Artificial intelligence control of a sequencing batch reactor for nitrogen removal via nitrite from landfill leachate

ALESSANDRO SPAGNI 1 and STEFANO MARSILI-LIBELLI 2

2 University of Florence, Department of Systems and Computers, Florence, Italy

Leachate generated in old landfills is a high-strength wastewater, which is particularly difficult to treat owing to its low biochemical oxygen demand/total Kjeldahl nitrogen ratio. This paper seeks to demonstrate that reliable leachate treatment by means of sequencing batch reactors (SBRs) is indeed possible by means of the application of a smart control system. This study assesses the results of a computer-controlled bench-scale SBR treating raw sanitary landfill leachate to achieve nitrogen removal through the nitrite shortcut. Significant improvements have been obtained by introducing a fuzzy inferential system based on simple process measurements (i.e. dissolved oxygen, oxidation-reduction potential and pH). The paper analyzes the results of a test period of over 280 consecutive days of operation, during which the fuzzy control system correctly recognized over 97% of the SBR phase transitions and provided smart adjustments of the process operating conditions in terms of phase length and external COD addition. In spite of time-varying process conditions, the application of fuzzy logic provided stable nitrogen removal via nitrite through continuous adjustments of the main process parameters and resulted in a decreased hydraulic retention time, an increased loading rate, a saving in the external COD addition and considerable aeration energy conservation.

Keywords: Sequencing batch reactor (SBR), control and automation, artificial intelligence, fuzzy logic, nitrite, landfill leachate.

Introduction

Sanitary landfill leachate is a high-strength wastewater and its management represents a major environmental concern. Leachate characteristics are strongly influenced by several factors such as the landfill operation, age, and climate. Landfills follow a series of phases in which chemical, physical and biological properties of the buried wastes are subject to considerable transformations. During landfill aging, the organic compounds in the leachate normally decrease and become less biodegradable, whereas the ammonia concentration tends to increase. As a consequence, leachate generated in old landfills is usually characterized by a low biochemical oxygen demand (BOD) to total Kjeldahl nitrogen (TKN) ratio. Recently, landfills have been operated as bioreactors, where the generated leachate is typically recirculated inside the landfill. Although significant benefits associated with landfill bioreactors have been demonstrated, ammonia concentrations tend to be higher than those present in leachate generated in conventional landfills.[1,2]

Sanitary landfill leachate treatment is usually obtained in multistage systems with a combination of chemical, physical and biological processes.[3] Among a number of biological treatment systems, sequencing batch reactors (SBRs) have been documented to be applicable for leachate treatment, in particular for biological nitrogen removal.[4] During the (conventional) nitrification process, ammonia is biologically oxidized to nitrate (with nitrite as intermediate) that is then reduced to molecular nitrogen using organic matter as an electron donor in the denitrification process. Since ammonia oxidation is normally the rate-limiting step, nitrite does not usually accumulate during the nitrification process.[5] When the BOD/TKN ratio is low, as in leachate from old landfills, external biodegradable organic matter must be added for biological denitrification causing a substantial increase in the operational costs.

Over the past decade, substantial research efforts have focused on the use of nitrite as a shortcut in the optimization of the nitrogen removal process. In fact, the potential advantages of nitrogen removal via nitrite are the decreases (theoretically 25%) in oxygen consumption with the ammonia oxidation to nitrite (nitritation) and the reduction (theoretically 40%) of organic matter demand during denitrification.[6,7] Several studies have considered the influence of different operational conditions (e.g. low
dissolved oxygen concentration, selective inhibition, temperature) in favoring nitrite accumulation.[8−10] Even if selective nitrite oxidizer inhibition has been described, biomass acclimation preventing stable nitrite build-up has sometimes been observed.[11] Numerous innovative biological processes have recently been proposed for nitrogen removal from ammonium-rich wastewaters using the nitrite route.[12]

Nitrite buildup can also be sustained by adjusting the duration of the oxic phases in SBRs as Sauter and Alleman[13] had already proposed three decades ago. Although the nitrite route has been studied for different kinds of high-strength wastewaters, most of these applications are related to sludge dewatering effluents.[14] Recently, the nitrite route has also been demonstrated for municipal wastewater treatment.[15,16]

