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# ANAEROBIC TREATMENT OF HIGH-STRENGTH CHEESE-WHEY WASTEWATERS IN LABORATORY AND PILOT UASB-REACTORS

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**Abstract**
*Start-up of the laboratory (3 l) UASB-reactor treating raw high-strength (up to 77 g COD/l) cheese-whey wastewaters as well as the treatment efficiencies (TE) and the maximal admissible organic loading rates (OLR) have been investigated under mesophilic (35°C) and submesophilic (20–30°C) conditions. A stable operation of the reactor with the TE higher than 90% on the total COD has been demonstrated up to the OLR of 28.5 and 9.5 g COD/l·day for mesophilic and submesophilic regimes, respectively. A successful start-up of the pilot (10.74 m$^3$) non-thermostated UASB-reactor treating raw cheese-whey wastewaters at ambient temperatures (ca. 24°C) has been completed in 3 months. Further exploitation of the reactor at the design OLR of 6.5 g COD/l·day showed its good operational stability with the TE close to 95% on the basis of total COD. After a proper start-up, the UASB-reactors can cope with preacidificated cheese-whey wastewaters (pH of about 4) even at elevated OLR that eliminates the necessity of alkalinity supplementation. © 1997 Elsevier Science Ltd.*

*Key words:* UASB-reactor, cheese-whey wastewater, start-up, mesophilic and submesophilic regime, treatment efficiency.

## INTRODUCTION

Cheese whey is a protein and lactose rich byproduct of the cheese industry and its cost-effective utilization or disposal has became increasingly important due to more stringent legislative requirements for effluent quality (Mawson, 1994). If for any reason (economic, sanitary, local) whey valorization technologies (such as protein and lactose recovery, spray drying, etc.) or direct utilization of whey for animal feed are not applicable, anaerobic treatment can be a solution to whey disposal. Many laboratory and pilot-scale trials of anaerobic treatment of whey have been conducted (Boening & Larsen, 1982; Switzenbaum & Danskin, 1982; De Haast *et al.*, 1985; Wildenauer & Winter, 1985; Barford *et al.*, 1986; Lo & Liao, 1986; Clark, 1988; Denac & Dunn, 1988; Schroder & De Haast, 1989; Yan *et al.*, 1989; Venkataraman *et al.*, 1992; Yan *et al.*, 1993; Cohen *et al.*, 1994; Malaspina *et al.*, 1995), but the majority of them dealt with deproteinated or diluted whey, a much simpler whey to treat.

Because of the very high biodegradability (close to 99%) and concentration (up to 70 g COD/l) and the very low bicarbonate alkalinity (usually about 50 meq/l) of raw whey (Mawson, 1994; Malaspina *et al.*, 1995), its direct treatment in high-loaded anaerobic reactors is considered as not very reliable due to difficulties frequently encountered in maintaining a stable operation.

The majority of these difficulties were apparently due to the tendency of rapid acidification of the waste. Marshal & Timbers (1982) reported that a 500-l pilot-scale fixed-film reactor receiving raw whey needed the addition of NaOH for pH control. Norstedt & Thomas (1984) found that without pH control, an anaerobic fixed-bed reactor could not achieve stable operation within 30 days. Lo & Liao (1986) observed that the anaerobic rotating biological contact reactor fed with cheese whey could not sustain a stable operation at hydraulic retention times (HRT) shorter than 5 days. Similarly, a minimum HRT of 5 days was needed in a pH-controlled fixed-film reactor (Wildenauer & Winter, 1985). Yan *et al.*, 1989, 1993 reported that the cheese-whey concentrations between 25 and 30 g COD/l were optimal at HRT of 5 days for a stable operation of UASB-reactor, while at the influent concentration of 38.1 g COD/l, an instability of the reactor was observed. This instability was interpreted by authors as the accumulation of volatile fatty acids (VFA) in the acidogenic stage beyond the assimilative capacity of the methanogenic stage. Similar findings were also reported early by Switzenbaum & Danskin

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(APHA, AWWA, WPCF, 1975). The values shown in the graphs and tables are the means for a minimum of at least two sample sets.

