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Anaerobic Treatment of Industrial Effluents: An Overview of Applications

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1. Introduction

Anaerobic treatment is an energy generating process, in contrast to aerobic systems that generally demand a high energy input for aeration purposes. It is a technically simple and relatively inexpensive technology which consumes less energy, space and produces less excess sludge in comparison to the conventional aerobic treatment technologies. Net energy production from biogas makes the anaerobic treatment technology an attractive option over other treatment methods.

Increasing industrialization trend in the worldwide has resulted in the generation of industrial effluents in large quantities with high organic content, which if treated appropriately, can result in a significant source of energy. Anaerobic digestion seems to be the most suitable option for the treatment of high strength organic effluents. Anaerobic technology has improved significantly in the last few decades with the applications of differently configured high rate treatment processes, especially for the treatment of industrial wastewaters. High organic loading rates can be achieved at smaller footprints by using high rate anaerobic reactors for the treatment of industrial effluents.

This chapter intends to bring together the knowledge obtained from different applications of the anaerobic technology for treatment of various types of industrial wastewaters. The first part of the chapter covers brief essential information on the fundamentals of anaerobic technology. The remainder of this chapter focuses on various anaerobic reactor configurations and operating conditions used for the treatment applications of different industrial wastewaters. Examples of applications that reflect the state-of-the-art in the treatment of industrial effluents by high rate anaerobic reactors are also provided.

2. Fundamentals of anaerobic digestion

Anaerobic digestion is a complex multistep process in terms of chemistry and microbiology. Organic material is degraded to basic constituents, finally to methane gas under the absence of an electron acceptor such as oxygen. The basic metabolic pathway of anaerobic digestion is shown in Fig. 1. To achieve this pathway, presence of very different and closely dependent microbial populations is required.
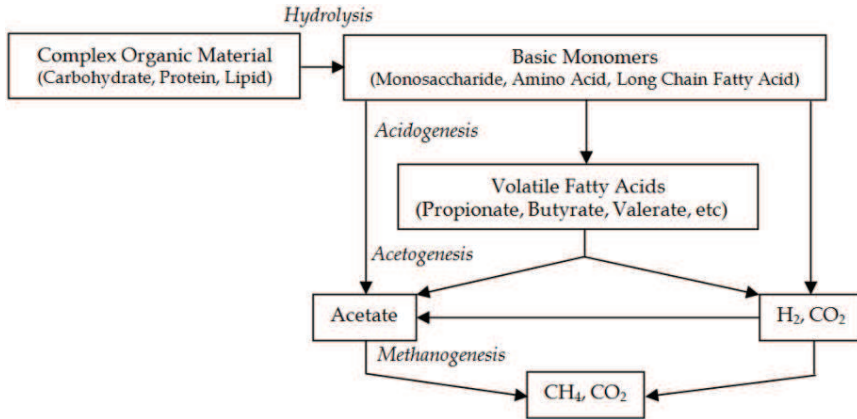
Fig. 1. Steps of anaerobic digestion process

The first step of the anaerobic degradation is the hydrolysis of complex organic material to its basic monomers by the hydrolytic enzymes. The simpler organics are then fermented to organic acids and hydrogen by the fermenting bacteria (acidogens). The volatile organic acids are transformed into acetate and hydrogen by the acetogenic bacteria. Archael methanogens use hydrogen and acetic acid produced by obligate hydrogen producing acetogens to convert them into methane. Methane production from acetic acid and from hydrogen and carbon dioxide is carried out by acetoclastic methanogens and hydrogenotrophic methanogens, respectively. Thermodynamic conditions play a key role in methane formation. Therefore, appropriate environmental conditions should be provided in order to carry out acetogenesis and methanogenesis, simultaneously (Rittmann & McCarty, 2001).

3. Reactor types

Many reactor configurations are used for the anaerobic treatment of industrial wastes and wastewaters. Among them, the most common types are discussed here and illustrated in Fig. 2.

3.1 Completely mixed anaerobic digester
The completely mixed anaerobic digester is the basic anaerobic treatment system with an equal hydraulic retention time (HRT) and solids retention time (SRT) in the range of 15-40 days in order to provide sufficient retention time for both operation and process stability. Completely mixed anaerobic digesters without recycle are more suitable for wastes with high solids concentrations (Tchobanoglous et al., 2003). A disadvantage of this system is that a high volumetric loading rate is only obtained with quite concentrated waste streams with a biodegradable chemical oxygen demand (COD) content between 8000 and 50000 mg/L. However, many waste streams are much dilute (Rittmann & McCarty, 2001). Thus, COD loading per unit volume may be very low with the detention times of this system which eliminates the cost advantage of anaerobic treatment technology. Typical organic loading rate (OLR) for completely mixed anaerobic digester is between 1-5 kg COD/m^3.day (Tchobanoglous et al., 2003).

3.2 Upflow anaerobic sludge blanket reactor

One of the most notable developments in anaerobic treatment process technology is the upflow anaerobic sludge blanket (UASB) reactor invented by Lettinga and his co-workers (Lettinga et al., 1980) with its wide applications in relatively dilute municipal wastewater treatment and over 500 installations in a wide range of industrial wastewater treatment including food-processing, paper and chemical industries (Tchobanoglous et al., 2003). Influent flow distributed at the bottom of the UASB reactor travels in an upflow mode through the sludge blanket and passes out around the edges of a funnel which provides a greater area for the effluent with the reduction in the upflow velocity, enhancement in the solids retention in the reactor and efficiency in the solids separation from the outward flowing wastewater. Granules which naturally form after several weeks of the reactor operation consist primarily of a dense mixed population of bacteria that is responsible for the overall methane fermentation of substrates (Rittmann & McCarty, 2001). Good settleability, low retention times, elimination of the packing material cost, high biomass concentrations (30000-80000 mg/L), excellent solids/liquid separation and operation at very high loading rates can be achieved by UASB systems (Speece, 1996). The only limitation of this process is related to the wastewaters having high solid content which prevents the dense granular sludge development (Tchobanoglous et al., 2003). Design OLR is typically in the range of 4 to 15 kg COD/m^3.day (Rittmann & McCarty, 2001).

3.3 Fluidized and expanded bed reactors

The anaerobic fluidized bed (AFB) reactor comprises small media, such as sand or granular activated carbon, to which bacteria attach. Good mass transfer resulting from the high flow rate around the particles, less clogging and short-circuiting due to the large pore spaces formed through bed expansion and high specific surface area of the carriers due to their small size make fluidized bed reactors highly efficient. However, difficulty in developing strongly attached biofilm containing the correct blend of methanogens, detachment risks of microorganisms, negative effects of the dilution near the inlet as a result of high recycle rate and high energy costs due to the high recycle rate are the main drawbacks of this system. The expanded granular sludge bed (EGSB) reactor is a modification of the AFB reactor with a difference in the fluid's upward flow velocity. The upflow velocity is not as high as in the fluidized bed which results in partial bed fluidization. (Rittmann & McCarty, 2001). OLR of 10-50 kg COD/m^3.day can be applied in AFB reactors (Ozturk, 2007) .