During the last few decades major efforts have been made on wastewater treatment monitoring, automation and control.[17] Several applications have been reported (in particular for SBR) on using dissolved oxygen (DO), pH and oxidation-reduction potential (ORP) for phase length optimization.[14−16,18−23] The vast majority of the SBR automation examples reported in the literature[14−16,18−27] mainly deal with the removal processes, whereas, surprisingly only a few actually describe the detailed results in terms of the operating parameters (e.g. energy consumption, efficiency/failure, phase length) of the controlled systems. This paper aims to address that deficiency and in this sense represents an extension of previous results.[23−26] In particular, a previous paper[24] describes the results of nitrogen removal via nitrite achieved in a bench-scale SBR, whereas this paper describes the main experimental results in terms of the improvement in the process efficiency and operating conditions management achieved by introducing a fuzzy control system, described in Marsili-Libelli et al.,[23] supervising all aspects of an SBR process conceived of for leachate treatment.

Materials and methods

Laboratory-scale SBR set-up

The study was carried out with a laboratory-scale SBR with a maximum working volume of about 24 L, operated at 20 ± 1°C in a thermally controlled room for almost 300 days. The pilot plant was supervised by a control system, controlling the duration of the phases and the external chemical oxygen demand (COD) addition in the form of sodium acetate (Hac).

Feeding, effluent and sludge withdrawal were carried out using peristaltic pumps, mixing was obtained using a mechanical stirrer, whereas an aquarium blower was used for aeration. The SBR was operated with a series of 4 sub-cycles, typical for the treatment of concentrated wastewaters, followed by one hour of settling. Figure 1 shows an example of the typical SBR cycle operated under fuzzy control. Each sub-cycle started with an anoxic-anaerobic phase followed by an oxic one. During the first minutes of the anoxic-anaerobic phase (of every sub-cycle), leachate (flow of 2.34 L/h) was added. The effluent was extracted during the last 3 minutes of the settling phase to reach the minimum reactor volume of 15 L. During the last minute of the fourth sub-cycle a small amount of mixed liquor was drawn to control the suspended solids concentration in the reactor: the sludge withdrawal was computed in order to obtain a mean solid retention time of about 25 days.

Leachate characteristics

Raw leachate was drawn from a municipal landfill located in northern Italy, stored at 4°C to reduce degradation and replaced approximately every month. This leachate was characterized by a high N/COD and a low BOD/COD ratio (Table 1) and therefore external COD was added as acetate to sustain the denitrification process. Other leachate characteristics are reported elsewhere.[23−26] Phosphorous was added as described in Spagni et al.[25]

<table>
<thead>
<tr>
<th>Table 1. Main characteristics of leachate.</th>
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<tr>
<td><strong>Unit</strong></td>
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<tr>
<td>TSS mg/L</td>
</tr>
<tr>
<td>VSS mg/L</td>
</tr>
<tr>
<td>Alk₄⁺ meq/L</td>
</tr>
<tr>
<td>pH</td>
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<tr>
<td>Kₛ₅</td>
</tr>
<tr>
<td>COD₄</td>
</tr>
<tr>
<td>COD₅</td>
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<tr>
<td>TKN mgN/L</td>
</tr>
<tr>
<td>NH₄⁺ N mgN/L</td>
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<tr>
<td>Ptot mgP/L</td>
</tr>
<tr>
<td>PO₄⁻ P mgP/L</td>
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Fig. 1. Example of a typical SBR cycle operated under fuzzy control. Note that the length of the oxic/anoxic periods as the volume are determined by the fuzzy controller.
Artificial intelligence control of a sequencing batch reactor

Fig. 2. Scheme of the process controller supervising the operation of the SBR.

**Seeding sludge**

The experimental set-up described in Spagni et al.[25] was used and the seeding sludge was therefore acclimated for almost 2 years to the leachate considered in this study. That study[25] concentrated on the possibility of using DO, pH and ORP signals for the development of the control system, whose results are analyzed in this paper.

