3 wastewater/h and 10 tonnes COD/day

Different biological treatment systems applicables	**Aerobic processes**				**Anaerobic processes***				
	Aerated lagoon	Activated sludge Low rate	medium rate	high rate	Lagoon	Contact	Submerged filter	UASB	EGSB
Operating conditions applicable to the different systems									
F/M (Food to Microorganism ratio) (kg COD/kg VSS.d)	?	0.2	0.5	1	?	0.54	0.32	0.28	0.35
Biomass concentration in aerated tanks and digesters (g VSS/l)	?	4	4	4	?	7	20	30	30
Organic volumetric loading rate (kg COD/m^3.day)	0.2	0.8	2	4	0.35	3.79	6.31	8.33	10.42
Hydraulic retention time (days)	10.4	2.6	1	0.5	6	0.55	0.33	0.25	0.2
Overflow rate in secondary settlers (m^3/m^2.h)	-	1.125	1.125	1.125	-	0.2	-	-	-
Expected treatment performances									
Total COD removal in %	93	97	95	80	90	90	90	89	80
Final water quality (mg COD/l)	146	63	104	417	208	208	208	229	417
Dimension of the installations necessary for the treatment									
Usual height of basins and reactors (m)	4	5	5	5	8.5	17.5	12	7	14
Volume of the reactors (m^3)	50000	12500	5000	2500	28800	2640	1584	1200	960
Surface occupied by the reactors (m^2)	12500	2500	1000	500	3388	151	132	171	69
Surface occupied by the secondary settlers (m^2)	-	178	178	178	-	1000	-	-	-
Total surface necessary for the treatment (m^2)	12500	2678	1178	678	3388	1151	132	171	69
Methane									
Yield (m^3 CH_4 0°C, 1 atm/kg COD removed)	-	-	-	-	0.35	0.35	0.35	0.35	0.35
Production (m^3 CH_4 0°C, 1 atm/day)	-	-	-	-	3150	3150	3150	3115	2800
Sludge									
Yield (kg VSS/kg COD removed)	?	0,1	0.4	0.7	0.08	0.05	0.05	0.07	0.05
Production (kg VSS/day)	?	970	3800	5600	720	450	450	623	400
Energetic aspects									
Consumption due to aeration** & pumping operations (kWh/day)	5813**	6063**	5938**	5000**	only pumping				
Potential production by methane combustion (kWh/day)	-	-	-	-	30024	30024	30024	29690	26688
Inoculation	no	no	no	no	preferable	yes	yes	yes	yes
Qualification of the personal to operate the treatment plant	low	high	high	high	low	high	high	high	high

* The hydraulic retention time, settler overflow rate, biomass concentration, sludge yield as well as the reactor performances and height were taken from industrial experiences in beet sugar mills (Huss, 1979; Schiweck et al., 1985; Verrier et al., 1985; Brookes, 2001) and lab or pilot scale experiences on cane sugar mill for UASB reactor (Yang et al., 1991; Ramjeawon et al., 1997). Aeration was considered to be performed with hydro-ejectors, which transfer 1.6 kg O_2/kWh (Fonade et al., 2000). For CH_4 it was considered that the removal of 1 kg COD produces 0.35 m^3 CH_4, which generates 12 MJ after combustion (Lescure et al., 1986) and that 1 MJ = 0.278 kWh.

their energy consumption, sludge production, need for inoculation, final water quality and qualification level of the staff needed for their operation is presented in Table 2. All the points were calculated considering the case of a sugar mill treating 4000 tonnes of cane/day and discharging 200 m^3/h of wastewater and 10 tonnes of COD/day.

This table clearly shows that the anaerobic processes consume much less space and volume than their aerobic counterparts (compare low rates with low rates; high rates with high rates) because their depth and biomass concentration are not limited by the oxygenation and agitation capacities of the aerators. Under these conditions, the height/length (or height/diameter) ratio of the anaerobic systems can be higher than that of the aerobic ones, as well as the organic volumetric load that they can receive. It can be seen that the energy that they produce as methane and which could be recovered by combustion is around or slightly over five times that consumed by the aerobic systems. On the other hand, it is equivalent to less than 3% of that obtained by bagasse combustion, considering that 275 kg of bagasse with 50% of moisture are produced per tonne of cane and that 3700 kJ are recoverable per kg of bagasse (Noël and Vellaud, 1977; Clarke, 1997). Notwithstanding, this corresponds to 29 tonnes of bagasse per day which could be used for other purposes with higher added values (i.e. paper manufacture) instead of being simply burnt. As expected, the effluent quality given by the low and medium rate aerobic activated sludge systems is better than that achieved by the anaerobic ones. This is not the case of the high rate aerobic systems, which must be considered as pre-treatments and would require to be followed by low rate aerobic reactors in order to achieve an effluent quality compatible with a discharge to the environment. Such a high rate aerobic unit in series with a low rate would allow, however, to reduce the size of the treatment plants compared to the ones designed with one sole aerobic unit operated at low or medium rates. In any case, it is important to keep in mind that it is difficult to control high rate activated sludge and so to obtain a stable operation. Moreover, they often present problems of odours and scum.