## RESULTS AND DISCUSSION

### Laboratory UASB-reactor

Since the efficiency of any high-rate anaerobic treatment process is mainly determined by a proper start-up of the reactor, special attention was paid to this procedure using the recommendations of Lettinga & Hulshoff Pol (1992b). During the first 42 days of the start-up (Fig. 1), the reactor was fed by a middle strength (less than 14 g COD/l) cheese-whey wastewater [Fig. 1(c)] supplemented by 1–3 g/l sodium bicarbonate to increase the reactor buffer capacity, while HRT was gradually decreased from 10.5 to 2.5 days. The OLR values achieved did not exceed 3 g COD/l·day [Fig. 1(a)], because we tried to maintain a total VFA concentration in the effluent below 0.5 g COD/l and keep a TE of the reactor higher than 95% on the basis of total COD [Fig. 1(b)]. The effluent pH slightly oscillated about 7.5 [Fig. 1(c)], and ethanol, acetate, propionate and butyrate were detected as the main constituents of effluent COD. The light-microscopic examination of samples taken from the sludge bed at day 42 showed a presence of small (0.5–0.8 mm) granule-like aggregates. Thus, the observations mentioned above testify about a successful adaptation of the seed sludge to cheese-whey wastewater.

To reach the high productivity of the system with the high-strength cheese-whey wastewater, OLR was then gradually increased up to 28.5 g COD/l·day (Fig. 1, days 43–146). During this period, the reactor demonstrated excellent TE, viz. higher than 97 and 95% with respect to centrifuged and total COD, respectively [Fig. 1(b)]. It should be noted that HRT applied [Fig. 1(a)] was usually shorter than the 5 days which is considered in the literature (Wildenauer & Winter, 1985; Lo & Liao, 1986; Yan *et al.*, 1989, 1993) as the minimal admissible HRT to achieve stable operation of anaerobic reactors treating raw cheese whey. Excessive foaming, sludge flotation, acidification of the reactor [effluent pH fluctuation was in the range of 6.8–8.1, Fig. 1(c)] and nutrient limitations have not been observed at all, which points to the development of the balanced microbial community inside the reactor. Large (1–2 mm) granule-like aggregates of the sludge were observed after 60 days. Some accumulation of undigested ingredients (white aggregates) inside the sludge bed was also detected but their presence did not apparently influence the overall reactor performance up to an OLR of 28.5 g COD/l·day.

In general, many factors are involved in the granulation process during the start-up of UASB-reactor, but a primary factor of concern (Colleran, 1988; Lettinga & Hulshoff Pol, 1992b) is the selection pressure, i.e. the removal of finely dispersed matter from the seed sludge. The selection pressure originates from both the superficial upflow velocity and the gas production rate. Despite the fact that the start-up in the experiments presented above has been made at a relatively low upflow velocity, the granulation process was observed. Consequently, it was mainly caused by increasing gas production rate under a gradual increase of the OLR. The other reason for successful granulation can also be related to the low concentration of acetate in the reactor

