Utilization of SBR Technology for Wastewater Treatment: An Overview

ARTICLE *in* INDUSTRIAL & ENGINEERING CHEMISTRY RESEARCH · OCTOBER 2002

Impact Factor: 2.59 · DOI: 10.1021/ie0201821

Joan Mata-Álvarez
University of Barcelona

REVIEWS

Utilization of SBR Technology for Wastewater Treatment: An Overview

S. Mace and J. Mata-Alvarez*

Facultat de Química, Departament d'Enginyeria Química, Universitat de Barcelona, Martí i Franquès 1, planta 6, E-08028 Barcelona, Spain

This review paper intends to provide an overall vision of SBR technology as an alternative method for treating wastewaters. This technology has been gaining popularity through the years, mainly because of its single-tank design and ease of automatation. The bibliographic review carried out here shows the efficiency and flexibility of this technology, as it is able to treat different kinds of effluents such as municipal, domestic, hypersaline, tannery, brewery, and dairy wastewaters; landfill leachates; etc.; under different conditions. The review includes relevant experiments carried out at the laboratory, pilot-plant, and industrial scales.

Introduction

Sequencing batch reactor (SBR) is the name given to wastewater treatment systems based on activated sludge, operated on a sequence of fill and draw cycles (Figure 1). These systems normally include a biological nutrient removal process. The unit operations involved in an SBR are equivalent to those of conventional activated sludge systems. Therefore, aeration and sedimentation−clarification are performed. The difference between the systems is that, in conventional systems, these two processes take place in two different tanks whereas, in SBR systems, they occur sequentially in the same tank.

Research on SBR reactors began in the 1970's,[1] simultaneously with the development of other discontinuous processes (for instance, Goronszy[2]). Even in 1914, the reactors based on active biomass designed by Arden and Lockett[3] were operated according to the principles of SBR technology.

One of the advantages of these batch systems is that they can easily be adapted for continuous variations of pollutant concentrations.[4] In fact, mass balances of batch systems describe the unstable behavior produced by the natural variations of volumetric flows and pollutant concentrations.[5]

With the growth in the use of microprocessor-based programmable logic controllers (PLCs) and the increase in the reliability of these systems, SBR treatment technology has become more popular. SBR treatment for wastewater can produce an effluent that is better than that obtained by a secondary treatment and can operate over a wide range of hydraulic and organic flow variations. Table 1 summarizes more benefits and advantages of this technology.

Papers by Norcross[6] and Ketchum[7] dealing with the design and physical features of sequencing batch reactors are important for an understanding of SBR characteristics. The first considers mechanical, process, and control aspects of the design of SBRs; the second clearly describes the SBR physical system and explains approaches used to develop the bases of design needed to meet different treatment objectives.

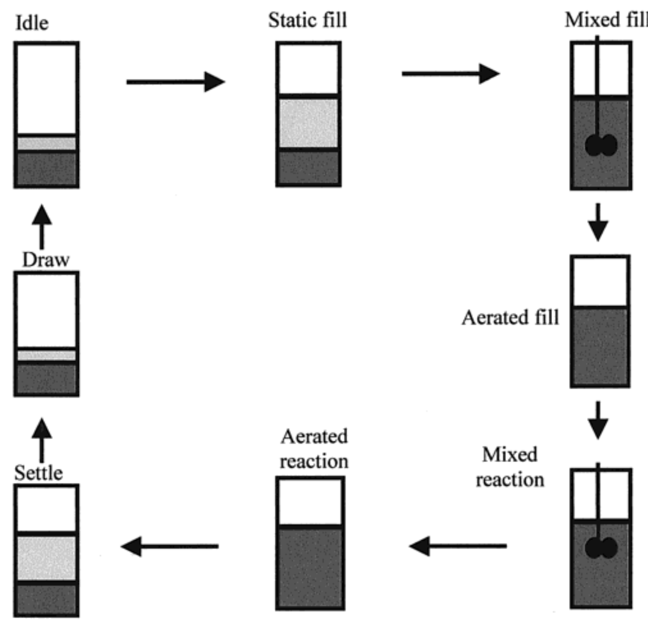

Figure 1. Schematic of SBR operation during one cycle.

Table 1. Benefits and Advantages of SBR Technology

lower cost than conventional biological treatment methods
less land required than conventional methods
capable of handling wide swings in hydraulic and organic loadings
easier to control filamentous growth and settling problems
less equipement to maintain
less operator attention required
greater operator flexibility
biomass cannot be washed out
bad settling can be recognized and corrected
PAC[a] can be added

[a] Powdered activated carbon.

* To whom correspondence should be addressed. Tel.: +34-4021305. Fax: +34-4021291. E-mail: jmata@medicina.ub.es.

10.1021/ie0201821 CCC: $22.00
Published on Web 10/22/2002

In July 2000, the Second International Symposium on Sequencing Batch Reactor Technology was held in Narbonne, France, which indicates the relevance of this technology. Some of the research and developments presented at this symposium are used as sources of data for this review. The diversity of papers in the literature dealing with sequencing batch reactor technology reflects the large number of topics within this area and the capacity of this system to adapt to this large variability. Thus, Hopkins et al.[8] carried out extensive comparative studies between continuous and batch systems based on biomass, pointing out that flexibility is one of the advantages of discontinuous systems such as SBRs.

In this paper, a bibliographic review of the various applications of this technology in wastewater treatment is given.

Sequencing Batch Reactors: An Overview

Municipal Wastewaters. The work by Bernardes and Klapwijk[9] reflects how readily biodegradable substrate plays an important role in biological nutrient removal processes. The authors carried out an investigation to evaluate the performance of SBR processing, including nitrification, denitrification, carbon oxidation, and phosphorus removal, on a presettled domestic wastewater from the Bennekom Municipal Treatment Plant (Bennekom, The Netherlands), with a capacity of 22 000 pe (population equivalents). The pilot-plant SBR consisted of two cylindrical polystyrene vessels, the first with a total volume of 0.35 m^3 (reactor 1) and the second with a total volume of 1.3 m^3 (reactor 2). The characteristics of the effluent after the addition of acetic acid were 443 mg/L COD (chemical oxygen demand), 71 mg/L TKN (total Kjeldahl nitrogen), and 7 mg/L $P-PO_4^{3-}$. The SBR pilot plant was operated for 5 months, with cycles of 4 h. The periods in reactor 1 were mixed fill, mixed react, and draw. The periods in reactor 2 were mixed react, mixed fill, mixed react, aerated react, settle, and draw. This system achieved a good performance for P and N removal, as it gave, on average, phosphate concentrations lower than 1 mg of P/L and nitrogen concentrations lower than 12 mg of N/L. In this experiment, the authors demonstrated that the readily biodegradable substrate concentration in the influent is very important for denitrification for two reasons: it is a limiting factor for good P removal, and it is important for good nitrogen removal. Normally, this external, easily biodegradable carbonaceous source consists of a mixture of alcohols and/or fatty acids. With similar objectives, Umble and Ketchum[10] treated municipal wastewater by SBR technology. Because of its operating flexibility, their SBR was used to provide biological treatment of wastewater for the oxidation of organic matter, removal of suspended solids, and nitrification. The performance of the reactor's 12-h cycle for biochemical oxygen demand (BOD_5), total suspended solids (TSS), and NH_3-N removals was 98, 90, and 89%, respectively. This is a special case, as the process included tertiary treatment to recover inorganic nutrients so that desirable algal groups could be obtained in an aquaculture component.

However, recently, some authors, such as Beccari et al.,[11] have examined other possibilities. In this paper, the authors studied the potential of using readily biodegradable COD obtained from acidogenic fermentation of the organic fraction of municipal solid waste (source selected) as an electron donor for denitrification. Experiments were carried out by using an SBR pilot plant, with a domestic wastewater coming from the wastewater treatment plant of Fusina (Venice, Italy). The results showed a remarkable improvement in both the denitrification rate and the flexibility of the response to influent load peaks. The main advantage of this approach is the savings resulting from the exclusion of an expensive external carbonaceous source. This study can be considered as one of the first suggesting the utilization of residual effluents as substitutes for chemical carbonaceous sources.[12-14]

There are also cases in which SBRs have been coupled with other reactors to meet the objective of using an internal C source. For instance, Rustrian et al.[15] described the treatment of a municipal wastewater through a system consisting of a two-step anaerobic digestion reactor (acidogenesis + denitrification and methanogenesis) for carbon removal coupled with an SBR for nutrient removal. Thus, the volatile fatty acids produced in the acidogenic reactor were used as a carbon source for biological dephosphatation in the SBR. The benefits of this system are, again, the savings of an external carbon source for denitrification and dephosphatation.

Another example of a combined method is found in the paper by De Sousa and Foresti,[16] in which a combined anaerobic–aerobic system for treating domestic sewage in tropical regions is proposed. It was composed of an upflow anaerobic sludge blanket (UASB) reactor (4 L) followed by two identical aerobic sequencing batch reactors (SBRs) of 3.6 L. In such a system, the UASB reactor removes a considerable fraction of the influent organic matter while the aerobic SBR oxidizes part of the remaining organic matter and ammonium nitrogen. To investigate the performance of this system for sewage treatment, a bench-scale installation fed with synthetic substrate simulating domestic sewage was operated continuously for 38 weeks. The results confirmed the initial hypothesis, because the system consistently produced high-quality effluents [BOD_5 and VSS (volatile suspended solids) lower than 10 mg/L]. The results also indicated that such combined anaerobic–aerobic systems compete favorably with conventional aerobic systems in three essential cost features: energy consumption, excess sludge production, and nutrient removal.

SBR systems have demonstrated even better performance than other alternatives. Dockhorn et al.[17] studied COD removal from a municipal wastewater for 2.5 years, comparing three different types of reactors (a completely mixed reactor, a cascade of three reactors, and an SBR) to determine the influence of the mixing characteristics of the reactor on the treatment processes and the effluent quality. The SBR gave very good results. On the other hand, it could be shown that COD removal efficiency increased as the mixing characteristics approached those of plug flow.

Mathematical models have also been considered in studies of the efficiency of SBRs for the treatment of municipal sewage. Among the numerous mathematical models that have been developed dealing with this kind of treatment, Bernardes et al.[18] presented an interesting report on the behavior in terms of respiration rate and nitrate removal for an activated sludge sequencing batch reactor with nitrification, denitrification, and carbon oxidation with a domestic wastewater. For model validation, an SBR pilot plant (1 m^3) receiving domestic

Table 2. Characteristics and Removal Percentages of Some Municipal Wastewaters Treated by SBR

ref	scale	characteristics	removals
Imura et al.[106]	small scale (17.84 m^3 effective capacity)	20 m^3/day treated 4 cycles/day (6-h cycles)	97.3% BOD 99% NH_4-N 95.6% SS 96% TP
Bischof et al.[107]		plant in Grammendorf, Germany is an example of the advantages of SBRs	
Bernardes and Klapwijk[9]	pilot plant	4-h cycles 2 reactors	83.1% N 85.7% P
De Sousa and Foresti[16]	bench scale UASB + 2SBRs	4-h cycles	95% COD 96% TSS 85% TKN
Umble and Ketchum[10]	laboratory	12-h cycles	98% BOD_5 90% TSS 89% NH_3-N
Beccari et al.[11]	pilot plant	internal carbon source used for denitrification	
Mines et al.[108]		12-h cycles	
Morgenroth et al.[109]		review of sequential processes in municipal wastewater treatment	
Rustrian et al.[15]	two-step anaerobic digestion reactor + SBR (2-L reactor)	increasing number of cycles/day (1−4) favors P removal but N removal decreases	98%COD 76% TKN 64% $P-PO_4$
Dockhorn et al.[17]	pilot plant	comparison of a CSTR, an SBR, and a cascade of three reactors	88.5% COD if SRT = 8 days 94.5% COD if SRT = 20 days
Teichgräber et al.[20]	full scale	presents steps for designing an SBR pilot plant acording to ATV guidelines	
Keller et al.[23]	full scale	47-h HRT 23-day SRT 850 m^3/day daily influent flow	complete biological nutrient removal

wastewater was operated for 3 months, and the results were compared with the model. The simulation values matched well with the measured respiration and nitrate removal rates. The model was able to predict the respiration rate and denitrification in one cycle with parameters taken from the previous one.