3.4 Anaerobic filters

The anaerobic filter (AF) has been widely applied in the beverage, food-processing, pharmaceutical and chemical industries due to its high capability of biosolids retention. In fact clogging by biosolids, influent suspended solids, and precipitated minerals is the main problem for this system. Applications of both upflow and downflow packed bed processes can be observed. Prevention of methanogens found at the lower levels of the reactor from the toxicity of hydrogen sulfide by stripping sulfide in the upper part of the column and solids removal from the top by gas recirculation can easily be achieved in downflow systems in comparison to upflow systems. However, there is a higher risk of losing biosolids to the effluent in the downflow systems. Design OLR is often in the range of 8-16 kg COD/m^3.day which is more than tenfold higher than the design loading rates for aerobic processes (Rittmann & McCarty, 2001).
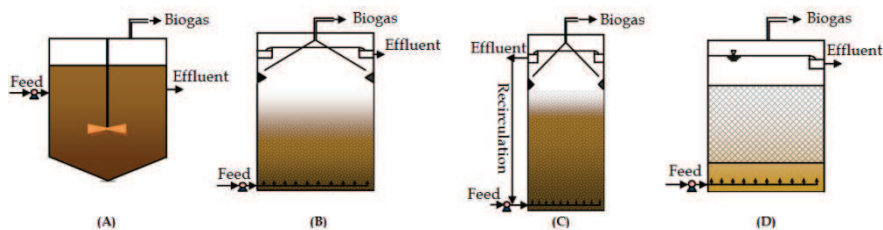
Fig. 2. Most commonly used anaerobic reactor types: (A) Completely mixed anaerobic digester, (B) UASB reactor, (C) AFB or EGSB reactor, (D) Upflow AF

4. Industrial applications

4.1 Corn processing industry
4.1.1 Process description

Corn is an important agricultural product that in the period of 2008-2009, nearly 789 million tons of corn was produced throughout the world (CRAR, 2009). Corn processing industries take corn apart and purify its different constituents and condition these constituents to be used in food and other industries (Anderson & Watson, 1982). Starch, gluten, dextrin, glucose and fructose are the main products produced by corn processing. Corn based glucose products are significant ingredients in major international markets (food, biochemical, pharmaceutical). Intermediate products, such as vegetable oil, protein or/and whole-wheat and fructose obtained from starch are utilized as raw material in catering factories, stockfarming facilities, and processing industries for sweeteners and beverages, respectively (Ersahin et al., 2007).

There are two distinct processes for corn processing; wet-milling and starch slurry derivatives production (refinery) and each process generates unique co-products. A simplified product flow diagram for a typical corn processing industry is given in Fig. 3 (Eremektar et al., 2002; Ersahin et al., 2007).

Wet milling is the breakdown of the corn into its components to provide starch slurry of very high purity and by products, incorporating with process water in countercurrent flow. Steeping is the most important process that is used to soften the grains for grinding, to break down the protein matrix to leave starch, and to remove the soluble matter from germ. Separated soluble proteins can be added to fiber and/or sold as protein. Steeped corn is passed through grinding mills to liberate germ from the corn kernel with as little damage as possible. The remaining material including starch slurry, gluten and fiber is screened by a fine screen and then passed through a squeezer. By this way, fiber is separated, washed, purified, and dewatered. The remaining slurry including starch and gluten is retained in a thickener and then gluten is concentrated by a centrifuge, thus lighter gluten is separated. (Ovez et al., 2001; Ersahin et al., 2006; Ersahin et al., 2007).

The starch slurry is further processed to produce dry starch, glucose, fructose and dextrin in the starch slurry derivatives units. Starch slurry is passed through centrifuge and then some of the starch is dried to get dry starch and malt sugar and marketed. Most of the remaining starch is converted into corn syrups and dextrose. In glucose refinery step, chemical and mechanical breakdown of starch slurry are carried out by acidification, mechanical breakdown unit and enzyme treatment tank. Then demineralization and evaporation processes are applied as the last step of glucose production. After evaporation, isocolumns are used in order to convert dextrose to fructose. (Ovez et al., 2001; Ozturk et al., 2005).
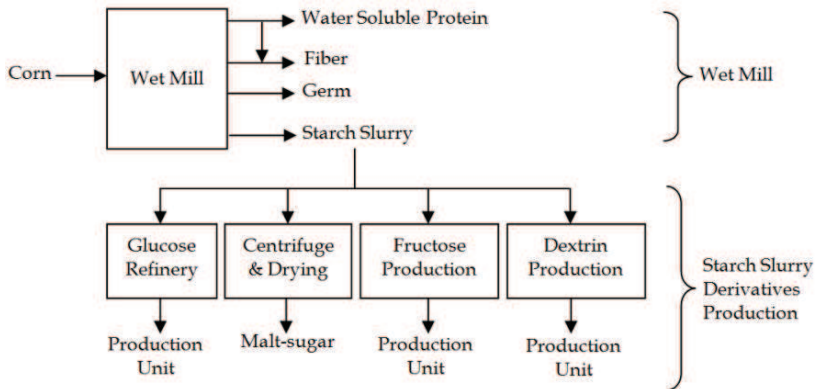
Fig. 3. Process flow diagram for a typical corn processing industry

4.1.2 Wastewater sources and characterization

Effluent from the corn milling industry is known as a high strength wastewater due to its high protein and starch content. The wastewater has a high COD, mainly of soluble and biodegradable character, with an initial inert COD content of less than 15%. The biodegradability of corn processing wastewaters is high in comparison to most of the other industrial effluents (Howgrave-Graham et al., 1994; Eremektar et al., 2002).

Typically, wastewater generation is mainly originated from evaporator vapor condensate, evaporator cleaning water and grinding mill cleaning water for wet milling process. Generally, the wastewater generated in germ and fiber washing and dewatering processes is recycled within the system (e.g. used for steeping). For starch slurry derivatives production, the wastewater sources are mainly consisting of cooler condensate, vacuum filter filtrate, activated carbon recovery water, and demineralization unit cleaning water from dextrose and fructose refinery (Ersahin et al., 2006). Table 1 includes the summary of characterization studies derived from different studies.

Parameter[1]	Unit	Reference				
		(Blanchard, 1992)	(Ovez et al., 2001)	(Eremektar et al., 2002)	(Johnson & May, 2003)	(Ersahin et al., 2006)
COD_{total}	mg/L	-	4850	3800	-	2810
$COD_{soluble}$	mg/L	-	3850	3230	-	-
BOD_5	mg/L	1000-3000	3000	2800	1000-2000	-
TKN	mg/L	-	174	84	-	60
NH_4-N	mg/L	-	-	23	-	-
TP	mg/L	-	125	33	-	-
TSS	mg/L	500	650	400	-	-
pH	-	-	5,2	-	-	-

[1] BOD_5: Biochemical oxygen demand; TKN: Total Kjeldahl Nitrogen; TP: Total phosphorus; TSS: Total suspended solids

Table 1. Comparison of different studies from the literature for the characterization of corn processing wastewaters

Wet milling process generates more pollution in terms of COD than refinery process. A pollution profile study for a corn processing industry conducted by Ersahin et al. (2007) indicated that refinery process produced more wastewater than wet milling process, however wet milling process generated wastewater with more COD load than refinery process. In this study the specific wastewater flows from wet mill and refinery processes were determined as 0,64 m^3/ton corn processed and 0,80 m^3/ton product, respectively. They also indicated that specific COD loads from wet mill and refinery processes were 2,65 m^3/ton corn processed and 1,41 m^3/ton product.

4.1.3 Anaerobic treatment applications for the treatment of corn processing wastewaters

High strength and biodegradable character of the corn processing wastewaters makes biological treatment systems appropriate for the treatment of this type of effluents (Howgrave-Graham et al., 1994). Generally two stage biological treatment, an anaerobic stage followed by an aerobic stage, is applied for the treatment of corn processing effluents.

The presence of sufficient amount of macronutrients and trace elements is required for the granulation and stability of anaerobic reactors (Speece, 1996; Ozturk, 2007). However, some agro-industrial effluents that are generated from industries such as corn processing may not contain these elements in the required amounts for the optimum growth of microorganisms. In these situations, trace elements may be supplemented prior to anaerobic processes for an effective treatment. For an optimum methane yield, the optimum Carbon/Nitrogen/Phosphorus (C:N:P) ratio was reported as 100:2,5:0,5 (Rajeshwari et al., 2000).

EGSB reactor system is one of the most appropriate anaerobic treatment process alternatives for the treatment of corn processing wastewaters. A full-scale application of EGSB reactor for the treatment of corn processing industry effluents was evaluated by Ersahin et al (2007). The industry had a three-stage advanced wastewater treatment plant (WWTP) including an EGSB reactor, intermittently aerated activated sludge system for biological nitrogen removal and chemical post treatment unit for phosphorus removal. The first stage is an anaerobic EGSB reactor with an effective volume of 1226 m^3. The average OLR and HRT values were 3,57 kg COD/m^3.day and 18,5 hours, respectively. Average influent COD concentration and pH value of the reactor were 2750 mg COD/L and 6,9, respectively. SRT in the anaerobic reactor was above 100 days in general and the ratio of volatile suspended solids (VSS)/TSS for the granular biomass averaged 80%. Methane production potential was reported as 850-1540 m^3/day for the investigated EGSB reactor for one year operating period. COD removal rates of the anaerobic and aerobic units were same at 85%. By this combination of biological treatment processes, the quality of the final effluent met the discharge limits of European Union (EU) Urban Wastewater Directive for Sensitive Regions (EU 91/271/EEC, 1991).