In the case of a wastewater containing initially approximately 2000 mg COD/l, the COD concentration after a simple anaerobic treatment may be lower than the value given as guideline by the World Bank for direct discharge of sugar mill effluents to surface waters (Table 1). At least, very often, the anaerobically treated effluent will be of good enough quality for reuse in the washing of cane (Chang et al., 1990). This corresponds to the first step towards the operation of sugar mills in water closed loop without discharge to the environment (Hsieh et al., 1995; Jensen and Schumann, 2001). Nevertheless, it is important to keep in mind that the zero discharge objective will be achieved only if the accumulation in the recycle line of micro-organisms, calcium hardness, salts and other compounds which are not anymore released to the environment can be addressed. In fact, such an accumulation would probably affect the operation of the sugar mill and the quality of the final product as this has been observed in another industrial sectors such as the paper mills which intended to adopt a zero discharge strategy (Habets et al., 1997).

Coming back now to the different treatment processes, except the low rate ones, they all have the disadvantage of requiring highly qualified personnel for their operation. The low rate processes are also those which imply the lowest investments, provided that the surface necessary for these installations is already the property of the sugar mill or that the land cost is extremely low. The losses in sugar production due to the non-utilization of the surfaces normally occupied for the culture of the cane will also have to be taken into account in the selection of technology. The design of this kind of system will moreover require particular precautions:

(1) the bottom and the walls of the basins generally built in earth will have to be waterproofed with a liner or by another means in order to avoid the pollution of the aquifer by infiltrations (Pawar et al., 1998).

(2) the wastewater will have to be fed at various points and towards the bottom in order to avoid the formation of short circuits and thus of dead volumes useless for the treatment. With the same objective, baffles could be installed in the lagoon.

(3) the anaerobic ponds will have to be covered to recover the biogas and burn it in order to eliminate the bad smells and avoid letting the CH_4 escape to the atmosphere where it contributes twenty three times more than CO_2 to the greenhouse effect. This can be implemented relatively easily using floating plastic membranes (DeGarie et al., 2000). The bad smell problem on the other hand is not to be feared in the aerated lagoons if a sufficiently high oxidoreduction potential is maintained (Fonade et al., 2000).

Beside the low investment that they require, another advantage of the low rate systems is that usually they will not have to be preceded by homogenisation basins, since they can play this role given their huge volume and long hydraulic retention time. A fall in their performance is however possible after some years following the accumulation of biomass leading to an increase in dead volumes. This will imply the need for regular dredging operations.

With regard to the other processes, their design will also require some care if they are selected. For instance, in the case of the activated sludge, the risks of "bulking" related to the presence of sugars in the effluent and which result in the formation of a poorly settling biomass should not be under-estimated since it would translate in a deterioration of treatment performances (Miller, 1971; Purchase et al., 1995). Fortunately, it seems that under precise operating conditions (loading rate below 1.4 and preferentially around 0.6 g COD/g $SS_{mixed\ liquor}$.d; sludge concentration of 4-5 g SS/l in the aeration tank; adequate nutrient supply), this phenomenon should be controlable (Bruijn, 1977). Otherwise several measures exist to control it (Kappeler and Gujer, 1994; Prendl and Kroiß, 1998). On the other hand, for the anaerobic processes, the calcium concentration will dictate the choice of technology. Below 450 mg/l, all the processes should be applicable whereas beyond 1 g/l, the anaerobic contact reactor will probably remain the sole option as this has been clearly observed previously in the case of beet sugar mills (Schiweck et al., 1985; Brookes, 2001). Indeed, it is the only process for which it will still be possible to manage the $CaCO_3$ precipitation. In the sludge bed reactors, the same phenomenon would result in an irremediable displacement of the active biomass (El Mamouni et al., 1995) while in the filters the packing material would progressively transform into a rock.

CONCLUSIONS

As the wastewater generated by the cane sugar mills is easily biodegradable, in principle it should be amenable to any kind of biological treatment. The high content of organic matter of these effluents suggests however that an anaerobic pre-treatment followed by aerobic polishing should be the most effective option from an economic point of view in order to produce a water of sufficient quality that can be safely discharged to the environment. A simple anaerobic treatment should, however, produce water that can be re-used for washing cane or for irrigating crops assuming that the latter practice does not adversely affect the quality of the groundwater.

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