An advanced mathematical model describing N and P transformations in an SBR treating municipal wastewater based on the concepts proposed by the IAWQ Task Group for Activated-Sludge Modeling, is found in the paper by Brenner.[19] This model can be used for the improvement of process design, analysis, and control.

In relation to full-scale applications, it is important to remark that, in Germany, SBR technology is applied in about 1.3% of the wastewater treatment plants (WWTPs).[20] For instance, in Bavaria, numerous small WWTPs utilize SBR technology.[21] In a paper by Teichgräber et al,[20] a guideline created to simplify the design of SBR plants is described. To illustrate the efficiency of SBRs at full scale, the results reported by Steinmetz[22] demonstrate the efficiency of two municipal SBR plants that were designed for 15 000 and 25 000 pe. The results show that SBR technology leads to very good and stable effluent concentrations when used for municipal wastewater, even in case of long frost periods and overloading. There is also the case of Keller et al.,[23] where complete biological nutrient removal in a single-tank sequencing batch reactor process is demonstrated at full scale with a typical domestic wastewater.

Finally, a quite different example of an industrial application is given in Figure 2, where a schematic flow diagram of an SBR-based plant is presented. These large reactors treat the reject water from four 6700-m^3 digesters treating the organic fraction of solid wastes in Barcelona, Spain. The SBR reactor volume is around 2000 m^3, and the daily flow rate is 220 m^3, which gives rise to a hydraulic retention time (HRT) of around 10 days (extended aeration operation). Some of the yields are as follows: COD is reduced from 7200 to less than 1500 mg/L and TN from 2300 to less than 200 mg/L.

Table 2 summarizes some characteristics and removal percentages reported in some of the papers examined in this section and provides more references of other authors that have treated these wastewaters by SBRs but are not cited here.

Reject Water from Wastewater Treatment Plants (WWTPs). In WWTPs, the sludge reject water contains up to 25% of the total nitrogen load in a flow, and it is usually returned to the head of the sewage treatment works. Nitrogen removal from this highly concentrated wastewater (about 800−1000 mg/L NH_4-N) can be achieved in the existing WWTP if it is extended with additional volumes of aeration tanks, which represents

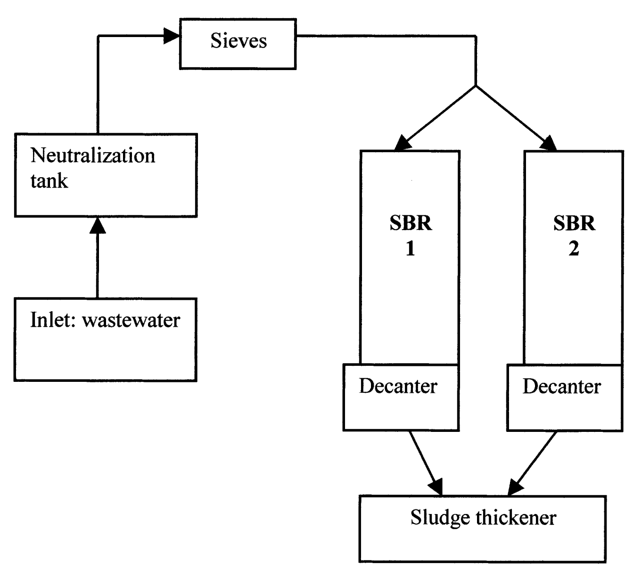

Figure 2. Schematic flow sheet of the wastewater treatment plant for the supernatant of the four 6700-m^3 digesters treating the organic fraction of municipal solid wastes of Barcelona, Spain.

Table 3. Some Relevant Studies of SBR Systems Treating Reject Waters

ref	scale	characteristics	results
Mossakowska et al.[110]	pilot plant		efficiency higher than 1 kg of NH_4−N m^{-3} day^{-1}
Siegrist[26]		comparison of chemical and biological methods for nitrogen removal from digester supernatant	separate treatment with intermittent nitrification/denitrification is an interesting solution
Janus et al.[25]	pilot plant	evaluation of pilot-plant investigations of five treatment options	high nitrogen removal efficiencies can be attained
Mossakowska et al.[111]	pilot plant	nitrification rate strongly dependent on O concentration	very high nitrification rate of 30−40 g of NH_4−N (kg of MLVSS)$^{-1}$ h^{-1}
Wett et al.[29]	full-scale plant treating loadings of up to 200 000 pe	process controlled by pH measurements	stable nitrification rates of 50−60 mg of NH_4−N L^{-1} h^{-1}
Bowen and Ketchum[112]		SBR used for the nitrification of effluents high in ammonia	
Ghyoot et al.[24]	laboratory scale	start-up of a membrane-assisted bioreactor (MBR) for nitrogen removal from sludge reject water	maximum organic loading rate for complete nitrfication of 0.16 kg of N (kg of SS)$^{-1}$ day^{-1} for the MBR equipped with an ultrafiltration unit
Vandaele et al.[27]	pilot-scale SBR and SBBR	average NH_4^+−N concentration of 668 mg/L	65% N removal at a maximum load of 0.7 kg of N m^{-3} day^{-1}
Arnold et al.[28]	pilot scale	NH_4^+−N effluent concentrations between 460 and 700 mg/L	more than 90% nitrogen removal with both SBR and SBBR

a substantial investment.[24] Therefore, separate treatment of this nitrogen-rich water might significantly save in costs as well as space. Several options for treating this supernatant are available, such as magnesium ammonium phosphate (MAP) precipitation, ammonia stripping, treatment in biofilm airlift suspension reactors or in membrane bioreactors, etc.[25] MAP precipitation is feasible but most expensive because of the required chemicals as well as the dewatering and drying of the precipitate. Air stripping is slightly cheaper, but it is still more expensive than biological treatment because of the complex process, cost of chemicals, and reconditioning of the ammonium sulfate solution to a fertilizer product.[26] Therefore, a biological treatment would be the best option. One of the promising alternatives is the use of an SBR for the treatment of this highly concentrated water. Two good examples found in the literature are the papers of Vandaele et al.[27] and Arnold et al.[28] The authors of both papers compare the use of an SBR and a sequencing batch biofilm reactor (SBBR) for the treatment of anaerobic digester supernatants. In general, they state that both activated sludge SBRs and SBBRs are applicable to the treatment of reject water with a high ammonia loading. Nitrogen removal efficiencies of more than 90% could be obtained with both systems. A reliable control of the process is necessary, however.[29] Table 3 presents some of the relevant references regarding studies of SBR systems treating this particular type of wastewater.

These examples, coming from domestic wastewater treatment, reflect the capability of sequencing batch reactors to achieve high-quality effluents, as biological nutrient and carbon removal take place with excellent efficiencies.

For the treatment of industrial wastewaters, additional challenges include the nutrient removal process and the SBR design because of the substantially higher concentrations of both carbon and nutrients.[30] The cases described below show the adaptability of SBR to the treatment of industrial wastewaters.

Winery and Brewery Wastewaters. The transformation of grapes into wine involves a sequence of operations in the winery during which considerable quantities of water are required, at intervals, for cleaning purposes. The resulting wastewater, heavily polluted by organic matter, constitutes a major source of environmental pollution, particularly during the harvest period. Given the particular characteristics of wine effluents and, in particular, the seasonal nature of the discharges, the best solution for their treatment seems to be a sequencing batch reactor, which is a very flexible tool and can cope with the seasonal nature of the discharges. Torrijos and Moletta[31] studied the depollution of a winery wastewater using an SBR process that was shown to be effective during the 1994 grape harvest in a winery producing 7300 hL annually located at Domaine du Mouton (Bordeaux, France). The SBR was fed once a day following a sequence of aeration/stirring for 20 h, decanting for 3 h, and pumping off of the clarified wastewater for the last hour. The results were 93% removal for total COD, 95% for soluble COD, and 97.5% for BOD_5. These results, as well as the simplified automatation, the low capital costs, and the moderate operating costs showed that the process is well-suited to the depollution of wastewater from small wineries.

This study, as well as one by Houbron et al.,[32] demonstrated that SBR technology applied to winery wastewater yields COD removal efficiencies higher than 95% and low sludge production. The same treatment can be applied to brewery wastewaters, with characteristics similar to those obtained for the winery wastewaters (high COD concentration, variable flow rate, and variable organic loading). In fact, breweries play an important role in agricultural industries. Their drinking-water consumption is high, as drinking water is used for many purposes, such as the attainment of the final product and the intensive cleaning of materials and tools. The wastewater effluent flow rate and organic loading present large fluctuations because of the peculiar characteristics of brewery operations; in fact, the flow rate can vary from 4 to 20 L of water consumed per liter of elaborated product.[33]

Two representative examples of the application of SBR technology to the biological treatment of brewery wastewaters are described below.

Ling and Lo[34] carried out some experiments with laboratory-scale aerobic sequencing batch reactors to study the treatment of brewery wastewaters. They tested the efficiency of an SBR in both suspended-growth and attached-growth modes, with hydraulic

Table 4. Some Significant Examples of SBR Technology Applied to Winery and Brewery Wastewaters

ref	scale	characteristics	removals
Wang et al.[113]		brewery wastewater used as an internal carbon source	
Torrijos and Moletta[31]	full scale	1 cycle/day	93% COD (total) 95% COD (soluble) 97.5% BOD_5
Houbron et al.[32]	industrial scale	24-h cycles	97.5% BOD_5 93−96.3% COD 50% TKN 88% TP
Ling and Lo[34]	laboratory scale	HRT of 0.56−6.06 days suspended- and attached-growth modes	>90% TOC, BOD_5, COD, and SS
Lo et al.[35]	laboratory scale	attached-growth mode HRT of 3.33 days	91% BOD 93.2% COD 84.6% N−NH3
Houbron et al.[33]	laboratory scale	1−3 cycles/day effluent contains 50−184 mg of COD/L and 58−83 mg of TSS/L	97% COD 60−80% TSS
Nguyen et al.[36]		fixed-film SBR, 25 and 35 °C	92% TBOD
Rodrigues et al.[114]		posttreatment maximum rate of 0.175 kg of NH_4^+−N (kg of VSS)$^{-1}$ day^{-1}	97% nitrification efficiency

retention times ranging from 0.56 to 6.06 days. The results demonstrated that brewery wastewater can be successfully treated using both suspended-growth and attached-growth aerobic sequencing batch reactors, with removals of over 90% of TOC (total organic carbon), BOD_5, COD, and SS (suspended solids).