A lab-scale AFB reactor using cultivated polyvinyl alcohol gel beads with a diameter of 2–3 mm, to treat corn steep liquor was investigated by Zhang et al. (2009). The effective volume of the reactor was 3,9 L. Influent COD concentration varied in a range of 2100-12900 mg/L. COD removal efficiencies of 96% and 91% were achieved at OLRs of 27,5 and 25 kg COD/m^3.day with HRTs of 10 h and 6 h, respectively. 610 g/L of biomass concentration was achieved by the biomass attachment of 1,02 g VSS/g PVA-gel beads.

Duran-deBazua et al. (2007) evaluated two stage biological treatment system consisting of anaerobic and aerobic processes for the treatment of effluents from a corn processing industry manufacturing tortillas, one of the Mexican traditional corn (maize) products. 500 ton corn/day was processed and an average wastewater flow of 2500 m³/day was generated in the industry. They proposed high rate anaerobic reactors such as packed bed type or UASB reactors depending upon the availability of the granular anaerobic biomass for the treatment of the effluents generated from corn processing industries. They indicated that 9,6-16,8 m³ biogas per ton of corn processed could be obtained by anaerobic treatment of these type of wastewaters.

ADUF (anaerobic digestion ultrafiltration), a membrane-assisted process for the separation of biomass from the treated effluent, was also investigated for the treatment of corn processing wastewaters (Ross et al., 1992). Both pilot (3 m³) and full scales (2610 m³) of completely mixed reactors were operated at mesophilic conditions with HRTs of 1,6 and 5,2 days and OLRs of 5 and 2,9 kg COD/m³.day, respectively. Pilot reactor provided 90% COD removal at an influent concentration of 8000 mg COD/L, although 97% COD removal was obtained by the full scale reactor with an influent COD concentration of 15000 mg/L. 8-37 L/m².h flux was achieved in a pilot scale ADUF process.

A mass balance for a two-staged wastewater treatment plant of a corn processing industry was presented in Fig. 4. The COD removal efficiencies of the anaerobic and aerobic stages of the treatment plant were 89% and 85%, respectively (Ozturk et al., 2001).
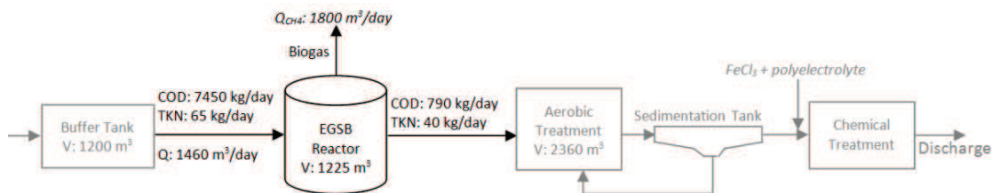

Fig. 4. Mass balance study for a wastewater treatment plant of the corn processing industry

4.2 Baker's yeast industry
4.2.1 Process description

Baker's yeast, which is one of the main products in the preparation of breadbaker, is manufactured through the aerobic fermentation of the selected strains of *Saccharomyces cerevisiae* according to their special qualities relating to the needs of the baking industry (Catalkaya & Sengul, 2006). The production of baker's yeast includes the processes, such as cultivation, fermentation, separation, rinsing and pressurized filtration as shown in Fig. 5.

The most common raw material of baker's yeast industry is molasses which is a by-product of sugar production due to its low cost and high content of sugar (Liang et al., 2009). After the dilution, clarification and sterilization, the molasses, which is commonly referred to as mash or wort, is fed to the fermentation vessels with nutrients. The grown cells at the early stages of fermentation are transferred into a series of progressively larger seed and semi-seed fermentors. At these stages of fermentation; molasses, nutrients and minerals are fed to the yeast at a controlled rate. At the end of the semi-seed fermentation, the content of the

tank at about 5 percent solids is concentrated to about 18-22 percent solids. The concentrated yeast which is called yeast cream is then washed with cold water and pumped to a semi-seed yeast storage tank where it is stored at 4 ^{0}C until it is used to inoculate the commercial fermentation tanks. The commercial fermentors are the final step in the process. After commercial fermentation, the yeast is pumped to the rotary drum filters and dewatered to a cake-like consistency with 30-33% yeast solids content. Depending on the market demands, the solids content of the yeast can be increased to 90–98% by drying and marketed as dry or instant baker's yeast (Ersahin et al., in press).
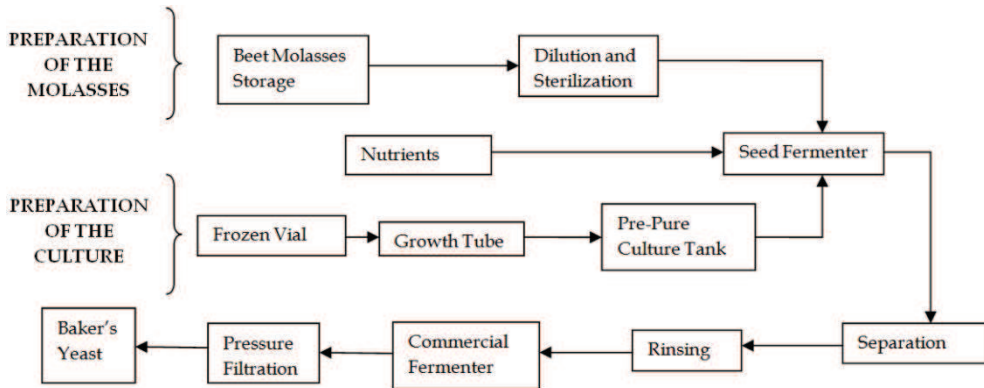

Fig. 5. Process flow diagram for a baker's yeast industry

4.2.2 Wastewater sources and characterization

During the fermentation process of the baker's yeast industry, large quantity of wastewater with high organic content, dark colour, high concentrations of total nitrogen, trimethylglycine and sulphate, variable phosphorus content and non-biodegradable organic pollutants are generated (Liang et al., 2009; Blonskaja et al., 2006). Colour is one of the most problematic parameters at the baker's yeast industry as a result of the presence of melanoid in the molasses which gives a brownish colour to the wastewater (Buyukkamaci & Filibeli, 2002). Molasses is the source of the most of contaminants in the wastewater with its content of 45-50% residual sugars, 15-20% non-sugar organic substances, 10-15% ash (minerals) and about 20% water. Yilmaz and Ozturk (1995) determined the initial soluble inert COD fraction of soluble COD in baker's yeast industry wastewaters between 10-15% under aerobic conditions.

The wastewater originated from baker's yeast industry can be classified into two groups as high strength process wastewater and low-medium strength process wastewater. The former one is generated from the yeast separators and processes such as centrifuges and rotary vacuum filters, whereas the latter one mainly constitutes the floor washing and equipment cleaning water (Catalkaya & Sengul, 2006). Table 2 presents some examples of baker's yeast industry wastewater characterization studies from the literature. Unlike from the other studies, Ozturk et al. (2010) reported a considerable decrease in the concentration of pollutant parameters such as COD, total nitrogen, sulphate, potassium, BOD$_5$ and colour for a baker's yeast industry after the installation of evaporation process.