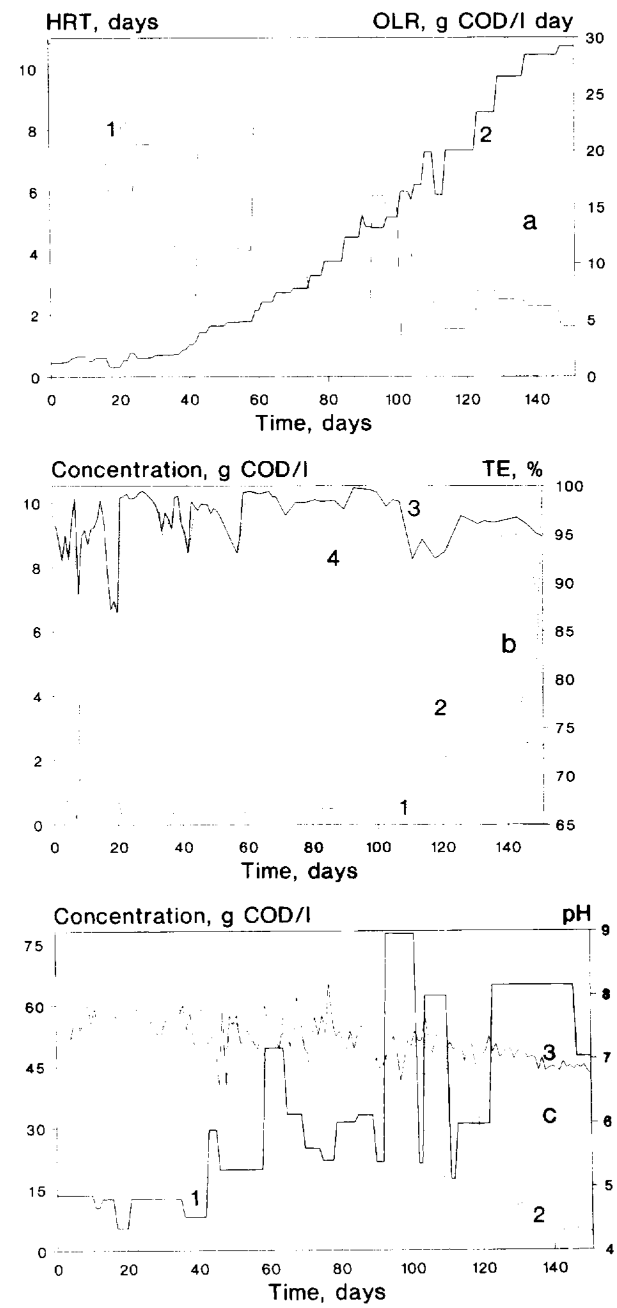


**Fig. 1.** Applied HRT, OLR, influent and effluent COD concentration, influent and effluent pH and TE for the laboratory UASB-reactor treating cheese whey-wastewaters at 35°C: (a) 1 — HRT; 2 — OLR; (b) 1 — centrifuged effluent COD; 2 — total effluent COD; 3 — treatment efficiency on centrifuged effluent COD; 4 — treatment efficiency on total effluent COD; (c) 1 — total influent COD; 2 — influent pH; 3 — effluent pH.

medium, which usually remained below 0.25 g COD/l during the start-up period. Such low acetate concentrations promote predominant growth of *Methanotrix* instead of *Methanosarcina*, resulting in formation of good settling granules (Colleran, 1988; Kalyuzhnyi *et al.*, 1996).

Taking into account the observed good buffer capacity of the reactor medium, the bicarbonate supplementing of the cheese-whey wastewater was stopped at day 78. It is seen in Fig. 1(c) that, despite the acidic influent pH, the reactor pH was self-maintained in the optimal range for anaerobic digestion of about 7.0. Thus, the acidification of cheese-whey wastewater which frequently occurs in production plants does not seem to be a limiting factor for a properly started-up UASB-reactor. In our experiments, the reactor coped easily even with the influent pH of 4.3 [Fig. 1(c), from day 134] under elevated OLR. This fact allows one to decrease the expense of bicarbonate or alkali supplementation during a full-scale anaerobic treatment of the cheese-whey wastewater. However, two conditions should be fulfilled in order to maintain a well-stabilized operation, viz. the system (especially the sludge bed) should remain well mixed, and the TE maintained at a high level. The wash-out of the sludge was generally not very noticeable up to an OLR of 28.5 g COD/l·day [compare the difference between effluent concentrations of total and centrifuged COD, Fig. 1(b), up to day 146], despite the fact that the sludge bed height reached approximately 3/5 of the working reactor height (day 145). A further increase in the OLR led to the intensification of sludge wash-out, although the TE on the basis of centrifuged COD remained high — more than 95% [Fig. 1(b), from day 147]. Under an OLR of 29.2 g COD/l·day, the sedimentability of the sludge was sharply reduced due to an extensive inclusion of cheese-whey ingredients into the structure of sludge aggregates and for this reason the experiment was stopped. Thus, an OLR of 28.5 g COD/l·day was probably the maximum admissible OLR for a stable operation of our UASB-reactor treating raw cheese-whey wastewater under mesophilic (35°C) conditions.

Taking into account that the average annual temperatures in the north part of Mexico are in the submesophilic range (20–30°C), an anaerobic treatment process without wastewater heating can be realized. Of course, non-optimal temperatures will lead to a decrease of the overall productivity of the process, but the elimination of expenses for wastewater heating may generate an additional attraction for this process under its implementation in the regions with a warm climate and limited investment resources. To check this possibility, the reactor was withdrawn from the thermostat and kept under the ambient temperature of the laboratory (20–30°C in August–September 1995). The data on the operational performance of the reactor under these conditions are presented in Fig. 2. It is seen that under an average temperature of 25°C, the reactor was rapidly adapted to the new conditions, and demonstrated TE higher than 90% on the basis of total COD under the OLR of 7–9.5 g COD/l·day. At day 9, the adjusting of influent pH to the neutral values was stopped. This did not lead to acidification of the reactor medium [Fig. 2(c)]. Thus, the bicarbonate supplementing was also unnecessary in this case. Some accumulation of undigested white aggregates inside the sludge bed was also observed and apparently was the main reason for the increased sludge wash-out under an OLR of 10.1 g COD/l·day [Fig. 2(b), days 33–45] because an