Another example of the treatment of brewery wastewaters with SBR technology is the experiment carried out by Lo et al.,[35] which was very similar to the one described above. They concluded that the highest treatment efficiency for suspended-growth reactors was achieved at an HRT of 3.3 days (with removals of 91% of BOD, 93.2% of COD, and 84.6% of NH_3−N). They deduced that attached-growth SBRs had the advantage of being able to function well at shorter HRTs than suspended-growth SBRs.

More recently, the studies of Houbron et al.[33] using an aerobic sequencing batch reactor for brewery wastewater treatment confirmed that sequencing batch reactor technology is quite effective on the laboratory scale.

To control the process of brewery wastewater treatment, Nguyen et al.[36] proposed an effective feedback-controlled system based on the dissolved oxygen concentration in the mixed liquor.

Table 4 summarizes some significant examples of SBR technology applied to this kind of effluent.

Landfill Leachates. There are many cases in the literature describing the effectivity of the SBR technology for the treatment of landfill leachates.

In experimental studies with biologic aerobic treatments and retention times of 20 and 40 days, Lo[37] reached a removal efficiency of NH_3−N in excess of 99%. Zaloum and Abbott[38] compared the typical lagoon treatment of raw leachate at a landfill site with an alternative employing a single-basin SBR. They studied the possibility of using the SBR after an anaerobic pretreatment, with a sludge retention time (SRT) of 50 days and an HRT of 3.2 days. They concluded that the SBR treatment of anaerobic lagoon effluent was the best option. With this treatment, the BOD, COD, and nutrient residual concentrations were within the stricter new proposed regulations in Quebec, Canada.

Timur and Ozturk[39] treated landfill leachate taken from a young municipal site (3−5 years old) containing high organic pollutants. They performed the treatment in a bench-scale anaerobic sequencing batch reactor (ASBR) and an anaerobic hybrid bed filter (AHBF) at mesophilic conditions. The ASBR achieved 73.9% TOC removal at a maximum organic loading rate of 2.8 kg of TOC m^3 day^{-1} for an HRT of 1.5 days. They concluded that, considering the flexibility of the ASBR in adapting to variations in volume and effluent composition and the high cost of AHBF systems, ASBRs are better for the treatment of young landfill leachates. In a later study, these authors evaluated the anaerobic treatability of municipal landfill leachate using a laboratory-scale ASBR at 35 °C. Experimental studies were conducted for a wide range of volumetric (0.4−9.4 g of COD L^{-1} day^{-1}) and specific [0.2−1.9 g of COD (g of VSS)$^{-1}$ day^{-1}] loading rates by varying the hydraulic retention time (HRT) from 10 to 1.5 days. Removals of COD were between 64 and 85%, depending on the applied rates.[40]

The possibility of using an internal biodegradable carbon source for denitrification has also been investigated in the field of landfill leachate treatment. In this sense, Yilmaz and Ozturk[41] investigated the utilization of SBR technology for biological nitrogen removal from landfill leachates, as well as the possibility of using the leachate as an external source of biodegradable carbon for the denitrification process. They concluded that an anaerobically treated landfill leachate with a high concentration of NH_4^+−N and low biodegradable COD can be efficiently treated in an SBR with a nitrogen removal of 90%, using $Ca(CH_3COO)_2$ as an external carbon source in the denitrification phase. They also observed that a young landfill leachate with COD/NH_4^+−N lower than 10 can be used as a C source. However, effluents with high COD/NH_4^+−N levels are not appropriate for use as C sources for denitrification.

A particular case is that of Diamadopoulous et al.,[42] who examined the feasibility of biologically treating a combined waste stream of landfill leachate and municipal sewage with a ratio of 1:9. The composition of the influent was 430 mg/L DBO_5, 1090 mg/L COD, and 133 mg/L total N (80% of NH_3−N). A laboratory-scale sequencing batch reactor with activated sludge (TSS of 3500 mg/L) was used to evaluate the performance of the biological treatment. The SBR was operated in daily time cycles with the phases of filling, anoxic, aeration reaction, settling, and drain. The results indicated that

Table 5. Some Significant Examples of SBR Technology Applied to Landfill Leachate Treatment

ref	scale	characteristics	removals
Lo[37]		retention times of 20−40 days	99% NH_3−N
Dollerer and Wilderer[43]	SBBR	12-h cycle	68% COD (average)
Diamadopoulos et al.[42]	laboratory scale	influent: 430 mg/L DBO_5, 1090 mg/L COD, 133 mg/L TN (80% N−NH_3) (3500 mg/L TSS) daily time cycles	95% BOD_5 99% NO_3−N 50% N
Zaloum and Abbot[38]	32-L SBR	SRT 50 days HRT 3.2 days	98.6−99.5% BOD 82.1−94.6% COD
Timur and Ozturk[39]	bench-scale ASBR and AHBF	maximum organic loading rate of 2.8 kg of TOC m^3 day^{-1} HRT of 1.5 days	73.9% TOC
Timur and Ozturk[40]	laboratory-scale ASBR, 35 °C	wide-range of volumetric (0.4−9.4 g of COD L^{-1} day^{-1}) and specific [0.2−1.9 g of COD (g of VSS)$^{-1}$ day^{-1}] loading rates obtained by varying the HRT from 10−1.5 days	64−85%, depending on applied rates
Traut et al.[44]	pilot scale	two medium-strength leachates 1 cycle/day	complete nitrification (NH_3^-−N < 0.1 mg/L)
Obbard et al.[115]		leachate treatment with reference to potential applications in Asia-Pacific countries	
Yilmaz and Ozturk[41]	laboratory	24-h cycles young landfill leachate with COD/NH_4^+−N ratios of more than 10 can be used as an external carbon source	>90% N removal
Doyle et al.[45]	300−900 mg/L influent	HRT of 5 days rate of 5.91 g of N/(L day) specific rate of 880 mg of N (g of VSS)$^{-1}$ day^{-1}	complete nitrification
Kennedy and Lentz[116]	laboratory	municipal leachate treated by continuous UASB and SBR	71−92% COD at HRTs of 24, 18, and 12 h

the biological treatment of this kind of effluent was possible (with removals of 95% of BOD_5 and 99% of NO_3^-−N during denitrification). However, the overall nitrogen removal for a full cycle was about 50%; consequently, an anoxic phase after the aeration phase was necessary, as was the addition of an external source of biodegradable carbon.

Dollerer and Wilderer[43] studied the biological treatment of landfill leachates with an SBBR (SBR with biofilm). They tested two different kinds of aeration systems, a reactor equipped with a membrane oxygenation system and a reactor that was bubble aerated. In this case, the emission of biodegradable organic substances was observed to be significantly reduced. The process was found to be remarkably stable, with an average COD removal rate of 68% in a 12-h cycle.

Some authors have compared the treatment of different landfill leachates. For example, Traut et al.[44] treated two medium-strength leachates taken from a municipal landfill site by an SBR system: one was obtained from domestic waste and the other from a mixture of industrial and domestic wastes. In both cases, the removal of COD was considerable, and the nitrification of NH_3−N was complete. Doyle et al.[45] performed experiments using a similar approach, but with high-strength leachates. They investigated the nitrification of a landfill leachate with high concentrations of ammonium (300−900 mg/L) in an SBR. Four leachates from four different landfills were treated for 2 years. In these 2 years, they obtained a highly specific microorganism culture that was able to give high nitrification rates. Complete nitrification resulted after an HRT of 5 days, with a rate of 5.91 g of N L^{-1} day^{-1} and a specific rate of 880 mg of N (g of VSS)$^{-1}$ day^{-1}. The good results obtained in the pilot plant allowed the construction at high scale of a plant in one of the landfills studied. Table 5 summarizes some examples of SBR technology applied to landfill leachate treatment.

Tannery Wastewaters. Tannery wastewater represents a powerful pollutant, mainly because of their high CODs and elevated chrome contents. Generally, these wastewaters are treated by physicochemical methods or by biological nitrification and denitrification, which can be followed by clarification/flocculation or activated carbon adsorption.[46] It is easy to find many papers in the literature dealing with tannery wastewater treatment that are mainly focused on electrochemical treatments, UASB reactor use, color removal, or recycling and recovery of useful materials from this wastewater such as chromium. However, there are few papers in which sequencing batch reactors are chosen for this wastewater treatment.

Thus, although it might appear as a contradiction, the largest wastewater treatment plant in Europe based on sequencing batch reactor technology is located at Nowy Targ, Poland,[47,48] where tannery wastewater is produced with a high content in chromium. The process technology was designed for application to a typical municipal wastewater with a separation unit to treat tannery wastewater containing chromium. Because of poor wastewater management in the city, the inflow to the WWTP included tannery wastewater with increasing chromium concentrations that caused operational problems. The process was evaluated for 2 years, and despite the high chrome concentrations in the influent, good removals of N and P were obtained, with concentrations reaching less than 1 mg/L in the effluent. A low nitrification rate (more likely to be associated with temperature effects than with process inhibition by Cr) and a high denitrification rate were also found. In addition to this nutrient removal, the Nowy Targ

WWTP also achieved the removal of chromium from concentrations of 4−10 to around 0.5 g of Cr/m^3.

In another case, Carucci et al.[49] studied the feasibility of treating this kind of wastewater with an SBR. The authors compared the SBR behavior with the performance of a continuous reactor. A laboratory-scale SBR was fed with a wastewater from a treatment plant in Pisa, Italy, with anoxic−aerobic conditions. Good nitrification was obtained. Denitrification was effective when the COD/TKN ratio in the influent was higher than 8. The removal of organic matter took place mainly during the anoxic period. This study demonstrated once again the efficiency of SBR reactors for treating industrial wastewaters, because of its advantages over continuous reactors, such as a greater versatility; the possibility of working with higher loads (less volume); and through the concentration gradients, the selection of a biomass able to cope with inhibitory substances.

Hypersaline Wastewaters. SBR technology has also demonstrated its effectiveness in the treatment of wastewaters with high salt contents. For instance, Woolard and Irvine[50] treated a hypersaline wastewater (3.5% in salts). They observed that conventional microorganisms were not capable of degrading the waste and that halophilic microorganisms, which are perfectly adapted to survive at high salinities, were necessary. These organisms were able to form a halophilic sludge in a sequencing batch reactor and to remove phenol and nutrients.

More recently, Glass and Silverstein[51] carried out an investigation to develop an acclimatation strategy allowing for the denitrification of high-nitrate and high-salinity wastewater. More precisely, they denitrified a wastewater with 8200 mg/L NO_3−N that had an ionic strength of 3 in an SBR with activated sludge (at pH 9). The nitrate concentration was increased from 2700 to 5400 and finally to 8200. Simultaneously, the wastewater ionic strength was increased from 0.8 to 2.7 and to 3.0 (5, 16, and 18% total dissolved solids, respectively). Although complete denitrification occurred, the maximum specific nitrate reduction rate decreased from 50 to 19 mg of NO_3^- (g of MLSS)$^{-1}$ h^{-1}.

Intrasungkha et al.[52] also arrived at the same results: they studied the effect of salinity on nitrogen and phosphorus removal in wastewater treatment processes, using artificial seafood processing wastewater. Laboratory-scale sequencing batch reactors were operated initially at low and then at increasing salt levels. Experimental data showed that the SBRs achieved good biological nutrient removal when the salinity levels in the influent were low (0.03−0.2% NaCl) but showed difficulties with biological phosphorus removal at salinity levels of 0.5%.