**Fuzzy control system**

The fuzzy controller is composed of a set of logical rules[17] that analyze the time variations of the three process signals (DO, pH and ORP). From this information, thoroughly analysed by Marsili-Libelli[21] and Marsili-Libelli et al.,[23] decisions are taken regarding the duration of the sub-cycles and all the other periodic operations (feed, sludge and water extraction, aeration and mixing). The controller can be operated either locally or from a remote client via a TCP/IP protocol.[23] The software implementing the fuzzy logic controller was deployed in the local PC after having been developed in the LabView™ 7.1 platform (National Instruments, Austin, TX, USA). Apart from the implementation of the fuzzy logic controller, this software managed data acquisition and filtering, together with supervisory functionalities and remote operation via the web. A schematic diagram of the complete system is shown in Figure 2.

The existence of significant process patterns in the SBR cycle and its detectability by artificial intelligence algorithms have been amply demonstrated.[18,20–23,25] However, never before these features have been incorporated into a stand-alone monitoring system conceived for long-term unattended operation. After a detailed investigation, the most significant behaviours indicating the end of the anaerobic/anoxic and the aerobic phases in the case of nitrogen removal were summarized in Table 2, from which it appears that all the relevant information is contained in the rate of change of the signals. These rules differ from those derived in[21] because in that case the process was designed for joint nitrogen and phosphorus removal. The use of the second ORP derivative (see Table 2) is justified by the need to detect the important “nitrate knee” discontinuity, marking the end of nitrite/nitrate reduction and the transition from anoxic into anaerobic conditions.

The controller could be operated in either manual or automatic mode, with additional safety time limits to avoid excessive phase duration. The logical rules were conceived to prevent full nitrification and favour nitritation conditions.

**Table 2.** Significant process transitions used by the pattern recognition algorithm.

<table>
<thead>
<tr>
<th>Phase</th>
<th>End of process</th>
<th>Indicator</th>
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<tr>
<td>Anaerobic/Anoxic</td>
<td>Nitrite/Nitrate reduction</td>
<td>Nitrate knee (ORP second derivative)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sharp ORP discontinuity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ammonia valley ORP discontinuity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DO tend to zero</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pH tends to zero</td>
</tr>
<tr>
<td>Aerobic</td>
<td>Ammonia oxidation</td>
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Process operation

During the first 80 days of the experiment, the SBR was operated with a fixed duration of the anoxic and oxic phases in order to verify the performance of the plant for COD and nitrogen removal. In this run-up period, the basic cycle of 24 hours was divided into 4 sequences of 2 and 3.75 hours of anoxic and aerobic phases, respectively. Due to the leachate characteristics used in this study (Table 1) a concentrated solution (20 g/L) of sodium acetate trihydrate, used as an additional biodegradable COD source for denitrification, was added during the anoxic-anaerobic phase (flow rate of 0.14 L/h) after the leachate feeding pump was switched off. Acetate was added after the feeding phase because the leachate addition can affect the ORP and pH signals[25] and could thus be misinterpreted by the control logic.

After 80 days of manual operation, the controller was switched to automatic operation to adjust the duration of the phases according to the leachate characteristics with the aim of maintaining nitritation condition. The control system was tested for 200 running days and during this period 1090 sub-cycles (anoxic/oxic phases) were performed.

Analytical methods

The plant was monitored online for pH, DO and ORP using WTW instruments. The plant was also monitored (according to the Standard Methods[28]) for total suspended solids (TSS; method 2540 D)), volatile suspended solids (VSS; 2540 E), ammonia (distillation according to the method 4500-NH3 B followed by method 4500-NH3 C or F depending on sample concentration and available amount), nitrite (4500-NO2− B), TKN (4500-Norg B), total phosphorous (Ptot; digestion using persulfate according to method 4500-P J followed by method 4500-P C), total COD (CODt; 5220 D), filtered COD (CODf; 5200 D after filtration) and alkalinity to pH 4.3 (Alk4.3; 2320 B). Nitrate and orthophosphate (PO43−-P) were measured by ionic chromatography (Dionex system DX 500) and conductivity at 20°C (K20) using a WTW ProfiLine Cond 197i conductivity meter. Sample filtration was carried out using Whatman GF/C glass microfibre filter.