Parameter[1]	Unit	Reference				
		(Ersahin et al., in press)	(Krapivina et al., 2007)	(Blonskaja et al., 2006)	(Altinbas et al., 2003)	(Gulmez et al., 1998)
pH	mg/L	6,5	-	-	6,2	5,9
COD	mg/L	6090	14400-25700	25020	15848	17100
TOC	mg/L	-	-	-	-	-
Magnesium	mg/L	-	-	-	30,7	-
Ferrous	mg/L	-	-	-	4,9	-
PO_4-P	mg/L	2,3	-	-	6,6	-
TSS	mg/L	583	-	-	835	-
VSS	mg/L	475	-	-	810	-
Alkalinity	mg $CaCO_3$/L	1475	-	-	2349	1675
Soluble COD	mg/L	4980	-	23420	15193	-
TKN	mg/L	274	-	-	1196	1185
NH_3-N	mg/L	132	-	-	206	250
TN	mg/L	-	250-350	1470	-	-
TP	mg/L	3	17,3-48,2	100	20,1	21
Sulphate	mg/L	485	3500-5300	2940	-	-

[1] TOC: Total organic carbon; TN: Total nitrogen

Table 2. Characterization of the effluent from the baker's yeast industry

4.2.3 Anaerobic treatment applications for the treatment of Baker's yeast wastewaters

Anaerobic processes appears to be economically more attractive in comparison to aerobic processes for the treatment of high strength wastewaters with the achievement of simultaneous organic matter and sulphate removal, low sludge production and low energy requirement. However, the effluents of the anaerobic treatment stages should be further treated by the other treatment technologies in order to fulfill the discharge requirements for baker's yeast industries.

Kalyuzhnyi et al. (2005) studied the anaerobic treatment of baker's yeast industry effluent by an UASB reactor as a pre-treatment followed by aerobic-anoxic biofilter and coagulation processes. According to the results, the UASB reactor was found to be quite efficient for both raw and diluted samples with COD removal efficiencies between 52-74% for the OLRs of 3,7-16 g COD/L.day. A stepwise increase in the OLR from 3,7 to 10,3 g COD/L.day during the treatment of the raw sample didn't make a significant effect on COD removal which was in the range of 60-67%. However, further increase in OLR to 16 g COD/L.day in the treatment of the diluted sample led to a drop in the COD removal to 52%. Complete removal of sulphate which was transformed into soluble sulphide was observed in the UASB reactor. In fact, the observed sulphide concentrations were not inhibitory for anaerobic sludge. Colour was not generally removed during the anaerobic treatment stage.

Gulmez et al. (1998) investigated the feasibility of anaerobic treatment technology for baker's yeast industry wastewater which was combined with the wastewater generated from pharmaceutical industry. The study was performed at a lab-scale UASB reactor with

an effective volume of 10,35 L and a sedimentation volume of 6,05 L at mesophilic conditions. The experimental study was carried out for 333 days. The first 198 days the system was only fed with baker's yeast industry wastewater. After the achievement of the steady-state operating conditions at the 140th day, COD removal rates of 62% and 64% were observed between 140th and 198th day at the OLRs of 2,4 kg COD/m3.day and 4,8 kg COD/m3.day, respectively. After the 198th day, the system was fed with the combination of baker's yeast and pharmaceutical industry wastewaters at different dilution ratios between 1/50 and 1/1000 (pharmaceutical industry wastewater volume/the total wastewater volume). The combination of pharmaceutical industry wastewater with baker's yeast industry wastewater at the lower dilutions resulted in a decrease in terms of COD removal.

Ciftci & Ozturk (1995) presented the performance of a full-scale two-staged UASB reactors (acid reactor+methane reactors) treating baker's yeast industry effluents. Long-term (nine years) average COD removal efficiency, biogas flow and methane conversion yield were reported as 75%, 18000 m3/day and 0,45 m3/kg COD$_{removed}$, respectively. However, a decrease in the biogas flow has been observed in the study of Ozturk et al. (2010) that was derived from a baker's yeast industry with an evaporation process as a result of a decrease in the pollutant loads.

Hybrid reactor, which combines an UASB reactor in the lower part with a filter in the upper part and promotes the advantages of both reactor types, was tested in order to overcome the disadvantages of fully packed anaerobic filters. The performance of hybrid upflow anaerobic filters depends on the contact of the wastewater with both the attached biofilm in the media and suspended growth in the sludge part (Buyukkamaci & Filibeli, 2002). A laboratory scale hybrid reactor with a fixed bed at the upper two-third of the reactor was used in this study. The reactor was operated at mesophilic conditions with three different types of wastewater sources including synthetic wastewater containing molasses, baker's yeast industry wastewater and meat processing industry wastewater. HRT was kept constant at 2 days and the OLR was approximately 9 kg/m3.day during the study. Average COD, TOC, and colour removal efficiencies were 78%, 76%, and 12% respectively.

Krapivina et al. (2007) studied the treatability of sulphate-rich high strength baker's yeast industry wastewater by using anaerobic sequencing batch reactor technology. Three different treatment schemes including anaerobic sequencing batch reactor with or without a polymeric filler and coupled micro-aerophilic/anaerobic sequencing batch reactor were investigated with an optimal sludge concentration of 17300 mg/L and an optimal reaction time of 22 hours in the reactor. The third treatment alternative prevented sulphate formation by the oxidation of the sulphide formed in the anaerobic stage of the process and left sulphur in the form of elemental sulphur which was a colloid, inert solid and could be removed from the wastewater easily by keeping the level of oxygen content in the micro-aerophilic reservoir at 0,1-0,15 mg/L. The solution of sulphate and sulphide removal problems resulted in an alleviation for sulphide inhibition of both methanogenesis and sulphate reducing bacteria and made the third alternative preferable for the treatment of sulphate-rich yeast wastewaters.

A mass balance study for the wastewater treatment plant of a baker's yeast industry which had an evaporation process was presented in Fig. 6 (Ozturk et al., 2010).
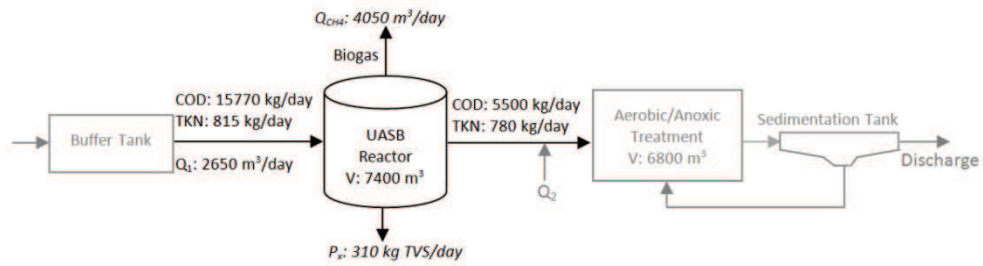
Fig. 6. Mass balance study for a wastewater treatment plant of the baker's yeast industry

The main problems encountered in the anaerobic treatment of the baker's yeast industries are the accumulation of the inorganic matter (i.e. $CaSO_4$, $MgNH_4PO_4$) in the reactor, ammonia toxicity due to high pH values (>8) and high hydrogen sulphur content in the biogas.

4.3 Confectionery industry
4.3.1 Process description
Confectionery industry is an important branch of food sector. The confectionery industry can be classified into three main segments: chocolate confectionery, sugar confectionery and flour confectionery. Chocolate confectionery, which has four category including chocolate bars, chocolate blocks, boxed chocolate and other chocolate, is the predominant category covering items made out of chocolate. Flour confectionery is obviously things made out of flour, whereas sugar confectionery covers the rest of confectionery (Edwards, 2000).
There is a wide range of products with different production schemes in the confectionery industry. Chocolate confectionery was selected to provide a flow diagram and process description (Fig. 7).
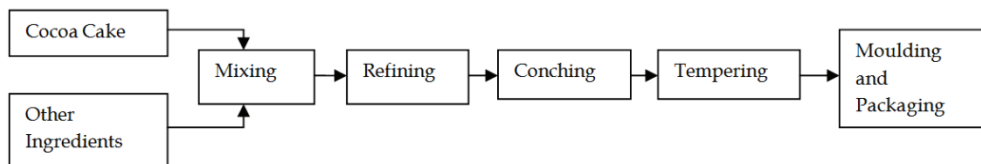

Fig. 7. Process flow diagram for a chocolate confectionery industry

Chocolate, which is made from the fruit of the cacao tree, is used as an ingredient for beverages and various kinds of confectionery. The cocoa cake is mixed in a heated kneading machine with the other ingredients such as sugar, cocoa butter, milk powder or crumb, vegetable fats, lecithin, condensed milk and flavourings. Refining machinery consists of cooled metal rollers which run at a higher speed to assist the crushing process. As the chocolate passes through the refiners the particles are crushed by the pressure between the rollers. After refining process, the chocolate is transferred to the conche-refiner for further processing. Heat is introduced to this process by mechanically working the mix by vigorous slapping agitation for several hours. The aim of this process is to ensure that the liquid is evenly blended. Conches are heated normally by a water jacket and can be continuous or batch design. Following conching, the liquid chocolate is tempered for several hours in

order to stabilize the cocoa butter crystals and make them more uniform in size. It also gives the chocolate a bright lustre and a sharp snap. The tempering process involves heating the chocolate liquor and then cooling it in several stages. The final steps in the process are moulding the chocolate, allowing it to cool and harden, and then finally packaging it (Aesseal Environmental Technology, 2003).