Wastewaters from Paper Industry. The paper industry is known to generate considerable quantities of wastewater, about 60 m^3/te of produced paper. This wastewater can have a COD as high as 11 000 mg/L. These data were reported in a recent paper by Thompson et al.[53] that reviews the treatment of pulp and paper mill effluents. Primary clarification is the main treatment applied to this wastewater, and it can sometimes be followed by secondary treatment, generally of a biological nature. However, one of the problems encountered in the treatment of kraft mill effluents by activated-sludge conventional processes is the settlement characteristics of the sludge, as well as the formation of filamentous microorganisms. The unaerated fill mode has been shown to prevent filamentous bulking.[6,54,55] Indeed, SBR systems have proven to be more resilient to shock loads of kraft mill effluents than aerated lagoons.[56]

Franta and Wilderer[57] fed SBRs with wastewaters from the paper industry and optimized the length of each reactor phase. They also investigated the best sludge age for the degradation of organic matter. Their results showed that the best COD removal occurred at a sludge age of 20 days, with a reaction phase of 12 h, and a feed phase of 30 min. GC/MS analyses showed that the recalcitrant COD that remained was formed by organic refractory compounds such as lignin.

Tripathi and Allen[58] investigated the influence of high-temperature biological treatment in four parallel sequencing batch reactors over 40 weeks in mesophlic (35 °C) and thermophilic (45, 55, and 60 °C) operation with a bleached kraft pulp mill effluent. The COD removal was significantly higher at 35 and 45 °C than at 55 and 60 °C. It was observed that AOX (adsordable halogenated compound) removal decreased with increasing temperature. Long-chain fatty acid removal was better at thermophilic conditions than at mesophilic conditions. Microorganisms responsible for an increase in suspended solids concentrations from 20 to 80 mg/L predominated at 55 and 60 °C.

Milet and Duff[59] and Kahmark and Unwin[60] also studied the treatment of this kind of effluent. Thus, Milet and Duff used a sequencing batch reactor to treat kraft accumulator and evaporator condensates. In the kraft pulping process, condensates that are formed in the digester and black liquor evaporators constitute only 5% of the total mill effluent volume but can account for as much as 40% of the total BOD discharged from a bleached kraft mill. The main pollutant in kraft condensates is methanol. For its biological removal, they used a strategy allowing for total control of the reactor, ensuring that complete and rapid nutrient removal would occur: this technology is based on use of the oxygen level to determine when the next cycle must start. This strategy was effective, with a 100% removal of methanol and an 88% removal of COD (which was 3780 mg/L at the beginning of the treatment).

In terms of monetary requirements, Villeneuve and Tremblay[61] reported that the use of an SBR can reduce capital costs by about 30%, compared to conventional systems.

Finally, it is important to note that this technology when treating paper mill effluents is used in Canada for the treatment of paper mill effluents.[62]

Table 6 summarizes some significant examples of SBR technology applied to this kind of effluent.

Food Industry and Dairy Wastewaters. Food industry wastewaters are characterized by their high content in nutrients, particularly nitrogen (about 200−400 mg/L TKN and 20−50 mg/L P). Raper and Green[63] described the design of two plants, a pilot plant near a food industry in Gipsland, Australia, and an industrial-scale plant for the combined treatment of urban wastewater and food industry effluent in Longford, Tasmania. These two plants treated effluents following pretreatment in anaerobic lagoons. Phosphorus removal was not necessary in either case. These authors demonstrated that 98% BOD removal and 95% N removal is possible, in a very effective and economic way.

One example of the treatment of dairy wastewaters can be found in the paper of Samkutty et al.[64] After 2

Table 6. Some Significant Examples of SBR Technology Applied to Paper Industry Effluents Treatment

ref	scale	characteristics	removals
Weeks and Oleszkiewicz[56]	laboratory scale	comparison of SBR vs lagoons	SBR provide better resistance to shock loads.
Franta et al.[117]	laboratory scale	residual COD consists of refractory organic compounds (lignins)	best COD removal at an SRT of 20 days and a reaction period of 22 h
Elefsinniotis et al.[118]	laboratory scale (10 L)	20 or 30 °C	>90% resin and fatty acids >70% COD
Franta and Wilderer[57]	laboratory scale	0.5-h feed phase 12-h reaction phase	best COD removal at an SRT of 20 days
Courtemanche et al.[55]	full scale	very high yield sulfite pulp mill	TSS, BOD, and toxicity limits achieved
Milet and Duff[59]	laboratory scale (1.5 L)	3780 mg/L COD (influent)	100% methanol 88% COD
Tripathi and Allen[58]	laboratory scale (1.5 L)	HRT of 12 h SRT of 10−15 days 8-h cycles	COD from 75% at 35 °C to 63% at 60 °C AOX from 70% at 35 °C to 60% at 60 °C

months of operation, very significant reductions of some parameters were reached (97% BOD, 93% COD, 97% TSS, 76% TS). In this dairy plant located in Louisiana, the conclusion was that an SBR is a good system for the primary and secondary treatment of dairy wastewaters. Similar results were obtained by Kolarski and Nyhuis[65] for dairies located in Germany (Mueller Milch and Westmilch).

Another important study is that of Mohamed and Saed,[66] who demonstrated SBR efficiency in the treatment of wastewaters from a dairy plant in Al-Rawabi, United Arab Emirates, with 2500 cows producing 30 000 L of milk per day and generating approximately 900 m^3 of wastewater per day. The sequence followed by the SBR consisted of a 30-min aeration feed, 12-h reaction with O_2, 1-h settling period without O_2, 30-min draw without O_2, and 15-min idle phase. With this cycle, removals of 96.7% of NH_3-N, 94% of COD, and 96% of SS were achieved.

Another case is that of Dugba and Zhang,[67] who evaluated the temperature-phased anaerobic digestion process for dairy wastewater treatment. Two thermophilic (55 °C)−mesophilic (35 °C) systems were tested against one mesophilic (35 °C)−mesophilic (35 °C), at two different hydraulic retention times (HRTs) (3 and 6 days) and five volatile solids (VS) loading rates (2, 3, 4, 6, and 8 g L^{-1} day^{-1}). Both thermophlic−mesophilic systems were found to be more effective in solids removal, biogas production, and coliform bacteria destruction.

In a more recent study, Ruiz et al.[68] set up two ASBRs (anaerobic SBRs) to be used to treat wastewater generated in the food industries. One ASBR was fed with a low-concentration slaughterhouse effluent (3.5−4.5 g of COD/day), and the other with a concentrated dairy wastewater (maximum load of 6 g of COD L^{-1} day^{-1}). An exhaustive kinetic study was carried out [TOC, volatile fatty acid (VFA), biogas production, etc.] in one cycle, which allowed for the development of a simple control system to manage the ASBR. Thus, the rate of biogas production allowed for the control of the cycle. After automation, the ASBR handling concentrated dairy wastewater worked at an average organic loading rate of 5.4 g of COD L^{-1} day^{-1}. The system also showed good adaptability to modifications in some parameters, such as concentration, temperature, etc.

A particular case is that of Garrido et al.,[69] who used two reactors in series (an anaerobic filter of 12 m^3 and an SBR of 28 m^3) to treat wastewaters from a laboratory specializing in milk analysis. This wastewater has characteristics similar to those of wastewaters found in the dairy industry (10 kg of COD/m^3 and 0.20 kg of N/m^3). The treated wastewater was the result of the mixture of the analyzed milk samples, with a high organic content, and other pollutants from the laboratory. In the anaerobic filter, the maximum organic load treated was 8 kg of COD m^{-3} day^{-1} and in the SBR between 1.5 and 2 kg of COD m^{-3} day^{-1}. COD and nitrogen removal were more than 98 and 99%, respectively.

More recent is the work by Mohseni and Bazari,[70] who investigated the treatability of a wastewater from a milk factory in a bench-scale sequencing batch reactor. More than 90% COD removal efficiency was achieved in the reactor.

Regarding full-scale plants for the treatment of dairy wastewaters, the paper by Torrijos et al.[71] described a solution based on SBR technology for treating wastewater from small cheese-making plants in the Jura Mountains (northeastern France). Pollution from these cheeese-making units is generally at the level of 200−300 pe. This solution proved to be extremely flexible and effective in treating the wastewater from cheese production, with average purification levels of 97.7% for total COD and 99.8% for BOD_5. The process was also financially advantageous, as the cost of treatment represented less than 1% of the price paid by the cooperative for its milk.

Finally, it is important to mention the paper by Gough et al.,[72] who developed an equation for BOD prediction in dairy effluents treated by SBRs at the 95% confidence level.

Table 7 summarizes some significant examples of SBR technology applied to this kind of effluent.

Slaughterhouse Wastewaters. Slaughterhouse wastewaters are characterized by their high contents in organic matter, suspended solids, oils, grease, and nitrogen and phosphorus compounds.

The review of Johns[73] describes progress made in the treatment of slaughterhouse wastewaters. In this review, some attention is paid to the treatment of slaughterhouse wastewaters with SBR technology. One of the cited papers is by Subramanian et al.,[74] who achieved very high removals of N and P by using an internal carbon source (a portion of partially treated anaerobic effluent). Removals of 92% for nitrogen and 84% for phosphorus (for HRT of 10−12 days and a sludge age of 30−35 days) were reached by Belanger et al.[75] They also found that fluctuations in the hydraulic or organic loads did not significantly affect performance.

It is clear that biological denitrification requires the availability of readily degradable carbon. Therefore, prior anaerobic removal of COD from slaughterhouse wastewater must be carefully balanced against this requirement if successful denitrification without the use of costly external carbon sources is the objective. This

Table 7. Some Significant Examples of SBR Technology Applied to Food Industry and Dairy Wastewaters Treatment

ref	scale	characteristics	removals
Nyhuis[119]	characteristics and plant concept of an SBR system for dairy wastewater treatment, with particular reference to plant flexibility, operational stability, and economics		
Mohamed and Saed[66]	laboratory scale	14-h cycle	94% COD 96% SS
Samkutty et al.[64]			97% BOD 93% COD 97% TSS 76% TS
Kolarski and Nyhuis[65]	0.4 Mgal/day four-basin SBR		significant improvement of denitrification, sludge bulking control, and biological P removal
Bian et al.[120]		cyclic activated-sludge SBR (developed with a biological selector and a variable volume)	excellent activated-sludge settling and treatment efficiency
Dugba and Zhang[67]	laboratory scale	comparison of two thermophilic−mesophilic and one mesophilic−mesophilic systems at HRTs of 3 and 6 days	
Donkin[121]	laboratory scale		
Ruiz et al.[68]	laboratory-scale ASBR	maximum loading rate of 6 g of COD L^{-1} day^{-1} influent: 20 g/L total COD, 16 g/L soluble COD, 5 g/L TOC mesophilic conditions (35 °C)	>90% COD
Garrido et al.[69]	12-m^3 anaerobic filter and 28-m^3 SBR	10 kg of COD/m^3 and 0.20 kg of N/m^3	>98% COD removal >99% N removal
Mohseni and Bazari[70]	bench scale	8-h cycles, influent COD of 410−480 mg/L	90% COD removal at an SRT of 20 days
Raper and Green[63]	full-scale pilot plant	12 h of aeration per day	98% BOD 95% N
Torrijos et al.[71]	full scale	200−300 pe	97.7% total COD 99.8% BOD_5

Table 8. Some Significant Examples of SBR Technology Applied to Slaughterhouse Wastewaters

ref	scale	characteristics	removals
Belanger et al.[75]		HRT of 10−12 days sludge age of 30−35 days	92% nitrogen 84% phosphorus
Subramanian et al.[74]	laboratory scale	6-h cycles	95% COD 92% TKN 90% TP 94% SS
Keller et al.[30]	laboratory scale	6.5-h cycles internal carbon source	consistent effluent quality (<2 mg/L P and <20 mg/L N)
Pochana and Keller[76]	laboratory scale	6 h cycles	95% N
Ruiz et al.[68]	laboratory-scale ASBR	maximum organic loading rate of 4.5 g of COD L^{-1} day^{-1}	86% total COD 91% soluble COD
Masse and Masse[122]	ASBR	operation at 20, 25, and 30 °C	92% total COD 80−96% SS

fact is reflected in a more recent paper by Keller et al.,[30] who studied the laboratory-scale treatment of these wastewaters using an SBR after the anaerobic pretreatment tank. This approach is typical for wastewaters with high concentrations of carbon. The anaerobic pretreatment degrades a high percentage of the wastewater, producing biogas (methane and carbon dioxide). As stated previously, it is important that the organic matter not be completely removed, so that it can be used later in the biological nutrient removal process. These authors used a wastewater from a slaughterhouse near Brisbane, Australia. In particular, they investigated the efficiency of a system formed by two SBRs for treating a mixture of two effluents coming from two different anaerobic tanks. The reactors were operated in 6.5-h cycles. The results obtained were different in the two SBRs, but both gave good results. The authors had the intention of scaling up this study. Their objective was to obtain good-quality effluents with concentrations of less than 20 mg/L N and less than 5 mg/L P.