Results and discussion

COD and nitrogen removal

Effluent COD was usually higher than 1.0 g/L due to the very low leachate biodegradability (COD removal efficiency of approx. 20–30%). Due to low COD biodegradability, no differences have been observed between the two different experimental periods, before and after the application of the fuzzy controller.[24,26]

During the first 80 days (fixed SBR phase length) nitrogen removal was achieved through the conventional nitrification—denitrification processes (Fig. 3a). Nitrate was the main nitrogen form present in the effluent, while nitrite concentration was usually below 0.5 mgN/L, with an exception around day 60, during which ammonia

Fig. 3. (a) Effluent ammonia, nitrite, ammonia concentration (left axis) and influent ammonia and TKN concentration (right axis); (b) NO2−/NOX (where NOX = NO2−+NO3−) and the NO2−/Ntot (where Ntot = NO2−+NO3−+NH4+) ratios.
and nitrite slightly accumulated in the reactor (Fig. 3a). Thus, the NO$_2$/$NO_X$ (where NO$_X$ = NO$_2$ + NO$_3$) and the NO$_3$/$N_{tot}$ (where N$_{tot}$ = NO$_2$ + NO$_3$ + NH$_4^+$) ratios also exhibited low values (Fig. 3b).

On day 80, the fuzzy control system was introduced. Soon after a substantial nitrite build-up was obtained whereas nitrate decreased to a concentration below 1.0 mgN/L (Fig. 3a). Thereafter nitrite always represented the main nitrogen form in the effluent, with the NO$_2$/$NO_X$ ratio remaining consistently higher than 95% (Fig. 3b). On approximately days 200 and 240, 2 nitrite peaks were observed. They were caused by the malfunction of the feed pump for the external COD addition resulting in a shortage of organic carbon. However, the control system was able to decrease the nitrite concentration after these faults in a few days, once the pump was fixed. Good nitrification efficiency (> 98%) and nitrogen removal efficiency (> 95%) were obtained over the whole experimental period.

**SBR performance under controlled operation**

The fuzzy control system was conceived so as to adjust the duration of the phases according to the leachate characteristics. It was tested for approximately 200 days running and during this period 1,090 subcycles (anoxic/oxic phases) were performed, 1027 (94%) of which were autonomously managed by the supervisory control system, whereas during the remaining 63 subcycles the control system was manually switched off for maintenance (Fig. 4a). Of the 1,027 subcycles performed under automatic control, the supervisory control system correctly detected the end of the phases and the external COD addition in 1,000 cases, with a 97.4% success percentage (Fig. 4b).

The fuzzy controller achieved a generalized cycle length reduction (Fig. 5). The react phases (anoxic+oxic) gradually decreased from 345 minutes, the value set for manual operation, to approximately 200 minutes after 10 days of controlled operation with a further reduction to approximately 160 minutes after 50 more days (Fig. 5). The phase-length decrease was not caused by a decrease of the leachate strength, but was related to a better management of the anoxic and oxic phases. In fact, the cycle duration decreased from 24 hours during the manual operation to an average of 18 hours in the fuzzy operation, with a 25% decrease in treatment time.

To simulate the time-varying characteristics of a real landfill leachate, starting from day 150 the feeding phase was gradually decreased from 12 minutes to 5 minutes in 10 days and then it was gradually increased to 20 minutes in approximately 50 days (Fig. 6a). During this varying feeding phase, the controller adjusted the external COD addition accordingly (Fig. 6a). On the contrary, the duration of the oxic phases first increased with the load, then after reaching a maximum on day 175 it decreased in spite of further load increments (Fig. 6b). Since the nitrification efficiency was not influenced by the loading conditions and no significant change in the mixed liquor TSS was observed, a possible explanation could be that the increase...
The leachate COD content was not included in the estimation of the energy consumption due to the biological oxidative processes. As a result, the daily fraction of the duration of the aeration phase was assumed to represent the ratio between the energy consumption and the amount of nitrogen load (\(d_{\text{aer}}/(gN/L)\)) as an estimation of the energy consumption for aeration.

in the nitritation rate shortened the oxic phase in spite of the increased load. Due to this unexpected behavior, the experiment was later replicated from day 190 to 220 and the same behavior was observed (Fig. 6b), thus confirming the previous hypothesis.