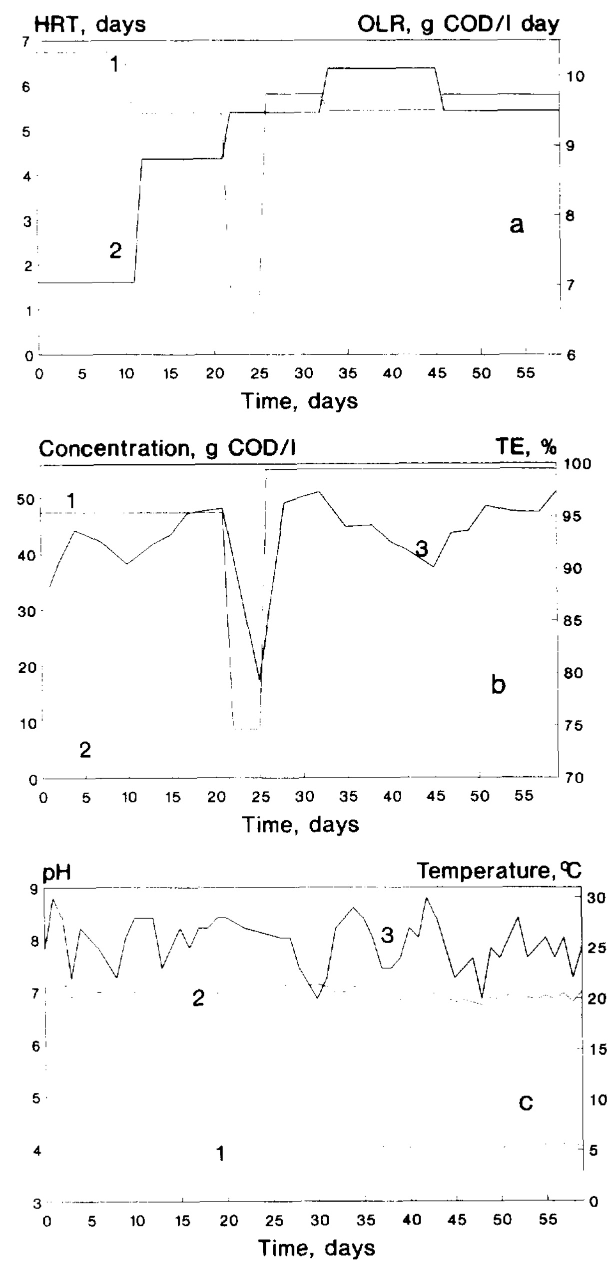


**Fig. 2.** Applied HRT, OLR, influent and effluent COD concentration, influent and effluent pH, TE and temperature for the laboratory UASB-reactor treating cheese-whey wastewaters under ambient temperature: (a) 1 — HRT; 2 — OLR; (b) 1 — total influent COD; 2 — total effluent COD; 3 — treatment efficiency; (c) 1 — influent pH; 2 — effluent pH; 3 — temperature.

observed effluent concentration of total VFA (1.5–1.6 g COD/l) and effluent pH [around 7, Fig. 2(c), days 33–45] did not imply overloading of the reactor. To avoid a development of sludge wash-out, the OLR was decreased to 9.5 g COD/l·day [Fig. 2(a), day 46] which was probably the maximum admissible OLR for stable operation of our UASB-reactor under submesophilic (average temperature of 25°C) conditions. As a result, TE on total COD increased to values higher than 95% [Fig. 2(b), days 46–59].

The findings described above were used for designing a pilot non-thermostated UASB-reactor. The design OLR was chosen as 6.5 kg COD/m$^3$·day, i.e. somewhat less than the maximum admissible OLR mentioned above for the laboratory reactor, to ensure a stable operation of the pilot reactor in the factory conditions.