In another study of factors affecting simultaneous nitrification/denitrification, Pochana and Keller[76] reached a reduction of 95% of nitrogen and observed that the addition of external carbon (acetate) increased the activity of simultaneous nitrification/denitrification. Table 8 summarizes some significant examples of SBR technology applied to this kind of effluent.

Piggery Wastewaters. This is a field where SBR technology has been widely used. This is because nitrogen contents are very high (1500 mg/L or more) and reaching the established limits with the conventional systems is difficult. The sole solution for treating these wastewaters through conventional systems would be the application of postdenitrification with the addition of an external carbon source, which leads to a more complex plant, higher operational costs, and greater difficulties. For these reasons, SBR technology seems to be the most feasible treatment approach for piggery wastewaters.[77]

For instance, in the paper of Su et al.,[78] an SBR was used for in situ studies at a pig farm in Taiwan. The influent volume was about 37.5 m^3, and the HRT was 3 days. Removals of 94.5% DBO, 88.7% COD, and 93.4% SS were reached. However, in this case, nitrogen and phosphorus removal was poor, reaching between 36.3 and 52.9% for N and 61.1% for P.

Table 9. Some Significant Examples of SBR Technology Applied to Piggery Wastewaters

ref	scale	characteristics	removals
Bortone et al.[79]	laboratory scale (5 L)	HRT of 10 days SRT of 28−34 days 24-h cycles initial concentrations: 844 mg/L NH_4^+−N, 10 580 mg/L total COD	93% COD 88−93% N_{tot} 95% P
Gemirli et al.[123]	laboratory scale		
Bortone et al.[80]	laboratory scale (5 L)	initial concentrations: 647 mg/L NH_4^+−N, 18 000 mg/L total COD	98% N >90% P
Masse et al.[87,88]		SBR with anaerobic digestion	
Masse and Droste[89]		anaerobic treatment	
Zhang et al.[90]		anaerobic treatment	
Andreottola et al.[86]		simulation model for biological nitrogen removal	
Su et al.[78]		influent volume of about 37.5 m^3 HRT of 3 days	94.5% BOD 88.7% COD 93.4% SS 36.3−52.9% N 61.1% P
Lee et al.[12]	1 cycle/day		90% N 89% P
Bernet et al.[81]	2 laboratory-scale SBRs	24-h cycle	85−92% TOC 87−95% TKN
Bernet et al.[82]		24-h cycle	81−91% TOC 85−91% TKN
Tilche et al.[77]	high scale		98% N, P, and COD
Kim et al.[84]	about 3400 mg/L NH_4^+−N (dilution 1/12)	intermittent feeding and 2-h aerobic−2-h anaerobic	99% BOD and NH_4^+−N
Edgerton et al.[83]	pilot scale		about 99% NH_4^+ and odor 79% COD
Tilche et al.[85]	full scale		>98% COD, N, and P

Regarding the use of an internal carbon source for denitrification, which was mentioned above, many examples in the biological treatment of piggery wastewaters are easy to find. In the case of Lee et al.,[12] fermented wastes of a pig farm were used as acetate substitutes to reach enhanced nutrient removals in an SBR. Thus, the SBR was fed with farm wastewater and was run through the following stages: 10-min anoxic feeding, 13-h oxic feeding, 7-h anoxic feeding, 3-h oxic feeding, 40-min sedimentation, and 10-min withdrawal from the reactor. The organic matter coming from fermented wastes or acetate was added at the beginning of the anoxic phase. No difference was observed between the reactor efficiency with acetate or fermented wastes. In the two experiments, 90% nitrogen removal and 89% phosphorus removal were obtained. Two additional studies concerning the use of internal carbon sources for biological nutrient removal from piggery wastewaters are those of Bortone et al.[79,80] and Ra et al.[13]

Bernet et al.[81,82] investigated piggery wastewater treatment for carbon and nitrogen removal in a combined anaerobic−aerobic system using two laboratory-scale sequencing batch reactors. With a cycle length of 24 h, 85−91% TOC and 85−91% TKN removals were reached.

At pilot scale is the study by Edgerton et al.,[83] which describes a pilot-scale SBR that was built to treat piggery wastewater in Australia. It achieved NH_4^+ and odor reductions of about 99% and a 79% COD removal.

Kim et al.[84] optimized the SBR operative mode for treating a piggery wastewater with a concentration of NH_4^+−N of about 3400 mg/L. The reactor was fed with diluted wastewater (1/12), based on the specific nitrification average rate of 0.0893 g of NH_4^+−N (g of SVS)$^{-1}$ day^{-1} and 94% NH_4^+−N removal. They also compared four different external carbon sources: wastewater, glucose, methanol, and sodium acetate. Their respective yields for denitrification were 0.0863, 0.086, 0.220, and 0.310 g of NO_x−N (g of SVS)$^{-1}$ day^{-1}. Different modes of feeding and aeration were tested. The best result was obtained with an intermittent feeding in a 2-h aerobic-2-h anaerobic cycle, with 99% BOD and NH_4^+−N removals. Thus, it was demonstrated that the most economical mode was the intermittent one.

The use of SBRs is also feasible at high scale. For example, in Italy, an SBR plant was installed, and after 10 years of operation, the results were better than those obtained in previous laboratory experiments.[77,85] The plant, in more than 1 year of operation, is obtaining more than 98% removal of nitrogen, phosphorus, and COD. The authors studying this plant also validated a model that was later used to simulate the plant behavior and even allowed for the simulation of plant performance under stressing conditions. Another model can be found in the paper by Andreottola et al.,[86] where a dynamic SBR simulation model for biological nitrogen removal based on activated-sludge model no. 1 by International Water Association (IWA) is presented. Validation of the model was carried out with a bench-scale SBR treating piggery effluent. An algorithm for optimization of the cycle length is also described.

SBRs can also be used in piggery wastewater treatment in anaerobic digestion. Cases found in the literature are those of Masse et al.,[87,88] Masse and Droste,[89] and Zhang et al.,[90] who studied the feasibility of the SBR system for psicrophilic anaerobic digestion. Table 9 summarizes some significant examples of SBR technology applied to this kind of effluent.

Others. SBR technology has also been used for the treatment of less common kinds of wastewaters, such as wastewater from car-washing[91] or recreational[92] centers.

In the first case, wastewater (200−250 m^3/day) was usually treated by physicochemical methods. However, to reach the permitted limits that would be imposed in the near future, it was decided to use an SBR with a

Table 10. Other Kinds of Wastewaters That Can Be Treated by SBR Technology

wastewater description	ref
synthetic phenolic wastewater, synthetic wastewater containing poly(vinyl alcohol) and effluent from a coke plant wastewater treatment system	Yu et al.[124]
wastewater from car-washing centers	Zilverentant[91]
wastewater from a recreational center	Rim et al.[92]
wastewater from a fine chemicals plant	Chen et al.[93]
coke plant wastewater	Yu et al.[125]
gray waters	Shin et al.[95]
coke plant wastewater	Yu et al.[54]
sugar industry wastewater	Burkhardt [94]
fuel-contamined wastewater,	Yocum et al.,[126]
mixture of sludge and diesel	Cassidy and Irvine[96]
phenolic wastewaters	Al- scalezarin et al.,[127] Buitron et al.,[128] Basu and Oleszkiewicz,[129] Yu and Gu,[54] Buitrón et al.,[97] scale et al.,[130] Yoong and Lant[131]
waters with BTX	Ma and Love[98]
waters with TNT and RDX	Shen et al.[99]
wastewater of a potato starch factory	Villaverde et al.[132]
nitroglycerin	Accashian et al.[133]
hazardous wastes	Herzbrun et al.[134]

volume of approximately 1470 m^3. The pilot plant demonstrated that an SBR is an appropriate technology for the treatment of this particular kind of wastewater.

In the second case, in South Korea, a pilot plant was installed to treat a wastewater coming from a recreational center. The main objective was to decrease BOD, suspended solids and total nitrogen and phosphorus. The removals obtained were 95% of BOD, 89% of SS, 70% of total nitrogen (TN), and 77% of total phosphorus (TP). The concentrations in the effluent were 73 mg/L BOD, 10.4 mg/L SS, 13.6 mg/L TN, and 0.9 mg/L TP. Nitrification and denitrification occurred at rates of 4.5 and 1.5 mg (kg of MLSS)$^{-1}$ h^{-1}, respectively (where MLSS represents mixed liquor suspended solids). The experiment showed that SBR is one of the more adequate technologies that can be used for treating organic matter and nutrients generated in recreational centers, where water quality and quantity undergo some relevant fluctuations.

In another particular case, an SBR was used for the treatment of wastewaters from a fine-chemicals plant (the main components were textile chemical products and plastic lubricants).[93]

SBRs have also been used for treating wastewaters from the sugar industry, with COD and nitrogen removals similar to those obtained in conventional plants, with lower construction costs, and with an energy savings of about 90%.[94]

In addition, SBRs have been implemented for the treatment of “gray waters”, that is, wastewaters produced in office buildings.[95] The SBR efficiency was found to be satisfactory, yielding an effluent with 20 mg/L COD, 5 mg/L BOD, and 0.5 mg/L ammonium.

More recently, Cassidy and Irvine[96] treated a mixture of sludge and diesel in a soil-slurry SBR and optimized the conditions by varying the amount of SS, the mixture rate, the retention time, etc. Moreover, this technology has also been used for the biodegradation of toxic compounds, such as in the treatment of phenolic wastewaters[97] and waters containing BTX (benzene, toluene, xilene)[98] or TNT and RDX.[99] Table 10 summarizes some types of less common wastewaters that can be treated by SBR technology.