During the last 50 days of operation, the control system was tested by manually changing the length of the feeding phase almost daily (Fig. 6a). These frequent changes resulted in a decreased efficiency in phase-end detection, which frequently coincided with the manual upper value (Time max), meaning that the control system could not identify the end of the reaction phase and reverted to the manual limit (Fig. 5). Furthermore, during the last 20 days the control was repeatedly disconnected (Fig. 4) because of the very high measurement disturbance introduced by probe aging, which in some way “fooled” the fuzzy controller and increased the rate of false positive detection. For this reason, the cycle length was reverted to manual (Fig. 4). Another important aspect considered in this experiment was the aeration energy-saving provided by the fuzzy controller. This saving was estimated by comparing the energy consumption in the manual and controlled modes.

Since air was supplied at a constant flow rate (approximately 60 L/h) and no significant differences in the nitrification efficiencies during the two experimental periods (i.e., manual vs. controlled) were observed, the duration of the oxic phase represents an estimation of the energy consumption due to biological oxidative processes. As a result, the daily fraction of the duration of the oxic processes per day (\(d_{\text{aer}}/(d)\)) to the volumetric nitrogen load (\(gN/(L \cdot d)\)) was assumed to represent the ratio between aeration energy consumption and amount of nitrified N (d of aeration/(gN/L) of loaded N; \(d_{\text{aer}}/(gN/L)\)). The leachate COD content was not included in the estimation because most of the organic matter removal was performed during the anoxic phase. Figure 7 shows this ratio before and after the introduction of the fuzzy controller, demonstrating that the latter produced a significant shortening of the oxic phase: the oxic phase length reduced from (average values) 6.7 (standard deviation of 2.2) and 7.4 (s.d. 2.3) with fixed-time phase length to 3.2 (s.d. 1.4) and 3.5 (s.d. 1.6) \(d_{\text{aer}}/(gN/L)\) with the application of the control system, for TKN and ammonia loads, respectively.

The very high aeration saving, approximately 50% which is twice the theoretical value, can be attributed to a number of factors. Firstly, steering the process towards the nitrite shortcut can generate a decrease in oxygen requirement up to 25%.[6–8] Secondly, the fuzzy controlled operation could have improved the nitrification rate through the selection of ammonium-oxidizing organisms better adapted to the new operational conditions. This could also explain the decrease of the oxic phase length with the increase of the nitrogen load (Fig. 6b). Thirdly, during the first experimental period (manual control), the SBR might have been operated with an oxic phase longer than required by the nitrification process (nitritation + nitratation). These considerations reinforce the conclusion that the fuzzy controller is indeed effective in improving energy-saving during the SBR operation.

The application of the fuzzy controller also produced a considerable improvement in the loading rates. In fact, with the SBR cycle length optimization the COD and N loads substantially increased, reaching a value approximately double of that measured before the application of the control system. The higher loading rate was a consequence of the increased number of cycles per day as a result of the shortened cycle duration, which produced a lower HRT. Moreover, due to the application of the nitrite shortcut, the amount of the external COD required to sustain the denitrification process was reduced by 35%.[24,26]

Conclusions

This paper discusses the benefits of applying a real-time controller to supervise the operation of a lab-scale SBR treating sanitary landfill leachate. The core of the controller is a fuzzy pattern recognition system operating on the time-variations of the process measurements (DO, ORP, pH) to detect the end of each process phase and adjust the process conditions accordingly. In the paper, a test period of over 280 consecutive days of real-time controlled operation was analyzed, during which the fuzzy control system correctly recognized over 97% of the SBR phase transitions, constantly providing the conditions for a sustained nitrogen removal via nitrite, even though the leachate characteristics varied widely. The results obtained in this study can be summarized as follows:

(i) leachate generated by old landfills can indeed be treated with SBR and stable nitrogen removal via nitrite can be achieved if the process is properly controlled;

(ii) the application of fuzzy logic substantially improves the efficiency of the process achieving a major decrease

![Fig. 7. Ratio between time of aeration per day (d_{\text{aer}}/(d)) and the N load (gN/(L \cdot d)) as an estimation of the energy consumption for aeration.](image-url)
in the SBR cycle length, which results in a decreased hydraulic retention time and an increased loading rate (iii) the management of the nitrite route using the developed control system results in a considerable saving of aeration energy.

References