4.3.2 Wastewater sources and characterization

Confectionery industry generates high amounts of wastewater which contains high concentrations of readily biodegradable organic materials characterized with high COD and BOD (Beal & Raman, 2000; Diwani et al., 2000). Orhon et al. (1995) determined the initial soluble inert COD percentage of confectionary industry wastewaters between 1,5-7,1% under aerobic conditions. Some examples from the literature for the characterization of the wastewater discharged from the confectionery industry were provided in Table 3.

Parameter	Unit	Reference			
		(El-Gohary et al., 1999)	(Orhon et al., 1995)	(Diwani et al., 2000)	(Ozturk & Altinbas, 2008)
COD	mg/L	4475	2840-6220	5000	19900
COD$_{soluble}$	mg/L	-	2500-5400	-	-
BOD	mg/L	2200	1840-4910	3200	-
TKN	mg/L	100	33-55	-	-
TP	mg/L	17,2	8,6-65	-	-
TSS	mg/L	649	260-440	177	1050
VSS	mg/L	490	-	-	-
pH	-	-	4-5,1	6	-
Oil and grease	mg/L	367	-	-	-

Table 3. Characterization of the wastewater discharged from the confectionery industry

4.3.3 Anaerobic treatment applications for the treatment of confectionery wastewaters

An UASB reactor may be a viable alternative for the primary treatment of the confectionery wastewater as this technology is designed to make the upflow velocity of the wastewater much lower than the settling velocity of the granules. In this way, the settling process uncouples HRT from SRT that results in the retaining of the biomass in the reactor (Beal and Raman, 2000).

El-Gohary et al. (1999) compared the performance of laboratory-scale aerobic and anaerobic systems treating confectionery wastewater. The experiments were conducted at a laboratory-scale one-phase UASB reactor with a sludge content kept around 22 g/L. The results showed that UASB system with a HRT of 12 hours and OLR of 4,4 kg BOD/m^3.day achieved COD and BOD removal efficiencies of 92,4% and 91,5%, respectively. Mean COD, BOD, TSS and oil and grease values analyzed in the effluent were all in agreement with the standards set by the regulatory authorities.

Berardino et al. (2000) provided the experimental results of semi-continuous tests of the anaerobic digestion of confectionery wastewater, carried out at different residence times and organic loads in a laboratory-scale upflow anaerobic filter at mesophilic conditions with

a working reactor volume of 10 L. COD removal rates didn't fall below 80% under the whole range of conditions, while a maximum removal rate of 92% was achieved.

Ozturk & Altinbas (2008) evaluated the treatment performance of one of the main confectionery industries in Turkey. The treatment plant of the investigated industry involved physical treatment system including screens, dissolved air flotation, equalization tank and two-staged biological system including anaerobic and aerobic reactors. The anaerobic stage of the industry included an EGSB reactor with 1200 m^3 volume operated at mesophilic conditions. Average OLR was 3 kg COD/m^3.day, however it could increase to 7,5 kg COD/m^3.day at shock loadings. COD removal rate at the anaerobic stage of the system was 91% with a biogas generation of 1880±640 m^3/day.

Single-reactor processes are sometimes insufficient for the treatment of the effluents with high COD loads due to the extensive treatment requirements to meet the strict discharge limits. In this situation, various types of anaerobic processes can be applied in order to enhance the treatment performance. The study of Beal and Raman (2000) both evaluated the feasibility of high-rate anaerobic treatment for the confectionery wastewater and examined the possibility of using a second-stage anaerobic reactor. The treatment system included an UASB reactor operated at 35 ^{0}C followed by a downflow anaerobic filter operated at ambient temperature (25 ^{0}C). The UASB reactor consistently achieved COD removal rate of 98% at the highest organic loadings, whereas COD removal efficiencies achieved by downflow anaerobic filter are above 50%. The COD treatment efficiency of the whole system is 99% at a total OLR of 12,5 kg/m^3.day with an effluent COD concentration below 400 mg/L that was not yet dischargeable but more amenable to aerobic treatment than the raw wastewater.

Moody & Raman (2001) investigated the performance of two dual-reactor high-rate anaerobic systems in the treatment of confectionery wastewater. Diluted wastewater from a confectionery plant, which had a COD concentration of 8000 mg/L, was fed to the primary reactors at a constant flow rate. Primary reactors, which were downflow anaerobic filter and UASB reactor, were operated at constant HRT of 1,6 day and achieved COD removal rate of 94% and 88%, respectively. Effluents from the primary reactors were combined and fed to the secondary reactors which were both downflow anaerobic filters with different packing media including brick pieces and plastic rings at different HRTs of 0,8, 1,6 and 3,2 days. The results showed that a brick media downflow anaeobic filter with a 1,6 day HRT, placed down-stream of a functional high-rate anaerobic reactor, achieved the best removal efficiency of 89% for COD parameter in comparison to the other HRTs and packing media.

A COD mass balance study for a two-staged wastewater treatment plant of a confectionery industry was presented in Fig. 8 (Ozturk & Altinbas, 2008).
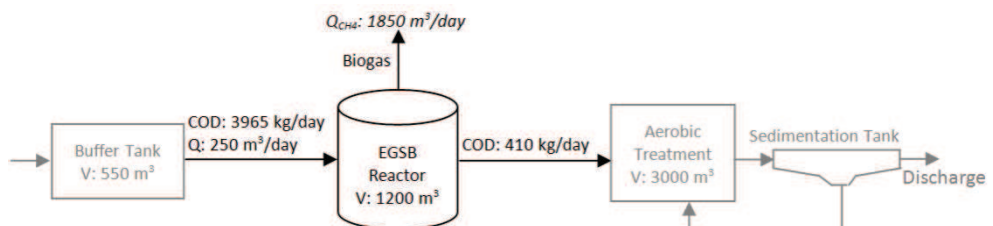

Fig. 8. Mass balance study for a wastewater treatment plant of the confectionery industry

4.4 Potato processing industry
4.4.1 Process description
Food processing industry has grown rapidly parallel to the world population growth as a result of the inevitable necessity of the food to feed billions of people. Potato is a very important and popular vegetable in human diet and its worldwide production has reached to 314,2 million by 2008 (FAOSTAT, 2008). Various types of products such as potato chips, frozen French fries and other frozen food, dehydrated mashed potatoes, dehydrated diced potatoes, potato flake, potato starch, potato flour, canned white potatoes, prepeeled potatoes are processed from potato. Due to the wide range of the products, the potato processing industries can differ in their process lines. Although the type of processing unit depends upon the product selection, the major processes in all products are storage, washing, peeling, trimming, slicing, blanching, cooking, drying, etc. The process line of a potato chips manufacturing plant is given in Fig. 9.
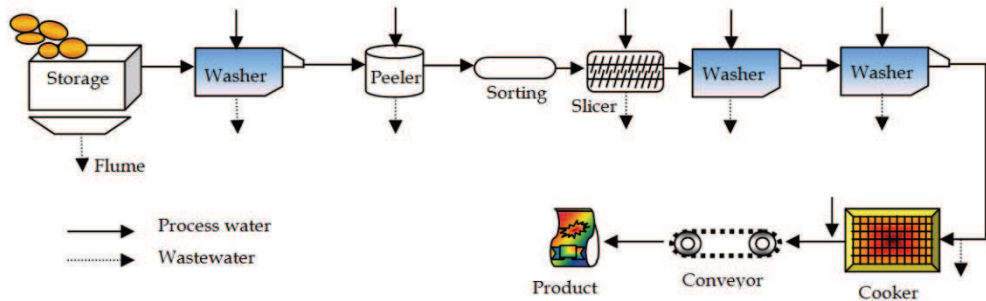