SBBR: SBR with Biofilm. During the past several years, a large number of applications based on SBRs have been developed. The common objective of them all was to control the composition and the activity of microbial communities, so that treatment yields as high as possible could be obtained. In fact, in 1992, Wilderer proposed sequential batch operations in a reactor based on a biofilm, to increase the ratio of efficiency to volume.[100]

Some other authors have packed SBRs with active carbon. Because of the adsorption processes occurring during the feeding stage, the concentrations of critical pollutants (volatile organics, inhibitor organic compounds) decreased considerably. During the reaction phase, biodegradation and desorption were the predominant processes. Wastewater was effectively treated, and carbon was biologically regenerated.[101−103] The use of packing materials in SBRs is an option that should be considered, at least from a technical point of view. At the Second International Symposium on Sequencing Batch Reactor Technology, for example, some authors presented studies done with biofilters. Irvine and Moe[104] performed studies that demonstrated that biofilters can be designed and operated as nonstationary processes that can remove pollutants in the gas phase. They concluded that periodically operated biofilters are better than biofilters operated continuously.

Zwerger et al.[105] stated that the use of zeolites as support materials for biofilms in wastewater treatment is possible. Zeolites have a high adsorption capacity, and bioregeneration is controlled through biological activity. SBBRs represent an appropriate system, because adsorption and desorption/bioregeneration can be unified in one cycle, and thus, the process is easy to control. There are also the cases of Vandaele et al.[27] and Arnold et al.[28] that have already been cited in this review, who treat reject water from wastewater treatment plants.

Figure 3 shows how biomass is attached to the support media, and Table 11 summarizes some of the advantages of this kind of reactor.

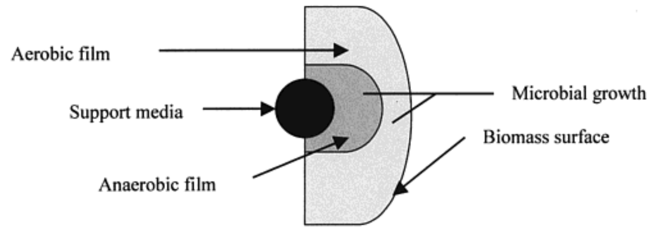

Figure 3. Biomass attachment to support media in SBBR systems.

Table 11. Advantages of SBBR Reactors

washout of biomass prevented
easy operation (biomass and the liquid inside the reactor are separated)
more biomass per unit volume of reactor
higher sludge retention times (SRTs)
more resistance to toxic loadings
higher rates of biodegradation
larger diversity of the microbial consortium
VOC emissions minimized

Conclusions

This review, comprising 134 references, reflects the large impact of SBR technology on wastewater treatment. Together with specific references regarding the performance of particular types of wastewater treatment, even at the industrial scale, the main advantage of SBRs is their great flexibility, which makes it possible to use these batch systems in a large variety of situations. SBRs are no more than batch reactors, but because of the nature of many industrial effluents, they are quite appropriate for wastewater treatment. Automation of SBR operations has made their implementation much easier and has definitely contributed to the development of SBR technology. It is clear today that, for small and medium-sized wastewater treatment plants, SBRs should be seriously considered, not only for economical reasons, but also for efficiency in the removal of organic matter and nutrients, provided that a previous and proper design is used.

Surely, since this review was submitted, a remarkable number of papers dealing with SBR technology will be published. This fact only emphasizes the growing success of this kind of system, which certainly will be increasingly used at the industrial scale in the future.

Literature Cited

(1) Irvine, R. L.; Davis, W. B. Use of Sequencing Batch Reactors for Waste Treatment—CPC International, Corpus Christi, Texas. In *Proceedings of the 26th Annual Purdue Industrial Waste Conference*; Purdue University: West Lafeyette, IN, 1971, p 450.

(2) Goronszy, M. S. Intermittent Operation of the Extended Aeration Process for Small Systems. *J. Water Pollut. Control Fed.* **1979**, *51*, 274.

(3) Arden, E.; Lockett, W. T. Experiments on the Oxidation of Sewage without the Aid of Filters. *J. Soc. Chem. Ind.* **1914**, *33*, 523.

(4) Irvine, R. L.; Wilderer, P. A.; Flemming, H.-C. Controlled unsteady-state processes—An overview. *Water Sci. Technol.* **1997**, *35* (1), 1.

(5) Irvine, R. L.; Ketchum, L. H., Jr. Sequencing Batch Reactors for Biological Wastewater Treatment. *Crit. Rev. Environ. Control* **1998**, *18*, 255.

(6) Norcross, K. L. Sequencing batch reactors—An overview. *Water Sci. Technol.* **1992**, *26*, 2523.

(7) Ketchum, L. H., Jr. Design and physical features of sequencing batch reactors. *Water Sci. Technol.* **1997**, *35* (1), 11.

(8) Hopkins, L. N.; Lant, P. A.; Newell, R. B. Using the flexibility index to compare batch and continuous activated sludge processes. *Water Sci. Technol.* **2001**, *43* (3), 35.

(9) Bernardes, R. S.; Klapwijk, A. Biological nutrient removal in a sequencing batch reactor treating domestic wastewater. *Water Sci. Technol.* **1996**, *33* (3), 29.

(10) Umble, A. K.; Ketchum, L. H., Jr. A strategy for coupling municipal wastewater treatment using the sequencing batch reactor with effluent nutrient recovery through aquaculture. *Water Sci. Technol.* **1997**, *35* (1), 177.

(11) Beccari, M.; Cecchi, F.; Majone, M.; Musacco, A. Improved biological nutrient removal resulted from the integrated treatment of wastewater and municipal solid waste. *Ann. Chim.* **1998**, *88* (11−12), 773.

(12) Lee, S.-I.; Park, J.-H.; Ko, K.-B.; Koopman, B. Effect of fermented swine wastes on biological nutrient removal in sequencing batch reactors. *Water Res.* **1997**, *31* (7), 1807.

(13) Ra, C. S.; Lo, K. V.; Shin, J. S.; Oh, J. S.; Hong, B. J. Biological nutrient removal with an internal organic carbon source in piggery wastewater treatment. *Water Res.* **2000**, *34* (3), 965.

(14) Graja, S.; Wilderer, P. A. Characterization and treatment of the liquid effluents from the anaerobic digestion of biogenic solid waste. *Water Sci. Technol.* **2001**, *43* (3), 265.

(15) Rustrián, E.; Aguilar, A. C.; Flores, O. L.; Houbron, E. SBR technology coupled to anaerobic digestion for nutrient removal from urban wastewater. In *Proceedings of the 2nd International Symposium on Sequencing Batch Reactor Technology*; IWA Publishing: London, 2000; Vol. 2, pp 209−212.

(16) De Sousa, J. T.; Foresti, E. Domestic sewage treatment in an upflow anaerobic sludge blanket sequencing batch reactor system. *Water Sci. Technol.* **1996**, *33* (3), 73.

(17) Dockhorn, T.; Dichtl, N. J.; Kayser, R. Comparative investigations on COD-removal in sequencing batch reactors and continuous flow plants. *Water Sci. Technol.* **2001**, *43* (3), 45.

(18) Bernardes, R. S.; Spanjers, H.; Klapwijk, A. Modelling respiration rate and nitrate removal in a nitrifying−denitrifying SBR treating domestic wastewater. *Bioresour. Technol.* **1999**, *67* (2), 177.

(19) Brenner, A. Modeling of N and P transformations in an SBR treating municipal wastewater. *Water Sci. Technol.* **2000**, *42* (1−2), 55.

(20) Teichgräber, B.; Schreff, D.; Ekkerlein, C.; Wilderer, P. A. SBR technology in Germany—An overview. *Water Sci. Technol.* **2001**, *43* (3), 323.

(21) Helmreich, B.; Schreff, D.; Wilderer, P. A. Full scale experiences with small sequencing batch reactor plants in Bavaria. *Water Sci. Technol.* **2000**, *41* (1), 89.

(22) Steinmetz, H. Full-scale application of SBR technology in municipal wastewater treatment plants with advanced nutrient removal. In *Proceedings of the 2nd International Symposium on Sequencing Batch Reactor Technology*; IWA Publishing: London, 2000; Vol. 2, pp 234−237.

(23) Keller, J.; Watts, S.; Battye-Smith, W.; Chong, R. Full-scale demonstration of biological nutrient removal in a single tank SBR process. *Water Sci. Technol.* **2001**, *43* (3), 355.

(24) Ghyoot, W.; Vandaele, S.; Verstraete, W. Nitrogen removal from sludge reject water with a membrane-assisted bioreactor. *Water Res.* **1999**, *33* (1), 23.

(25) Janus, H. M.; Helle, F. Don't reject the idea of treating reject water. *Water Sci. Technol.* **1997**, *35* (10), 27.

(26) Siegrist, H. Nitrogen removal from digester supernatant—Comparison of chemical and biological methods. *Water Sci. Technol.* **1996**, *34* (1−2), 399.

(27) Vandaele, S.; Bollen, F.; Thoeye, C.; November, E.; Verachtert, H.; Van Impe, J. F. A comparison of SBR and SBBR for nitrogen removal out of ammonia rich sludge liquors and problems encountered. In *Proceedings of the 2nd International Symposium on Sequencing Batch Reactor Technology*; IWA Publishing: London, 2000; Vol. 1, pp 67−74.

(28) Arnold, E.; Böhm, B.; Wilderer, P. A. Application of activated sludge and biofilm sequencing batch reactor technology to treat reject water from sludge dewatering systems: A comparison. *Water Sci. Technol.* **2000**, *41* (1), 115.

(29) Wett, B.; Rostek, R.; Rauch, W.; Ingerle, K. pH-controlled reject-water treatment. *Water Sci. Technol.* **1998**, *37* (12), 165.

(30) Keller, J.; Subramaniam, K.; Gosswein, J.; Greenfield, P. F. Nutrient removal from industrial wastewater using single tank sequencing batch reactors. *Water Sci. Technol.* **1997**, *35* (6), 137.

(31) Torrijos, M.; Moletta, R. Winery wastewater depollution by sequencing batch reactor. *Water Sci. Technol.* **1997**, *35* (1), 2497.

(32) Houbron, E.; Torrijos, M.; Moletta, R. Application de procédé SBR aux effluents vinicoles. Résultats de trois années de suivi. In *2ème Congrès International sur le Traitement des Effluents Vinicoles*; Cemagref − DICOVA: Bordeaux, France, 1998; pp 189−196.

(33) Houbron, E.; Sanchez, L. A.; Zepeda, P.; Rustrian, E. Brewery wastewater treatment using an aerobic sequencing batch reactor. In *Proceedings of the 2nd International Symposium on Sequencing Batch Reactor Technology*; IWA Publishing: London, 2000; Vol. 2, pp 93−96.

(34) Ling, L.; Lo, K. V. Brewery wastewater treatment using suspended and attached growth sequencing batch reactors. *J. Environ. Sci. Health A* **1999**, *34* (2), 341.

(35) Lo, K. V.; Cheuk, W.; Wong, R. Treatment of malting wastewater using suspended-growth and attached-growth sequencing batch reactors. *Environ. Technol.* **1999**, *20* (2), 227.

(36) Nguyen, A. L.; Duff, S. J. B.; Sheppard, J. D. Application of feedback control based on dissolved oxygen to a fixed-film sequencing batch reactor for treatment of brewery wastewater. *Water Environ. Res.* **2000**, *72* (1), 75.

(37) Lo, I. M.-C. Characteristics and treatment of leachates from domestic landfills. *Environ. Int.* **1996**, *22* (4), 443.

(38) Zaloum, R.; Abbott, M. Anaerobic pretreatment improves single sequencing batch reactor treatment of landfill leachates. *Water Sci. Technol.* **1997**, *35* (1), 207.