**Pilot UASB-reactor**

Taking into account the submesophilic (i.e. non-optimal) temperatures [Fig. 3(c)] under which this reactor was operated, as well as the quality of the seed sludge (disperse and almost non-adapted to the cheese whey) the middle-strength wastewaters [Fig. 3(b)] were chosen for the first month of the start-up of the reactor. Moderate COD concentrations of influent were maintained by effluent recycle to the equalization tank. Some adjusting of influent pH by sodium carbonate/hydroxide was also applied until day 17 [Fig. 3(c)]. The initial OLR was 0.2 g COD/l·day, but its maintenance needed a very long HRT and, hence, very low superficial upflow velocity (gas production rate was also relatively low) making it difficult to form the active sludge. Therefore, in spite of the potential danger of a rapid wash-out of the seed sludge, the HRT was decreased to 12.5 days at day 8, resulting in OLR values higher than 1 g COD/l·day [Fig. 3(a)]. The sludge wash-out was indeed very noticeable but progressively decreased with time. A very slow increase of OLR was maintained until TE reached values higher than 93% on the basis of total COD [days 9–50, Fig. 3(a) and (b)]. During the next 40 days, the OLR was increased to the design value of 6.5 kg COD/m$^3$·day [Fig. 3(a)]. Nevertheless, with the accelerated regime of OLR increasing, TE with respect to total COD remained higher than 90% [Fig. 3(b)], and the effluent pH oscillated around 7.0 [Fig. 3(c)].

Thus, the successful start-up of the pilot UASB-reactor treating the raw cheese-whey wastewaters under submesophilic conditions (average temperature — 24°C) was completed in a matter of 3 months. Further exploitation of the reactor at the design OLR [days 90–122, Fig. 3(a)] showed its good operational stability with TE close to 95% [Fig. 3(b)]. The effluent from the UASB-reactor, usually having 1.8–2.5 g COD/l, was post-treated aerobically and used for watering lawns. Based on successful trials of the pilot UASB-reactor, the factory Normex is planning to construct a full-scale installation for the treatment of all cheese-whey wastewaters produced.

A comparison of data presented here with the literature data for various anaerobic treatment systems for roughly similar wastewaters (Table 2) indicates that our results (at 35°C) are among the best in terms of TE and significantly surpass the other UASB-treatment systems previously described on the basis of the OLR achieved. Moreover, OLR values achieved by us under the submesophilic con-

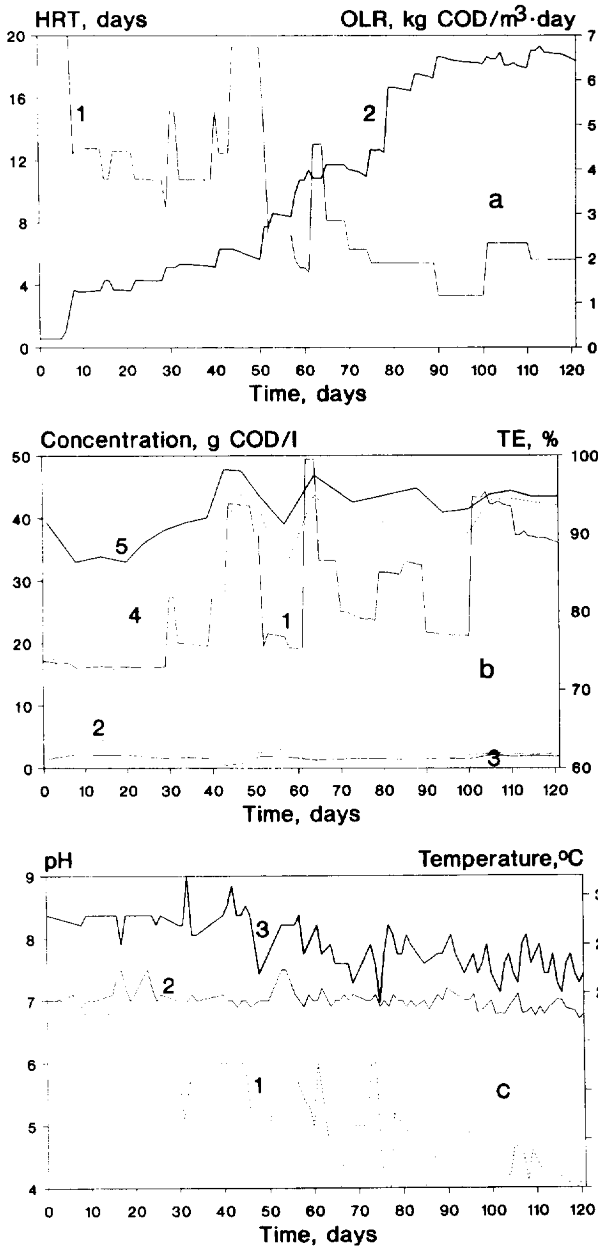


**Fig. 3.** Applied HRT, OLR, influent and effluent COD concentration, influent and effluent pH, TE and temperature for the pilot UASB-reactor treating cheese whey wastewaters under ambient temperature: (a) 1 — HRT; 2 — OLR; (b) 1 — total influent COD; 2 — total effluent COD; 3 — centrifuged effluent COD; 4 — treatment efficiency on total effluent COD; 5 — treatment efficiency on centrifuged effluent COD; (c) 1 — influent pH; 2 — effluent pH; 3 — temperature.