Fig. 9. Process flow diagram for a potato chips industry

4.4.2 Wastewater sources and characterization
Potato processing wastewater contains high concentrations of biodegradable components such as starch and proteins, in addition to high concentrations of COD, TSS and TKN. Therefore, wastewater production and composition of potato processing plants depend on the processing techniques to a large extent (Senturk et al., 2010a). Raw potatoes must be washed thoroughly to remove sand and dirt prior to other processes. Water consumption for fluming and washing varies from 18,5 to 7,9 liters per ton of potatoes. Peeling of potatoes contributes the major portion of the organic load in potato processing waste. Among three different peeling methods (abrasion peeling, steam peeling and lye peeling), lye peeling is the most popular peeling method used today. Therefore, lye peeling wastewater is the most troublesome potato waste due to very high pH (11–12), high organic content mostly in colloidal form (Hung et al., 2006). The wastewater flows from different potato processing industries were reported as 17 m³/ton potato processed (Hung et al., 2006), 5-8 m³/ton potato processed (Guttormsen & Carlson, 1969), 3,9 m³/ton potato processed (Austerman-Houn & Seyfried, 1992) and 5,8 m³/ton potato processed (Cooley et al., 1964). Several publications on the characteristics of wastewaters resulting from various types of potato processing plants are summarized in Table 4.

Parameter[1]	Unit	Reference				
		(Senturk et al., 2010b)	(Wang et al., 2009)	(Kalyuzhnyi et al., 1998)	(Hadjivassilis et al., 1997)	(Austerman-Houn & Seyfried, 1992)
Industry	-	Potato chips[2]	Potato starch	Potato maize	Potato chips	Potato chips[3]
COD	mg/L	5250 – 5750	1100 – 4500	5500 – 18100	4000 – 7000	389 – 5899 (3638)[4]
Soluble COD	mg CaCO$_3$/L	2500 – 3000	-	3200 – 7400	-	-
BOD$_5$	mg/L	4000 – 5000	-	-	2000 – 3000	155 – 3465 (1977)
Alkalinity	mg/L	2000 – 2500	-	-	-	-
pH	-	7,0 – 8,0	5,0 – 8,5	6,0 – 11,0	-	-
TKN	mg/L	200 – 250	-	-	-	88 – 509 (296)
Ammonia	mg/L	50 – 60	8,9 – 48,5	-	-	-
Sulphate	mg/L	40 – 50	-	-	-	-
TP	mg/L	90 – 100	-	-	-	6 – 51 (25)
TS	mg/L	4800 – 5000	-	-	-	-
TVS	mg/L	4400 – 4500	-	-	-	-
TSS	mg/L	-	-	2700 – 7100	1000 – 3000	-
VSS	mg/L	-	-	1400 – 6600	-	-

[1] TS: Total solids; TVS: Total volatile solids
[2] Potato peeling and cutting process wastewater
[3] Process wastewater which is a mixture of potato washing water after sand separation and potato fruit water after starch recovery
[4] Values in paranthesis represent the average values

Table 4. Characteristics of wastewaters resulting from various types of potato processing

4.4.3 Anaerobic treatment applications for the treatment of potato processing wastewaters

Senturk et al. (2010a) investigated the mesophilic anaerobic treatment of potato processing wastewater obtained from a factory producing potato chips, maize chips and other snacks. They used a laboratory scale mesophilic anaerobic contact reactor which had similar features with activated sludge systems. The reactor was operated at different OLRs and HRTs ranging from 1,1–5,0 kg COD/m^3.day and 5,11–1,06 day, respectively, and it achieved COD removal efficiencies between 78–92%. Furthermore, various kinetic models such as Monod first order model, Stover–Kincannon model, Grau second-order and Michaelis–Menten models have been applied to the experimental data in order to determine substrate balance, maximum utilization rate and volumetric methane production. The applied models showed good agreement ($R^2 > 0,98$) with the experimental data and methane yield was determined as 0,394 L CH$_4$/g COD$_{removed}$.

A novel anaerobic–aerobic integrative baffled bioreactor supplied with porous burnt-coke particles was developed for the treatment of potato starch wastewater by Wang et al. (2009). This bioreactor was found to be effective for the removal of COD (88,4–98,7%) and NH$_3$–N (50,4 to 82,3%), in high-strength starch wastewater.

Musluoglu (2010) studied the co-digestion of potato chips production industry waste with the waste activated sludge from two different full-scale facilities. Average biogas potentials in both completely mixed reactors were between 600-650 m^3/ton VS$_{added}$.

The performances of laboratory scale UASB (0,84 L) and anaerobic packed-bed reactors (APB) (0,7 L) treating high strength potato leachate were compared by Parawira et al. (2006).

The maximum OLRs that could be applied to the UASB and APB reactors for stable operation were approximately 6,1 and 4,7 g COD/L day, respectively. More than 90% COD removal efficiency was reported for both type of reactors. On the contrary to the results obtained by Linke (2006) at an anaerobic completely mixed reactor treating solid potato waste, the methane yield increased with increasing organic loading rate up to 0,23 L CH_4/g $COD_{degraded}$ in the UASB reactor and 0,161 CH_4/g $COD_{degraded}$ in the APB reactor.

The effect of recirculation rate on packed bed reactors (1 L) treating potato leachate at different OLRs ranging between 4–12 kg COD/day was studied by Mshandete et al. (2004). The methane yield for the bioreactor with the lower recirculation flow rate (10 mL/minute) ranged between 0,10-0,14 m^3 CH_4/kg $COD_{removed}$, while for the other bioreactor it was between 0,14–0,20 m^3 CH_4/kg $COD_{removed}$. Lower methane yields were achieved at higher OLRs. While the methane yield of the reactor operated at high recirculation rate was more than the other bioreactor, in terms of process stability the reactor operated at low recirculation rate was superior. Process failure, indicated by low pH, high volatile fatty acid (VFA) concentration, was experienced at an OLR of 12 kg COD/m^3.day in the reactor operated at high recirculation rate. This was attributed to the high recirculation flow rate which provided rapid mixing and fast diffusion of the accumulated VFAs into the biofilm where microbes were accumulated.

The efficiency of the UASB process for the treatment of raw and pre-clarified potato maize waste up to the OLR of about 13-14 g COD/L.day was illustrated by Kalyuzhnyi et al. (1998). Although the reactor performed high COD removal efficiencies (63-81%) for raw potato maize waste (PMW), some problems such as excessive foaming and sludge flotation were experienced due to the accumulation of undigested ingredients at high OLR (> 10 g COD/L.day) and moderate HRT (> 1 day). These problems were eliminated by the application of shorter HRTs in order to enable better washout of light ingredients that were accumulated in the reactor, or by temporarily decreasing OLR. Methane yield varied from 0,24 to 0,44 L/g $COD_{removed}$ for raw PMW and from 0,30 to 0,37 L/g $COD_{removed}$ for pre-clarified PMW.

The anaerobic treatability of potato processing effluents by an anaerobic contact reactor operated at thermophilic conditions was studied by Senturk et al. (2010b). The OLR of the reactor was gradually increased from 0,6 kg COD/m^3.day to 8,0 kg COD/m^3.day by decrementing the HRT from 9,2 days to 0,69 days. The reactor could be operated at high OLRs without process failure and the average COD removal efficiency obtained at 8,0 kg COD/m^3.day was 86%. The average methane gas production was reported as 0,42 m^3 CH_4/kg $COD_{removed}$ and the methane content in the biogas ranged between 68–89%.