(39) Timur, H.; Ozturk, I. Anaerobic treatment of leachate using sequencing batch reactor and hybrid bed filter. *Water Sci. Technol.* **1997**, *36* (6−7), 501.

(40) Timur, H.; Ozturk, I. Anaerobic sequencing batch reactor treatment of landfill leachate. *Water Res.* **1999**, *33* (15), 3225.

(41) Yilmaz, G. I.; Ozturk, I. Biological ammonia removal from anaerobically pretreated landfill leachate in sequencing batch reactors (SBR). *Water Sci. Technol.* **2001**, *43* (3), 307.

(42) Diamadopoulos, E.; Samaras, P.; Dabou, X.; Sakellaropoulos, G. P. Combined treatment of landfill leachate and domestic sewage in a sequencing batch reactor. *Water Sci. Technol.* **1997**, *36* (2−3), 61.

(43) Dollerer, J.; Wilderer, P. A. Biological treatment of leachates from hazardous waste landfills using SBBR technology. *Water Sci. Technol.* **1996**, *34* (7−8), 437.

(44) Traut, M.; Coetzee, M.; Robinson, H. D.; Novella, P. H. Treatment of landfill leachate in a sequencing batch reactor (SBR)−A pilot-scale study. In *Proceedings of the 15th International Conference on Solid Waste Technology Management*; Mersky, R. L., Ed.; University of Pennsylvania: Philadelphia, PA, 1999; pp 1091−8043.

(45) Doyle, J.; Watts, S.; Solley, D.; Keller, J. Exceptionally high-rate nitrification in sequencing batch reactors treating high ammonia landfill leachate. *Water Sci. Technol.* **2001**, *43* (3), 315.

(46) Scaglia, E. Treatment of tannery wastewaters. *Inquinamento* **2000**, *42* (16), 90.

(47) Kabacinski, M.; Hultman, B.; Plaza, E.; Trela, J. Strategies for improvement of sludge quality and process performance of sequencing batch reactor plant treating municipal and tannery wastewater. *Water Sci. Technol.* **1998**, *38* (4−5), 69.

(48) Banas, J.; Plaza, E.; Styka, W.; Trela, J. SBR technology used for advanced combined municipal and tannery wastewater treatment with high receiving standards. *Water Sci. Technol.* **1999**, *40* (4−5), 451.

(49) Carucci, A.; Chiavola, A.; Majone, M.; Rolle, E. Treatment of tannery wastewater in a sequencing batch reactor. *Water Sci. Technol.* **1999**, *40* (1), 253.

(50) Woolard; Irvine, R. L. Treatment of hypersaline wastewater in the sequencing batch reactor. *Water Res.* **1995**, *29* (4), 1159.

(51) Glass, C.; Silverstein, J. Denitrification of high-nitrate, high-salinity wastewater. *Water Res.* **1999**, *33* (1), 223.

(52) Intrasungkha, N.; Keller, J. I.; Blackall, L. Biological nutrient removal efficiency in treatment of saline wastewater. *Water Sci. Technol.* **1999**, *39* (6), 183.

(53) Thompson, G.; Swain, J.; Kay, M.; Forster, C. F. The treatment of pulp and paper mill effluent: A review. *Bioresour. Technol.* **2001**, *77*, 275.

(54) Yu, H. Q.; Gu, G. W. Treatment of phenolic wastewaters by sequencing batch reactors with aerated and unaerated fills. *Waste Manage.* **1996**, *16*, 561.

(55) Courtemanche, M.; Tremblay, H.; Villeneuve, F. Sequencing batch reactor technology: An old technique successfully applied to the treatment of pulp and paper mill effluents containing high residuals of sulphite. In *Proceedings of the Environmental Conference & Exhibit*; TAPPI Press: Atlanta, GA, 1997; Vol. 2, p 853.

(56) Weeks, B.; Oleszkiewicz, J. A. Shock loading lagoons and activated sludge treating bleached kraft mill wastewater. In *Proceedings of the 1993 Environmental Conference*; Can. Pulp Paper Assoc.: Montreal, Canada, 1993; pp 39−42.

(57) Franta, J.; Wilderer, P. A. Biological treatment of papermill wastewater by sequencing batch reactor technology to reduce residual organics. *Water Sci. Technol.* **1997**, *35* (1), 129.

(58) Tripathi, S.; Allen, D. Comparison of mesophilic and thermophilic aerobic biological treatment in sequencing batch reactors treating bleached kraft pulp mill effluent. *Water Res.* **1999**, *33* (3), 836.

(59) Milet, G. M. D.; Duff, S. J. B. Treatment of kraft condensates in a feedback-controlled sequencing batch reactor. *Water Sci. Technol.* **1998**, *38* (4−5), 263.

(60) Kahmark, K. A.; Unwin, J. P. Pulp and paper effluent management. *Water Environ. Res.* **1999**, *71* (5), 836.

(61) Villeneuve, F.; Tremblay, H. Sequencing batch reactor technology: An old technique applied to the treatment of pulp and paper mill effluents. In *Proceedings of the 1995 Environmental Conference*; TAPPI Press: Norcross, GA, 1995; Vol. 2, pp 713−719.

(62) Cocci, A. A.; McCarthy, P. J.; Almost, S. 1998 Sequencing batch reactors in the pulp and paper industry: A bench-marking study. In Proceedings *of the 1998 Environmental Conference*; TAPPI Press: Norcross, GA, 1998; Vol. 3, p 1203.

(63) Raper, W. G. C.; Green, J. M. Simple process for nutrient removal from food processing effluents. *Water Sci. Technol.* **2001**, *43* (3), 123.

(64) Samkutty, P. J.; Gough, R. H.; McGrew, P. Biological treatment of dairy plamt wastewater. *J. Environ. Sci. Health A* **1996**, *31* (9), 2143.

(65) Kolarski, R.; Nyhuis, G. The use of sequencing batch reactor technology for the treatment of high-strenght dairy processing waste. In *Proceedings of the 50th Annual Industrial Waste Conference*; Purdue University: West Lafeyette, IN, 1995; pp 485−494.

(66) Mohamed, F.; Saed, M. Wastewater management in a dairy farm. *Water Sci. Technol.* **1995**, *32* (11), 1.

(67) Dugba, P. N.; Zhang, R. H. Treatment of dairy wastewater with two-stage anaerobic sequencing batch reactor systems−Thermophilic versus mesophilic operations. *Bioresour. Technol.* **1999**, *68* (3), 225.

(68) Ruiz, C.; Torrijos, M.; Sousbie, P.; Lebrato, M. J.; Moletta, R. The anaerobic SBR process: Basic principles for design and automatation. *Water Sci. Technol.* **2001**, *43* (3), 201.

(69) Garrido, J. M.; Omil, F.; Arrojo, B.; Méndez, R.; Lema, J. M. Carbon and nitrogen removal from a wastewater of an industrial dairy laboratory with a coupled anaerobic filter−sequencing batch reactor system. *Water Sci. Technol.* **2001**, *43* (3), 249.

(70) Mohseni, B. A.; Bazari, H. Biological treatment of milk factory wastewater by sequencing batch reactor. In *Proceedings of the 2nd International Symposium on Sequencing Batch Reactor Technology*; IWA Publishing: London, 2000; Vol. 2, pp 153−156.

(71) Torrijos, M.; Vuitton, V.; Moletta, R. The SBR process: An efficient and economic solution for the treatment of wastewater at small cheesemaking dairies in the Jura mountains. *Water Sci. Technol.* **2001**, *43* (3), 373.

(72) Ghough, R. H.; Samkutty, P. J.; McGrew, P.; Arauz, J.; Adkinson, R. W. Prediction of effluent biochemical oxygen demand in a dairy plant SBR wastewater system. *Journal of Environmental Science Health A* scale **2000**, *35* (2), 169.

(73) Johns, M. R. Developments in wastewater treatment in the meat processing industry: A review. *Biotechnol. Resour.* **1995**, *54*, 203.

(74) Subramanian, K.; Greenfield, P. F.; Ho, K.-M.; Johns, M. R.; Keller, J. Efficient biological nutrient removal in high strength wastewater using combined anaerobic sequencing batch reactor treatment. *Water Sci. Technol.* **1994**, *30*, 315.

(75) Belanger, D.; Bergevin, P.; Lapierre, J.; Zaloum, R. Conception, control and efficiency of a sequencing batch reactor for the purification of wastewater from an slaughterhouse. *Sci. Tech. Eau* **1986**, *19*, 142.

(76) Pochana, K.; Keller, J. Study of factors affecting simultaneous nitrification and denitrification. *Water Sci. Technol.* **1999**, *39* (6), 61.

(77) Tilche, A.; Bacilieri, E.; Bortone, G.; Malaspina, F.; Piccinini, S.; Stante, L. *Water Sci. Technol.* **1999**, *40* (1), 199.

(78) Su, J. J.; Kung, Ch.-M.; Lin, J.; Lian, W.-Ch.; Wu, J.-F. Utilization of Sequencing Batch Reactor for in situ piggery wastewater treatment. *J. Environ. Sci. Health A* **1997**, *32* (2), 391.

(79) Bortone, G.; Gemelli, S.; Rambaldi, A.; Tilche, A. Nitrification, denitrification and biological phosphate removal in sequencing batch reactors treating piggery wastewater. *Water Sci. Technol.* **1992**, *26* (5−6), 977.

(80) Bortone, G.; Malaspina, F.; Stante, L.; Tilche, A. Biological nitrogen and phosphorus removal in an Anaerobic/Anoxic Sequencing Batch Reactor with separate Biofilm Nitrification. *Water Sci. Technol.* **1994**, *30* (6), 303.

(81) Bernet, N.; Delgenès, N.; Delgenès, J. P.; Moletta, R. Combined organic carbon and nitrogen removal from piggery wastewater using anaerobic and aerobic SBR. *Eau, Ind., Nuisances* **1998**, *212*, 56.

(82) Bernet, N.; Delgenès, N.; Akunna, J. C.; Delgenès, J. P.; Moletta, R. Combined anaerobic−aerobic SBR for the treatment of piggery wastewater. *Water Res.* **1999** *34* (2), 611.

(83) Edgerton, B. D.; McNevin, D.; Wong, C. H.; Menoud, P.; Barford, J. P.; Mitchell, C. A. Strategies for dealing with piggery effluent in Australia. *Water Sci. Technol.* **2000**, *41* (1), 123.

(84) Kim, C. W.; Choi, M. W.; Ha, J. Y.; Lee, H. G.; Park, T. J. Optimisation of operating mode for sequencing batch reactor (SBR) treating piggery wastewater with high nitrogen. In *Proceedings*

of the 2nd International Symposium on Sequencing Batch Reactor Technology; IWA Publishing: London, 2000; Vol. 1, pp 190−198.

(85) Tilche, A.; Bortone, G.; Malaspina, F.; Piccini, S.; Stante, L. Biological nutrient removal in a full-scale SBR treating piggery wastewater: Results and modelling. *Water Sci. Technol.* **2001**, *43* (3), 363.

(86) Andreottola, G.; Bortone, G.; Tilche, A. Experimental validation of a simulation and design model for nitrogen removal in sequencing batch reactors. *Water Sci. Technol.* **1997**, *35* (1), 113.

(87) Masse, D. I.; Patni, N. K.; Droste, R. L.; Kennedy, K. J. Operation strategies for psychrophilic anaerobic digestion of swine manure slurry in sequencing batch reactor. *Can. J. Civil Eng.* **1996**, *23*, 1285.