**Table 2. Comparison of various anaerobic treatment processes for cheese whey**

| Reactor[a] | Waste | Temp, °C | HRT, days | Inf. conc., g COD/l | OLR, g COD/l.day | TE, % | Reference[d] |
|---|---|---|---|---|---|---|---|
| UFFLR | Sour whey | 35 | 5 | 79 | 14 | 95 | 1 |
| DSFFR | Whey | 35 | 5 | 13 | 2.6 | 88 | 2 |
| FBR | Whey | 35 | 0.4 | 7 | 7.7 | 90 | 3 |
| FBR | Whey | 35 | 0.1–0.4 | 0.8–10 | 6–40 | 63–87 | 4 |
| AAFEB | Powder | 28–31 | 0.4–1.1 | 10 | 8.9–27 | 77–93 | 5 |
| | Whey | 35 | 0.6–0.7 | 5–15 | 8.2–22 | 61–92 | 5 |
| AnRBC | Whey | 35 | 5 | 64 | 10.2 | 76 | 6 |
| | Whey | 35 | 6–11 | 61–70 | 6.3–10 | 76 | 6 |
| SDFA | Whey | 4.3 | | 69.8 | 16.1 | 99 | 7 |
| UASB | Deproteinated whey | 35 | 1.5 | 11 | 7.1 | 94 | 8 |
| UASB | Whey | 33 | 5 | 5–28.7 | 0.9–6 | 97–99 | 9 |
| DUHR | Whey | 35 | 7 | 68 | 10 | 97 | 10 |
| UASB | Whey | 35 | 2.3–11.6 | 5–77 | 1–28.5 | 95–99 | This study |
| UASB[b] | Whey | 22–30 | 5.4–6.8 | 47–55 | 7–9.5 | 90–94 | This study |
| UASB[c] | Whey | 20–29 | 3.3–12.8 | 16–50 | 1–6.7 | 90–95 | This study |

[a]UFFLR = upflow fixed-film loop reactor; DSFFR = downflow stationary fixed-bed reactor; FBR = fluidized-bed reactor; AAFEB = anaerobic attached-film expanded-bed reactor; AnRBC = anaerobic rotating biological contact reactor; SDFA = semicontinuous digester with flocculant addition; UASB = upflow anaerobic sludge-blanket reactor; DUHR- = downflow–upflow hybrid reactor.
[b]Laboratory reactor.
[c]Pilot reactor.
1 = Wildenauer & Winter (1985); 2 = De Haast *et al.* (1985); 3 = Boening & Larsen (1982); 4 = Denac & Dunn (1988); 5 = Switzenbaum & Danskin (1982); 6 = Lo & Liao (1986); 7 = Barford *et al.* (1986); 8 = Schroder & De Haast (1989); 9 = Yan *et al.* (1989); 10 = Malaspina *et al.* (1995).

ditions are comparable with those obtained by other authors under mesophilic conditions.

## CONCLUSIONS

The principal feasibility of the UASB process (35°C) for the anaerobic treatment of the high-strength (up to 77 g COD/l) cheese-whey wastewaters has been demonstrated up to an OLR of 28.5 g COD/l·day with the treatment efficiencies higher than 95 and 90% on the basis of dissolved and total COD of the effluent, respectively.

A transfer of the UASB process from the mesophilic to the submesophilic (20–30°C — typical temperatures for Saltillo region) conditions led to a decrease in the overall productivity of the reactor, but TE of about 90% on the basis of total COD can be reached under an OLR of 7–9.5 g COD/l·day.

For the start-up of the pilot (10.74 $m^3$) UASB-reactor treating the raw cheese-whey wastewaters under submesophilic conditions (average temperature — 24°C) with the unadapted disperse sludge as the inoculum, a period of 3 months was needed. After reaching the design OLR of 6.5 g COD/l·day, the reactor has demonstrated a good operational stability with TE close to 95% with respect to the total COD.

After a proper start-up, the UASB-reactors can cope with the preacidificated cheese-whey wastewaters (pH of about 4) even at an elevated OLR, thus eliminating the necessity of alkalinity supplementation.

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