The performance of two-stage anaerobic digestion of solid potato waste under mesophilic and thermophilic conditions was evaluated by Parawira et al. (2007). A solid bed reactor was used as the hydrolytic stage of the two staged process. An UASB reactor fed with the leachate obtained from the hydrolysis reactor was used in the second step of the two-stage system with three different temperature combinations (mesophilic+mesophilic, mesophilic+thermophilic, thermophilic+thermophilic). They found that the methane yield of the mesophilic system (0,49 m^3 CH_4/kg $COD_{degraded}$) was significantly higher than the thermophilic system (0,31 m^3 CH_4/kg $COD_{degraded}$). However, thermophilic operation reduced the complete digestion period of the waste (from 36 to 25 days) and higher OLRs up to 36 kg COD/m^3.day could be applied to the UASB reactor.

The biogas yield of a completely stirred reactor treating solid potato waste at thermophilic conditions was found as 0,85–0,65 L/g TVS for the OLRs in the range of 0,8–3,4 g TVS/L.day, respectively (Linke, 2006). The results indicated a gradual decrease in the biogas

yield and methane content (from 58% to 50%) of the biogas depending on the increase in the OLR of the reactor.

The performance of two types of two-stage systems, one consisting of a solid-bed reactor connected to an UASB reactor, and the other consisting of a solid-bed reactor connected to a methanogenic reactor packed with wheat straw biofilm carriers, were investigated by Parawira et al. (2005). While the performance in terms of methane yield was the same (0,39 m^3 CH_4/kg VS_{added}) in the straw packed-bed reactor and the UASB reactor, the packed-bed reactor degraded the potato waste in a shorter time due to the improved retention of methanogenic microorganisms in the process.

4.5 Opium alkaloid industry
4.5.1 Process description

Opium is known to contain about 26 types of alkaloids such as morphine, narcodine, codein, papvarine and thebain (Sevimli et al., 1999). There are many different methods for the extraction of alkaloids from natural raw materials. Most of the methods depend on both the solubility of the alkaloids in organic solvents and solubility of their salts in water (Hesse, 2002). The process flow scheme of a wet-mill opium alkaloid industry, which mainly consists of grinding, solid-liquid and liquid-liquid extraction and crystallization processes, was given in Fig. 10.
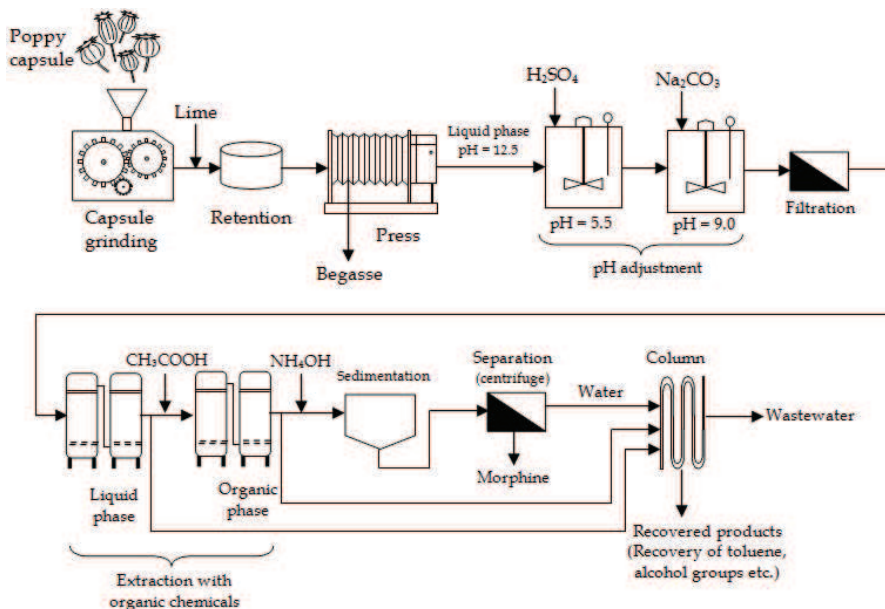

Fig. 10. Process flow diagram for an opium alkaloid industry

Firstly opium poppy capsules are grinded and treated with an alkaline solution (lime), and then the slurry is pressed to extract the liquid that contains the alkaloids. The pH of the liquid is adjusted to 9,0 and the impurities are separated by a filtration process. In the extraction process, the alkaloids are extracted with acetic acid solution and other organic solvents such as toluene and butanol. The morphine is crystallized by adding ammonium

and separated from the solution by centrifuges. The used solvents and the water are sent to the distillation column in order to recover toluene, alcohol groups and the remaining wastewater is treated in a wastewater treatment plant (Sevimli et al., 1999).

4.5.2 Wastewater sources and characterization

Opium alkaloid industry wastewaters are highly polluted effluents characterized with high concentrations of COD (mainly soluble), BOD_5 and TKN, dark brown colour and low pH. Alkaloid industry wastewaters are generally phosphorus deficient; therefore phosphorus addition might be required for biological treatment. Soluble COD content and acetic acid related COD of the wastewater can be as high as 90% and 33%, respectively (Aydin et al., 2010). Sevimli et al. (1999) determined the initial soluble inert COD percentage of opium alkaloid industry wastewaters as 2%. Aydin et al. (2010) reported the initial soluble and particulate inert COD content of opium alkaloid industry wastewaters under anaerobic conditions as 1,64% and 2,42%, respectively. Although no available data could be found in the literature for the sulphate content of the alkaloid industry wastewaters, it may be present at high concentrations due to the addition of sulphuric acid at the pH adjustment stage. Ozdemir (2006) reported a sulphuric acid usage of 48,3 kilograms per ton of opium processed. Furthermore, the alkaloid wastewaters might contain some toxic organic chemicals such as N,N-dimethylaniline, toluene which are inhibitory for biological treatment (Aydin et al., 2010). The general characteristics of opium alkaloid plant effluents given in the literature are presented in Table 5.

Parameter	Unit	Reference					
		Bural et al. (2010)	Aydin et al. (2010)[1]	Ozdemir (2006)	Sevimli et al. (1999)	Timur & Altinbas (1997)	Deshkar et al. (1982)
COD	mg/L	30000-43078	18300–42500(25560)	22000-34780	36500	21040	18800
Soluble COD	mg $CaCO_3$/L	28500-40525	17050–39470	-	-	-	-
BOD_5	mg/L	16625-23670	4250–22215(12000)	21250	32620	12075	15000
Alkalinity	mg/L	-	315–4450 (1290)	144-1050	-	4450	-
pH	-	4,5–5,36	4,9–6,3 (5,4)	-	4,95	5,1	8,4
TKN	mg/L	396–1001	550–841(673)	1001	1030	380	1870
NH_3-N	mg/L	61,6–259	73–141(98)	61,6-172,5	140	110	35
TP	mg/L	4,0–5,21	3,1–15,0	4-5,21	65	2,0	1,3
TS	mg/L		27235–29750	-	-	27235	15475
TSS	mg/L	555–2193	565–2295	1120-1700	1400	1005	38
TVS	mg/L	382–1395	320–1775	580-990	-	805	-
Color	Pt-Co	4375–4750[2]	2150–2550	4750	-	-	-

[1] Numbers in parenthesis represent the median values.
[2] After coarse filtration