(88) Masse, D. I.; Droste, R. L.; Kennedy, K. J.; Patni, N. K.; Munroe, J. A. Potential for the psychrophilic anaerobic treatment of swine manure using a sequencing batch reactor. *Can. Agric. Eng.* **1997**, *39* (1), 25.

(89) Masse, D. I.; Droste, R. L. Microbial interaction during the anaerobic treatment of swine manure slurry in a sequencing batch reactor. *Can. Agric. Eng.* **1997**, *39* (1), 35.

(90) Zhang, R. H.; Yin, Y.; Sung, S.; Dague, R. R. Anaerobic treatment of swine waste by the anaerobic sequencing batch reactor. *Trans. ASAE* **1997**, *40* (3), 761.

(91) Zilverentant, A. G.; Wilderer, P. A.; Irvine, R. L.; Doellerer, J. Pilot-testing, design and full-scale experience of a sequencing batch reactor system for the treatment of the potentially toxic wastewater from a road and rail car cleaning site. *Water Sci. Technol.* **1997**, *35* (1), 259.

(92) Rim, Y. T. A full-scale test of a biological nutrients removal system using the sequencing batch reactor activated sludge process. *Water Sci. Technol.* **1997**, *35* (1), 241.

(93) Chen, C. H.; Horng, R. Y.; Juang, S. S.; Tzou, W. Y.; Hsin, S.; You, H.-S.; Cheng, S. S. A successful case study of fine chemical plant wastewater treatment. *Water Sci. Technol.* **1997**, *35* (1), 87.

(94) Burkhardt, C. Sequencing Batch Reactors in the Sugar Industry. *Zuckerindustrie* **1999**, *124* (10), 776.

(95) Shin, H.-S.; Lee, S.-M.; Seo, I.-S.; Kim, G.-O.; Lim, K.-H.; Song, J.-S. Pilot-scale SBR and MF operation for the removal of organic and nitrogen compounds from greywater. *Water Sci. Technol.* **1998**, *38* (6), 79.

(96) Cassidy, D. P.; Irvine, R. L. The effect of operating conditions on the performance of soil slurry SBRs. *Water Sci. Technol.* **2001**, *43* (3), 223.

(97) Buitrón, G.; Soto, G.; Vite, G.; Moreno, J. Strategies to enhance the biodegradation of toxic compounds using discontinuous processes. *Water Sci. Technol.* **2001**, *43* (3), 283.

(98) Ma, G.; Love, N. G. Biodegradation of BTX in anoxic and microaerobic sequencing batch reactors. *Water Sci. Technol.* **2001**, *43* (3), 275.

(99) Shen, C. F.; Hawari, J. A.; Paquet, L.; Ampleman, S.; Thiboutot, S.; Guiot, S. R. Explosive biodegradation in soil slurry batch reactors amended with exogenous microorganisms. *Water Sci. Technol.* **2001**, *43* (3), 291.

(100) Wilderer, P. A. Sequencing batch biofim reator technology. In scale*rnessing Biotechnology for the 21st Century*; Ladisch, M. R., Bose, A., Eds.; Americam Chemical Society, Washington, DC, 1992; pp 475−479.

(101) Chozick, R.; Irvine, R. L. Preliminary Studies on the Granular Activated Carbon−Sequencing Batch Biofilm Reactor. *Environ. Prog.* **1991**, *10*, 282.

(102) Jaar, M. A. Biologische Regeneration Schadstoffbeladener Aktivkohle am Beispiel der Modelsubstanzen 3-Chlorobenzoesaure und Thioglykols. Dissertation, Hamburger Berichte zur Siedlungswasserwirtschaft, TU Hamburg-Harburg, Hamburg, Germany, 1991; p 9.

(103) Kolb, F. R.; Wilderer, P. A. Activated Carbon Membrane Biofilm Reactor for the Degradation of Volatile Organic Compounds. *Water Sci. Technol.* **1995**, *31* (1), 205.

(104) Irvine, R. L.; Moe, W. M. Periodic biofilter operation for enhanced performance during unsteady-state loading conditions. *Water Sci. Technol.* **2001**, *43* (3), 231.

(105) Zwerger, W.; Beler Baykal, B.; Wilderer, P. A. Application of granular zeolite as support material for biofilms and as temporary sink for ammonium. In *Proceedings of the 2nd International Symposium on Sequencing Batch Reactor Technology*; IWA Publishing: London, 2000; Vol. 1, pp 92−101.

(106) Imura, M.; Suzuki, E.; Kitao, T.; Iwai, S. Advanced treatment of domestic wastewater using sequencing batch reactor activated sludge process. *Water Sci. Technol.* **1993**, *28* (10), 267.

(107) Bischof, F.; Charatjan, M.; scalebelski, N.; Hoefken, M.; Junge, K.; Kohlmann, J. The sequencing batch reactor (SBR) process for municipal wastewater treatment in sewage plants for <5000 population equivalents. *Chem. Technol. (Leipzig)* **1995**, *47* (1), 31.

(108) Mines, R. O., Jr.; Milton, G. D. Bionutrient removal with a sequencing batch reactor. *Water, Air, Soil Pollut.* **1998**, *107* (1−4), 81.

(109) Morgenroth, E.; Wilderer, P. A. Continuous flow and sequential processes in municipal wastewater treatment. In *Biotechnology*, 2nd ed.; Winter, J., Ed.; Wiley-VCH: New York, 1999; Vol. 11a, pp 321−334.

(110) Mossakowska, A.; Hultman, B. Observations of the sludge properties in an SBR reactor with nitrification of reject water. *Vatten* **1994**, *50* (1), 47.

(111) Mossakowska, A.; Reinius, L.-G.; Hultman, B. Nitrification reactions in treatment of supernatant from dewatering oof digested sludge. *Vatten* **1997**, *53* (1), 9.

(112) Bowen, R. B.; Ketchum, L. H., Jr. Treatment of anaerobic digester supernatant and filter press filtrate sidestreams with a sequencing batch reactor. In *Water Resources in the Urban Environment 98, Proceedings of the National Conference on Environmental Engineering*; ASCE Press, Wilson, T. E., Ed.; 1998; pp 530−535.

(113) Wang, F.; Peng, Y.; Yu, E.; Li, B.; Chen, A. Nitrogen removal in sequencing batch reactor (SBR). *J. Environ. Sci.* **1994**, *6* (2), 164.

(114) Rodrigues, A. C.; Brito, A. G.; Melo, L. F. Posttreatment of a brewery wastewater using a sequencing batch reactor. *Water Environ. Res.* **2001**, *73* (1), 45.

(115) Obbard, J. P.; Barr, M. J.; Robinson, H. D.; Carville, M. S. Landfill leachate: characteristics and biological treatment in Hong Kong. Resour. *Environ. Biotechnol.* **1999**, *2* (3), 235.

(116) Kennedy, K. J.; Lentz, E. M. Treatment of landfill leachate using sequencing batch and continuous flow upflow anaerobic sludge blanket (UASB) reactors. *Water Res.* **2000**, *34* (14), 3640.

(117) Franta, J.; Helmreich, B.; Pribyl, M.; Adamietz, E.; Wilderer, P. A. Advanced biological treatment of papermill wastewaters: Effects of operation conditions on COD removal and production of soluble organic compounds in activated sludge systems. *Water Sci. Technol.* **1994**, *30* (3), 199.

(118) Elefsiniotis, P.; Hall, E. R.; Johnson, R. M. Contaminat removal from recirculated white paper by ultrafiltration and/or biological treatment. In *Proceedings of the International Environmental Conference*; TAPPI Press: Atlanta, GA, 1995; Vol. 2, p 861.

(119) Nyhuis, G. Sequencing batch reactor (SBR) system for the dairy industry. *Wasser Luft Boden* **1993**, *37* (6), 24 (in German).

(120) Bian, Y.; Slater, N.; Wood, D. Flexibility in operating a CASS dairy wastewater treatment plant. In *WEFTEC '97 Conference Proceedings*; Water Environment Federation: Alexandria, VA, 1997; Vol. 3, p 399.

(121) Donkin, M. J. Statistical analysis to associate specific microorganism populations with operating conditions and treatment performance in laboratory-scale systems treating dairy processing wastewater. *Environ. Technol.* **1999**, *20* (10), 1085.

(122) Masse, D. I.; Masse, L. The effect of temperature on slaughterhouse wastewater treatment in anaerobic sequencing batch reactors. *Bioresour. Technol.* **2001**, *76* (2), 91.

(123) Gemirli, F.; Bortone, G.; Orhon, D.; Tilche, A. Fate of residuals in nitrification−denitrification treatment of piggery wastewaters. *Bioresour. Technol.* **1993**, *45* (3), 205.

(124) Yu, H. Q.; Gu, G. W.; Song, L. P. The effect of fill mode on the performance of sequencing-batch reactors treating various wastewaters. *Bioresour. Technol.* **1996**, *58* (1), 49.

(125) Yu, H. Q.; Wilson, F.; Tay, J.-H.; Gu, G.-W. Effects of addition of ferric hydroxide or powered activated carbon on sequencing batch reactors treating coke-plant wastewater. *J. Environ. Sci. Health A* **1997**, *32* (5), 1605.

(126) Yocum, P. S.; Irvine, R. L.; Bumpus, J. A. Bioremediation of water contamined with jet fuel-4 in a modified sequencing batch reactor. *Water Environ. Res.* **1995**, *67* (2), 174.

(127) Al- Hazarin, I. M.; Nakhla, G. F.; Farooq, S. Start-up of sequencing batch reactors for toxic wastewater treatment. *J. Environ. Sci. Health A* **1991**, *26* (5), 673.

(128) Buitrón, G.; Capdeville, B.; Horny, P. Improvement and control of the microbial activity of a mixed population for degradation of xenobiotic compounds. *Water Sci. Technol.* **1994**, *29* (7), 317.

(129) Basu, S. K.; Oleszkiewicz, J. A. 2-Chlorophenol biodegradation in sequencing batch reactors at different temperatures. In *Proceedings of the National Conference on Innovative Technologies for Site Remediation and Hazardous Waste Management*; ASCE Press: Reston, VA, 1995, p 552.

(130) Ha, S.-R.; Qishan, L.; Vinitnantharat, S. COD removal of phenolic wastewater by biological activated carbon-sequencing batchreactor in the presence of 2,4-DCP. *Water Sci. Technol.* **2000**, *42* (5−6), 171.

(131) Yoong, E. T.; Lant, P. A. Biodegradation of high strength phenolic wastewater using SBR. *Water Sci. Technol.* **2001**, *43* (3), 299.

(132) Villaverde, S.; García, P. A.; Lacalle, M. L.; Fdz-Polanco, F. New operational strategy for total nitrogen removal from industrial wastewaters highly loaded with nitrogen. *Water Sci. Technol.* **2000**, *41* (12), 85.

(133) Accashian, J. V.; Smets, B. F.; Kim, B.-J. Aerobic biodegradation of nitroglycerin in a sequencing batch reactor. *Water Environ. Res.* **2000**, *72* (4), 499.

(134) Herzbrun, P. A.; Irvine, R. L.; Malinowski, K. C. Biological Treatment of Hazardous Wastes in the SBR. *J. Water Pollut. Control Fed.* **1985**, *57*, 1163.

Received for review March 11, 2002
Revised manuscript received August 1, 2002
Accepted September 5, 2002

IE0201821