Table 5. Characteristics of opium alkaloid industry effluents

4.5.3 Anaerobic treatment applications for the treatment of opium alkaloid wastewaters

Sevimli et al. (2000) investigated the mesophilic anaerobic treatment of opium alkaloids industry effluents by a pilot scale UASB reactor (36 L) operated at different OLRs (2,8 – 5,2

kg COD/m^3.day) at a HRT of 2,5 days. Although they experienced some operational problems, COD removal efficiency of 50–75% was achieved throughout the operational period. One of the most detailed and long termed study on the anaerobic treatability of effluents generated form an opium alkaloids industry was presented by Aydin et al. (2010). The treatment performance of a lab-scale UASB reactor (11,5 L) was investigated under different HRTs (0,84–1,62 days) and OLRs (3,4–12,25 kg COD/m^3.day) at mesophilic conditions. Although, the COD removal efficiency slightly decreased with increasing OLR and decreasing HRT, the reactor performed high COD removal efficiencies varying between 74%–88%. Furthermore, a severe inhibition caused by N,N-dimethylaniline, coming from the wastewater generated in the cleaning operation at the derivation unit tanks of the industry, was experienced in the study. During the inhibition period the treatment efficiency and biogas production dropped suddenly, even though the OLR was decreased and HRT was increased as a preventive action. Despite these interventions, the reactor performance could not be improved and the reactor sludge had to be renewed due to the irreversible inhibition occurred for four months. The reactor could easily reach to the same efficiency level after the renewal of the sludge. Average methane yield of the opium alkaloids industry wastewater was reported as 0,3 m^3 CH_4/kg $COD_{removed}$. Dereli et al., (2010) applied Anaerobic Digestion Model No.1 (ADM1), a structured model developed by IWA Task Group (Batstone et al., 2002), for the data obtained by Aydin et al. (2010). ADM1 was able to simulate the UASB reactor performance in terms of effluent COD and pH, whereas some discrepancies were observed for methane gas predictions.

Ozdemir (2006) investigated the co-digestion of alkaloid wastewater with acetate/glucose by batch experiments, therefore the usage of these co-substrates did not improve removal efficiency significantly but acclimation period of microorganisms was reduced. Continuous anaerobic treatment of alkaloid industry wastewater was further investigated by Ozdemir (2006) using three lab scale UASB reactors (Reactor 1: fed with alkaloid wastewater after hydrolysis/acidification, Reactor 2: fed with raw alkaloid wastewater, Reactor 3: fed with alkaloid wastewater together with sodium acetate as co-substrate) operated at different OLRs (2,5–9,2 kg COD/m^3.day) and a HRT of 4 days. Although all of the reactors performed well at low OLRs (~80% COD removal efficiency), process failure was experienced in R1 and R2 reactors at the OLR of 9,2 kg COD/m^3.day.

Ozturk et al. (2008) studied the anaerobic treatability for the mixture of wastewater generated from the distillation column and domestic wastewater of an alkaloid industry by a full-scale anaerobic Internal Cycling (IC) reactor with an OLR of 5 kg COD/m^3.day. COD and VFA removal efficiencies were 85 and 95%, respectively. Biogas production rate of 0,1-0,35 m^3 CH_4/$COD_{removed}$ was obtained. The main problems stated in this study were high salinity and sulphate concentrations.

4.6 Other industries
4.6.1 Anaerobic treatment applications for the treatment of other industrial wastewaters

A large quantity of wastewaters has generated from many different industries which, especially including high organic contents, if treated by anaerobic technology, a remarkable source of energy can be gained. Considerable attention has been paid to high rate anaerobic digesters such as UASB and EGSB reactors in order to provide possibility to treat industrial wastewaters at a high OLR and a low HRT (Rajeshwari et al., 2000). Application of anaerobic digestion for the industrial effluents is not limited with the industries discussed in

Wastewater Type	Reactor Type/Operating Temperature (°C)	Capacity (m³)	OLR (kgCOD/m³.day)	COD removal (%)	Methane yield (m³/kg COD)	Reference
Pulp and Paper	Baffled/35	0,01	5	60	0,141-0,178	(Grover et al., 1999)
Pulp and Paper	Anaerobic Contact/-	-	-	80	0,34	(Rajeshwari et al., 2000)
Slaughterhouse	UASB/-	450	2,1	80	-	(Del Nery et al., 2001)
Slaughterhouse	AF/-	21	2,3	85	-	(Johns, 1995)
Cheese Whey	Baffled/35	0,015	-	94-99	0,31	(Antonopoulou et al., 2008)
Cheese Whey	Upflow Filter/35	0,00536	-	95	0,55 (biogas)	(Yilmazer & Yenigun, 1999)
Textile	UASB/35	0,00125	-	>90	-	(Somasiri et al., 2008)
Textile	Fluidized Bed/35	0,004	3	82	-	(Sen & Demirer, 2003)
Coffee	Hybrid (UASB + AF)/23	10,5	1,89	77,2	-	(Bello-Mendoza & Castillo-Rivera, 1998)
Coffee	UASB/35	0,005	10	78	0,29	(Dinsdale et al., 1997)
Brewery	Sequencing Batch/33	0,045	1,5-5	>90	0,326	(Xiangwen et al., 2008)
Brewery	AF/34-39	5,8	8	96	0,15	(Leal et al., 1998)
Brewery	AF Fluidized Bed/35	0,06	8,9-14	75-87	0,34	(Anderson et al., 1990)
Olive Oil	UASB/37	-	12-18	70-75	-	(Azbar et al., 2010)
Olive Oil	Hybrid (UASB +AF)/35	-	17,8	76,2	-	(Azbar et al., 2010)
Sugar Mill	UASB/33-36	0,05	16	>90	0,355	(Nacheva et al., 2009)
Sugar Mill	Fixed Bed/32-34	0,06	10	90	-	(Farhadian et al., 2007)
Distillery	Granular bed-Baffled/37	0,035	4,75	80	-	(Akunna & Clark, 2000)
Distillery	Fixed Film/37	0,001	23,25	64	-	(Acharya et al., 2008)

Table 6. Anaerobic treatment applications for different industrial wastewaters

the previous sections. Besides, it has a wide potential for wastewater treatment applications of many industries such as pulp and paper, slaughterhouse, cheese whey, textile, coffee, brewery, olive oil, sugar mill, distillery, etc. It is not possible to present all industrial wastewater treatment application examples of anaerobic digestion in a chapter; instead, examples from a number of selected studies were given in Table 6.

5. Conclusions and future perspectives

Anaerobic biotechnology has a significant potential for the recovery of biomethane by the treatment of medium and/or high strength wastewaters especially produced in agro-industries. By using this technology, ~ 250-300 m³ biomethane can be recovered per ton $COD_{removed}$ depending on the inert COD content of the substrate. COD removal rates are generally between 65-90% in these systems. Anaerobic biotechnology, when used in the first

treatment stage, provides the reduction of aeration energy and excess sludge production in the followed aerobic stage, thus increasing the total energy efficiency of the treatment plant. Besides, it contributes to the increase in the treatment capacity of the aerobic stage. Also it is possible to obtain a considerable increase of production capacity for an industry if an anaerobic first stage treatment is applied before aerobic stage in an industrial wastewater treatment plant treating medium strength organic waste. In case of nitrogen removal in a two-stage (anaerobic+aerobic) biological wastewater treatment process, it may be necessary to bypass some of the influent stream from anaerobic to aerobic stage in order to increase the denitrification capacity. Autotrophic denitrification with H_2S in the biogas is an important option that should be kept in mind to reduce organic carbon requirement for denitrification in two-stage treatment process treating wastewaters that contains high organic matter and high nitrogen (Baspinar, 2008). It is more appropriate to apply pre-treatment as phase-separation (two-staged) for industrial wastewaters containing high sulphate concentration.

There are many full-scale applications for the operation of anaerobic processes under sub-mesophilic (27-30 ^{0}C) and high pH conditions, especially for the treatment of high strength wastewaters with high nitrogen content. In such conditions, full nitrification but partial denitrification at aerobic stage or an innovative nitrogen removal technology, Sharon/Anammox process, may be applied.

Another option for the pre-treatment of wastewater streams containing high COD (>40000 mg/L), total dissolved solids (TDS), TKN and potassium is an evaporation process that useful material can be recovered and residual condensate may be further treated by an anaerobic process.

Recently, co-digestion applications of treatment sludge with other organic wastes have increased dramatically due to the subsidies for renewable energy produced from wastes. In this respect, organic solid wastes and biological treatment sludge can be co-digested by installation of anaerobic co-digesters at the same location with available industrial-scale anaerobic bioreactors or near the sources of wastes to be digested.

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Waste Water - Treatment and Reutilization

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